Ideal site selection of fast electrical vehicle charging stations within urban environments: A GIS-AHP approach

Solidifying electric vehicle charging infrastructure in the city of Amsterdam with fast-charging stations

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Preface

I proudly present my graduation thesis for the Technical University of Eindhoven and the program of Construction Management and Engineering. My time at TU/e has encouraged me to be innovate and this study is a reflection of that. I have always had a passion for sustainability, energy, smart cities and electric vehicles and in this study I was able to touch on each of the subjects. I enjoyed the independence I had with creating my graduation thesis and studying an exciting, interesting and revolutionary topic. I was able to get an in-depth understanding of decision making techniques and develop my skills with GIS software. Needless to say, I am pleased with the results and am happy to have had the opportunity to study at TU/e.

I would like to thank my university supervisors, Dr. Dujuan Yang and Professor Theo Arentze, for the great advice and the time invested in helping me. I appreciated the feedback during meetings and keeping my on track.

I was thrilled to team this study with Fastned, a Dutch start-up company expanding the network of fast-charging throughout the Netherlands. Collaborating with the people at Fastned gave the study a realistic insight and made it much more interesting for me. I liked knowing that this study could eventually help make real-word decisions. I would like to thank the members of Fastned for their hospitality, advice, and knowledge.

Lastly I would like to thank my family, friends, and especially my girlfriend for the endless support and encouragement. My time in the Netherlands has been special and I know I have grown to be a better person. Without you it would not be possible!

Sincerely,
Geoff Ward

Abstract

Electric mobility and electric vehicles (EVs) have been recent areas of focus for much of the developed world. One country in particular, the Netherlands, has experienced a striking acceptance of EVs in the last years highlighting their commitment to alternative forms of mobility. This trend will continue as the Dutch government aims for 1 million EVs on the road by 2025. An impressive supporting network of public slow-charging points has been placed throughout the Netherlands to support EV acceptance and curb range anxiety. Long charging times and capacity limitations with slow-chargers have created an inefficient charging network that has a low charge-to-vehicle turnover rate. A new charging technology, fast-charging, significantly reduces charging time to 20 minutes or less, considerably quicker than slow-charging. So far, fast-charging only makes up about two percent of the public charging infrastructure in the Netherlands and the majority of these stations are located in rural areas along highways. Urban environments are prime areas for fast-charging stations but have largely been unrealized. This study uses a geographical information system (GIS) based analytic hierarchy process (AHP) approach for selecting ideal locations for fast electrical vehicle charging stations in Dutch urban environments. The synergies of a GIS-AHP tool allow for effective decision making while considering multiple, and often conflicting urban factors. The study has been teamed with Fastned, an innovative Dutch company who is leading placement of public fast-charging stations in the Netherlands. Fastned's expert knowledge is used to judge the importance of selection criteria, resulting in criteria weights for created GIS layers. GIS layers are combined following the AHP structure to reach the final objective layer. The synergistic method develops an efficient, realistic and geographically substantial solution to the complex decision-making problem of fast-charging site selection within Dutch urban environments, and will examine the case study city of Amsterdam. An analysis of top site selections and their urban characteristics are presented. The sensitivity analysis proves the tool is effective at incorporating expert knowledge into the tool. The working GIS-AHP tool has proven to be flexible and powerful for decision makers and will act as evidence that a selected fast-charging station location is truly ideal based off of urban characteristics. This study has been the first of its kind to use a GIS-AHP approach towards location-allocation for electric vehicle fast-charging stations.

Chapter 1 Introduction

Electric vehicle (EV) adoption has been a growing trend throughout the developed world in the last decade and is forecasted for continued growth. The shift toward EVs can be attributed to advantages over traditional internal combustion vehicles (ICEs): (1) electric vehicles are environmentally friendly as they have zero direct emissions, (2) are more efficient in a well-to-wheel comparison, (3) have the highest of safety ratings, (4) and are virtually noiseless. The effects of climate change, worsening air-quality levels, and worries about the future of fossil fuel availability are turning consumers against traditional transportation practices. Several countries and municipalities throughout the world have set ambitious targets for the number of EVs on their roads, in hopes to reap the numerous benefits of the newest trend in the automobile industry. EVs still have obstacles to overcome before they are widely accepted as a dependable mode of transport. Concerns over EVs are (1) battery range, (2) long recharging times and (3) an inefficient public charging network. Concerns can be addressed with an efficient charging infrastructure at the public's disposal to support the number of EVs on the road. The disadvantages are beginning to evaporate as charging locations are expanding and charging and battery technologies are being improved.

1.1 Problem definition

In the Netherlands, the EV market and charging infrastructure demand are experiencing exponential growth, which will continue for the next ten years with the incredibly ambitious goal of 1 million EVs on the road by 2025. Market growth needs to be sustained with a fast and efficient charging network that can support the future demand of electric vehicles. Currently, slow-charging points have supported the number of EVs in the Netherlands but this technology has limitations with available space and long, inconvenient charging times. Fast-charging is an upgraded charging technology that can charge more cars in less space, in less time, and with less energy loss. Fast-charging stations are beginning to be developed in the Netherlands, but mainly in rural areas along highways to act as charging links between cities. Dutch urban environments contain the majority of the country's inhabitants and EV demand and thus have the highest need for public charging facilities. The inefficiencies of the current public slow-charging infrastructure will hinder EVs being used on a mass scale**.** The complexities and uncertainties of site selection in a city is an issue for decision makers, impeding effective fast-charging placement even if Dutch cities are a prime environments for fast-charging placement.

An opportunity has presented itself to expand the scientific community's view on the field of location-allocation problems. Past approaches have used optimization models that are solved by algorithm procedures. Qualitative factors are missing from these approaches. Including qualitative criteria and expert knowledge into decision making is useful for the accomplishing the goals of decision makers. Furthermore, a geographic solution will give a simple, visual result to the complexities of decision making in urban environments. This research will shed light on a new approach within the quickly evolving field of electric mobility. The research problem is then a combination of the two identified problems. Together they read:

"There is an absence of expert knowledge within fast-charging location-allocation problems."

1.2 Research objective and questions

The objective of this study is to develop a geographic tool which is able to analyze Dutch urban environments while considering fast-charging factors. In the end, the analysis needs to reveal which locations in the city are preferable for fast-charging station development. The city of Amsterdam will be the case study city to test the tool because of its commitment of electric mobility and complexity as an urban environment. The analytic tool will need to facilitate the decision making process, provide geographic results to adequately address the research questions and solve the research problem(s). From an academic standpoint the objective is to explore location-allocation as a site selection tool, choose an applicable and substation model, and test the model's significance in a verifiable application with fast-charging stations. The ultimate question of the study is:

"How can the best fast-charging locations be selected within Dutch urban environments?"

Asking the main research questions brings up additional related questions such as: (1) which factors make a fast-charging station ideal? (2) Which factors are most important when deciding on a fast-charging location? (3) How effective is the selected model as a site selection tool? (4) How can this research model be improved and extended?

1.3 Research methodology

The selected research method is geographic information system paired with the decision making technique, analytic hierarchy process. Abbreviated GIS-AHP, the method was selected because of its strong synergies emerging from the combination of two dependable techniques. The method contributes advantages in group decision making, can include expert knowledge into the location selection process, and visually represents data as mapped results. In addition, the GIS-AHP approach fills a missing gap in field of electric vehicle charging station (EVCS) location-allocation. Fast-charging site selection is a location-allocation problem, meaning there are conflicting factors and locations to consider. There are many approaches to solving such a problem, but it depends on the research objectives. This research considers the objectives of the supporting fast-charging company, Fastned, who are leading the placement of fast-charging stations in the Netherlands, and plan to expand their stations in urban environments. An ideal location must satisfy additional stakeholders such as: the local municipality, grid company, and local EV users.

GIS are powerful tools for spatial analysis which provides functionality to capture, store, query, analyze, display and output geographic information (Rikalovic, Cosic, & Lazarevic, 2014). GIS not only has the ability to represent the reality of our world through digital maps and data sets, it has the power to manipulate and analyze. Most data used by managers and decision makers are geographical which makes the use of geographic information systems a natural method to select for a site selection problem. GIS can be designed as a systems for the resolution of complex problems of planning and management (Sanchez-Lozano, Teruel-Solano, Soto-Elvira, & Garcia-Cascales, 2013). GIS tools are commonly used in conjunction with other methods such as the method for multi-criteria decision making, location allocation, and agent based modeling. There are two types of GIS data representations: (1) raster datasets and (2) vector datasets. Raster datasets are represented by a mesh or grid of rectangles. Each element is called a cell or pixel and has information and geographic information assigned to it. Vector datasets maintain geometric features of the represented figures by being displayed as dots, lines, and polygons.

AHP is a specific, structured technique of multi-criteria decision making (MCDM) that models a decision problem using a hierarchy whose apex is the main objective of the problem and the possible alternatives to be evaluated are located at the base (Sanchez-Lozano, Teruel-Solano, Soto-Elvira, & Garcia-Cascales, 2013). The structure is composed of specific decision factors, called selection criteria, which lead to the main decision objective. AHP is particularly applied to group decision making and is a flexible technique used to find the best suited decision based on a specific goal. The technique combines mathematics and psychology to include human perception and judgements into the decision. AHP is often implemented with GIS to bring out the advantages of both methods. Combining GIS and AHP creates a noticeable synergy, allowing expert opinions and decision makers' preferences to be captured and represented as a geographic solution.

1.4 Research process

Because of the nature of the selected method, the research process is split into two phases. The first phase will generate selection criteria based on a literature review, university advice, and expert knowledge, and construct the AHP structure. Fastned, a company collaborating with the research, will complete a pairwise comparison survey which ranks selection criteria in order of importance and provides the criteria weights. Criteria weights will be incorporated into the GIS data with the software QGIS. The first process phase will complete objectives regarding critical fast-charging factors and decide which factors are most important.

The second phase is about building the GIS side of the tool in the software QGIS. GIS datasets found from open sources are processed and manipulated into representable layers for the case study urban environment. Each layer will match up with the determined selection criteria from the first phase. The finalized tool will be able to analyze open source GIS data and reveal ideal locations in the case study city to develop fast-charging stations based on expert judgements. The GIS-AHP tool will be tested through a sensitivity analysis to see how ideal selection changes when expert opinion and criteria weights change, and to establish the tool's level of certainty. Results from the second phase will be give answer to the main research question and the sub question over the tool's effectiveness. The study will end with overall conclusions, discussions, and further recommendations

Figure 1.1 is the research process model for this study. The two distinct phases can be seen by the model's paths. The left path describes the AHP technique to form selection criteria and criteria weights that will be used for the QGIS layers. On the right is the GIS tool development. Reworks of the questionnaire and GIS layers are added to insure quality and that the research is meeting the goals and the research objectives. Supervisors and company experts help decide when the two phase decisions are adequate.

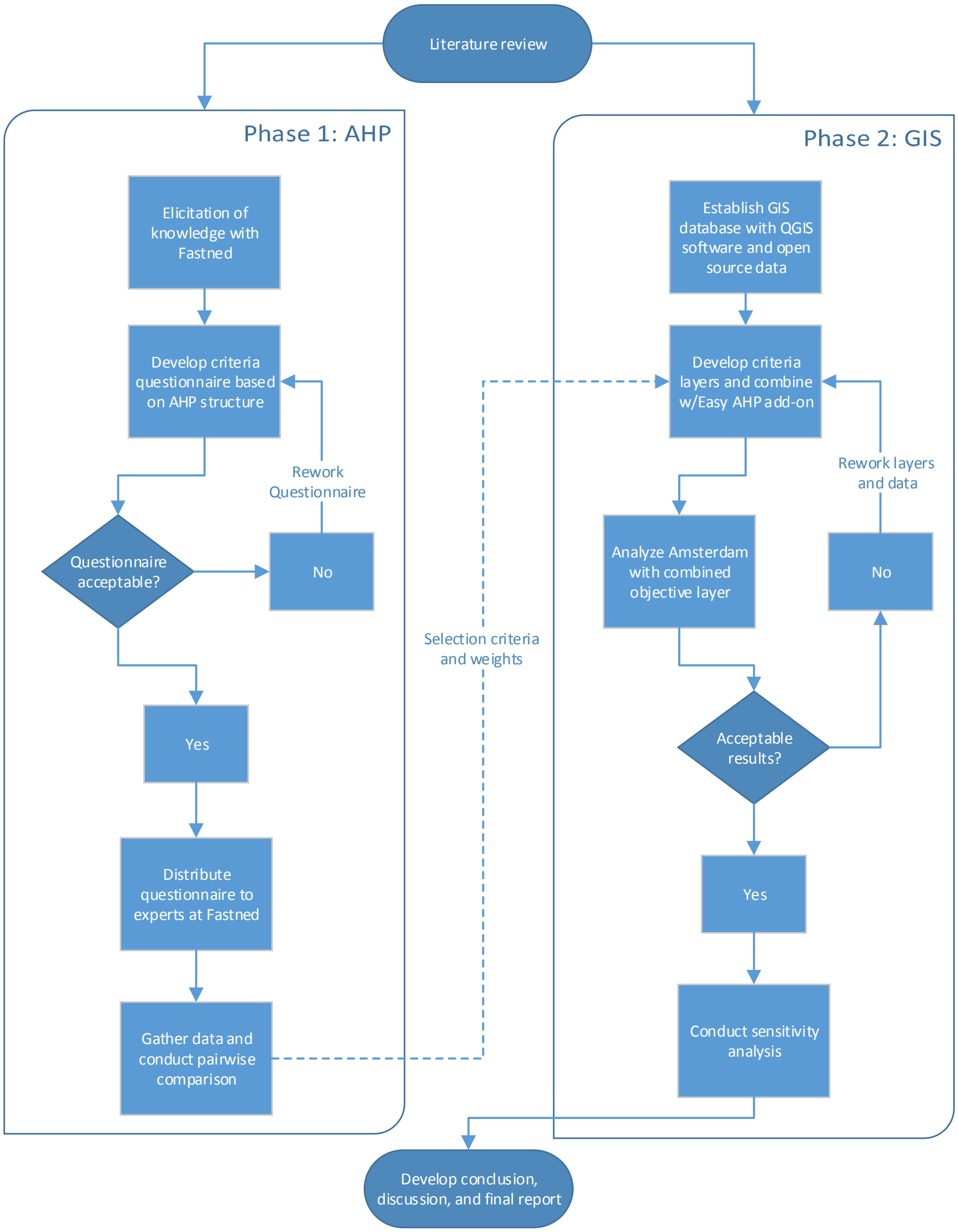


Figure 1.1: Research process model

1.5 Expected results

Research results will aid decision makers when developing fast-charging stations within Dutch cities. Results will extend the understanding of what factors go into an ideal location for fast-charging stations and rank by order of critical importance. Furthermore, the research explores the method GIS-AHP as a location-allocation solution toward the field of EVCS. The following results have been expected:

- List of important selection criteria for fast-charging with weighted rankings;
- Stakeholder objective-based hierarchy structure of selection criteria;
- GIS layers which represent all selection criteria and the final objective layer;
- Top locations for fast-charging stations in the case study city of Amsterdam with defendable evidence;
- Insightful discussion about location characteristics and research limitations;
- Recommendations for research extensions.

Chapter 2 Background

The quickly evolving topic of electric vehicles is popular and dynamic. Excitement over the new innovation has sparked a vast amount of studies, especially in the field of charging point location selection, aimed to understand and support the new market. In order to keep up with the fast-paced field, only literatures published within the last five years were reviewed to keep relevant.

This section aims to familiarize the reader with the basics of electric mobility, electric vehicles, charging methods, and the organizations who are working to grow and innovate the EV market. There is an examination of the Netherlands and how they are a world leader in EV implementation with a focus on the capital city of Amsterdam. The background section ends with a clear idea of why EVs are advantageous over traditional mobility and why fast-charging stations are critical to the future success of the EV market.

2.1 Electric vehicles

Electric mobility relates to the electrification of the automobile, which boils down to propulsion by an electric motor, powered by electric battery and recharged by the flow of electricity. It may be thought that this form of transportation is only recently invented, but came into existence in the mid-19th century and was amongst the earliest automobiles until the internal combustion engine (ICE) became the dominant and most popular automobile. As the number of ICEs rose, a supporting infrastructure was built around the ICE including a vast road network and countless refueling stations, which, for the time being, halted the potential for electric vehicles.

Nowadays, EVs are making a case for the future answer to the world's mobility problems. With concerns over climate change, energy security, environmental impacts, health risks and the continued growth demand in transportation services, there is an important movement to turn away from traditional combustion engine vehicles and towards emission free electric vehicles (Guo & Zhao, 2015). EVs show promise to enhance mobility while reducing impact on the environment because they offer a lower operating cost than combustion engine cars, they are emit no pollution, and are almost noiseless (Wang & Lin, 2013). The benefits of EVs are beginning to be noticed by consumers and the conventional automobile market is facing a fundamental change.

EVs face an uphill battle against an established ICE market. Inconvenient charging times, limited driving range, and a poor public charging infrastructure have been main concerns. Change is beginning to take place as new technology innovations are improving battery range and decreasing charging times. Government subsidies and tax incentives have been important to encourage EV adoption and fuel the growth of the EV market. Electric mobility has the power to create economic opportunities and improve the way the world moves. In the past few years, Europe has gone through the initial adoption phase of electric mobility (Amsterdam Roundtables Foundation, 2014).

EVs can fall into a wide range of mobility types. This definition includes plug-in hybrid electric vehicles (PHEV), range-extended electric vehicles (REEV), full battery electric vehicles (BEV or FEV) and fuel cell electric vehicles (FCEV), but excludes (conventional) hybrid electric vehicles (Amsterdam Roundtables Foundation, 2014). *In this research, only full electric vehicles and* *plug-in hybrid electric vehicles will be considered, since these types have potential to use public fast-charging.* It must be noted that the majority of current PHEVs and some FEVs are unable to fast-charge due to their battery type, though, this will change in the future as battery technology innovation takes place.

2.1.1 Batteries and range

Batteries are considered a key elements to the success of EVs as they ultimately decide driving range and charging speeds. Batteries for recent EVs are primarily based on Li-ion technology (Amsterdam Roundtables Foundation, 2014). Size and capacity vary depending on the manufacturer and car model. For example, the 2016 Nissan Leaf offers a 24 kWh and 30 kWh Li-ion battery which can travel up to an advertised 135km and 172km, respectively. While the Tesla Model S has the option for a 70 kWh and 85 kWh Li-ion battery which can travel up to a rated 390 km and 426 km, respectively. Studies have shown the typical range of EVs (100-130km) is more than sufficient for the majority of journeys in one day (Hatton, Beella, Brezet, & Wijnia, 2009). Therefore, EVs can cover most people's daily commute. Still, electric vehicles batteries have a low energy density compared to liquid fossil fuels which has hampered full-scale market penetration (Hatton, Beella, Brezet, & Wijnia, 2009). It is expected that battery technology innovation will continue to substantially improve range, power capacity, and power density.

2.1.2 Advantages

The shift towards EVs is for a simple reason; an increase of advantages in mobility for consumers. Advantages over a traditional ICE vehicle include:

Zero greenhouse gas emissions - EVs have zero emissions from driving if the electricity is generated from renewable energy sources (Speidel & Braunl, 2014) such as solar, wind, hydro, or bio-mass power. This results in a substantial carbon footprint reduction and a 'green' solution to mobility.

Energy efficiency - Well-to-wheel studies have proved the EVs improved energy efficiency compared to conventional vehicles, even when charging from comparable fossil fuel generated electricity (Dharmakeerthi, Mithulananthan, & Saha, 2014). This improvement is approximately 3 times higher than an ICE (Mobility and Transport, 2012). EVs get the most out of the energy source and conserve valuable energy resources.

Noise reduction **-** EVs are practically noiseless compared to the internal combustion engine, especially at low speeds, reducing noise pollution from traffic. They produce so little sound that there is concern that pedestrians will be unable to have adequate warning for an approaching vehicle. Quite mobility will reduce disruption of nearby inhabitants and the environment.

Improved safety - No combustion engine or heavy components located directly in front of the driver allows for additional engineering and space to absorb head-on impacts. The Tesla Model S has boasted one of the highest safety ratings of any car produced with a perfect 5-start rating (Tesla Motors, 2013).

Lower operation cost – Electricity prices fluctuate based on geographic region, but the price per distance traveled is less expensive compared with ICEs. The uncertain price of petrol fuel is also a consideration as high petrol prices turn EV into a considerably less expensive operational form of mobility.

2.1.3 Disadvantages

EVs have their share of negative factors for the time being. Highlighted drawbacks are:

Insufficient charging infrastructure - Absence of proper charging infrastructure is a cause for range anxiety (Tu, Li, Fang, Shaw, & Zhou, 2015). Range anxiety is where the EV driver fears running out of fuel before reaching their intended destination or next charging point, which is an obstacle to mass deployment (Zhang, Schaffer, Brown, & Samuelsen , 2015).

Limited driving range **-** Battery capacity limitations means that EVs can only travel a short distance (in comparison of ICEs) before needing to recharge, depending on the exact vehicle and battery characteristics.

Long charging times **-** A typical slow-charging session takes 4 – 8 hours. This is much longer than the ICE refueling time of around 5-10 minutes.

High initial investment **–** Innovative products are generally more expensive than established products. This is the case for EVs as initial purchasing costs are higher than ICEs.

Grid Impact **–** A negative impact on the electrical grid operation can occur in the case of an uncoordinated contemporary charging of a huge number of EVs (Sbordone, et al., 2015). Consequences can be power outages and voltage fluctuations.

When consumers believe the advantages of EVs outweigh the disadvantages, the automotive market shifts. Further improvement in battery and charging technology will further help tilt the scales towards the argument for EVs. Technological developments could change charging behavior and the need for charging infrastructure in the future (Amsterdam Roundtables Foundation, 2014).

2.2 Charging infrastructure

Electric vehicle charging points are an important element of electric mobility by supplying electric fuel for EVs. The establishment of a convenient recharging system is one of the most important factors to encourage the widespread use of EVs (Wang & Lin, 2013) and the growth of the EV market (Shahraki, Cai, Turkay, & Xu, 2015). Achieving this goal has been approached in different ways including battery swapping, induction charging, and the most commonly known, wired charging using a cable and plug. Chargers, or a charging point, refers to a single grid connection mechanism. Chargers can have one or more charging cables to service multiple EV models. A charging station is two or more chargers, made for a higher service capacity and much like a traditional refueling station.

The majority of electric vehicle chargers are located in private settings, either at home or work spaces. Other chargers are considered semi-public as they are available to a select group of people, through clubs, organizations, or other restricted spaces. Public electric vehicle charging points have been emerging in order create an ample refueling range for EVs, and reduce the phenomenon of range anxiety. Charging stations and chargers are not all equal and are generally split into two categories: slow-charging and fast-charging. The categories are separated based on power output in the unit of kilowatts (kW), the form of electric current, either direct current (DC) or alternating current (AC), and the type of plug adapter. Plug types include the CHAdeMO adapter, CCS (Combo) adapter, and the AC (Mennekes) adapter. The AC "Mennekes" adapter is typically for slow-charging and, as the most common, is considered the standard of Europe. For fast-charging, the Japanese designed CHAdeMO and US/European CCS adapter are most common. A charger diagram can be found in the appendix (figure A.1).

The charger power level is the main parameter that has an influence on charging time, cost, equipment, and effect on the grid (Sbordone, et al., 2015). The International Electrotechnical Commission (IEC), an origination setting standards for electric technologies, denotes four standard modes of chargers: (1) *mode 1* – slow-charging from a common electrical socket, (2) *mode 2* – slow-charging from a regular socket with protection arrangement, (3) m*ode 3* – slow or fast-charging using specific EV multi-pin socket with control protection functions and (4) m*ode 4* – fast-charging using special charger such as CHAdeMO.

Table 2.1: Charger overview

<table>
<tr><th>IEC mode</th><th>Type</th><th>Power rating</th><th>Current</th><th>Availability</th><th>Charging time</th></tr>
<tr><td>1</td><td rowspan="4">Slow</td><td>3.3 kW</td><td rowspan="2">AC - Singe phase</td><td>Private</td><td>6-8 hours</td></tr>
<tr><td rowspan="2">2</td><td>7.4 kW</td><td rowspan="3">Private and public</td><td>3-4 hours</td></tr>
<tr><td>10 kW</td><td rowspan="3">AC - Three phase</td><td>2-3 hours</td></tr>
<tr><td rowspan="2">3</td><td>22 kW</td><td>1-2 hours</td></tr>
<tr><td rowspan="3">Fast</td><td>43 kW</td><td rowspan="3">Public</td><td>20-30 minutes</td></tr>
<tr><td rowspan="2">4</td><td>50 kW</td><td rowspan="2">DC</td><td>20-30 minutes</td></tr>
<tr><td>120 kW</td><td>10 minutes</td></tr>
</table>

Slow-charging inefficiencies

Slow-charging has helped set a foundation for EV growth, though, the inefficiencies are too evident to ignore. A lengthy charging time is challenge for acceptance of EVs (Tu, Li, Fang, Shaw, & Zhou, 2015) typically taking between 4 – 8 hours per vehicle. Speidel and Braunl (2014) revealed striking inefficiencies related to slow-charging. It was discovered that 24% of the total energy of a slow-charging point is used to maintain the charge when the EV is fully charged. In addition, 8% of the time parked was used to charge the EV while the other 92% was used to maintain the charge. This results in a high *capacity utilization,* the time a charging point is occupied by an EV divided by the total time the charge point was available, and a low *charge utilization,* the time an EV is actually charging divided by the time the car is connected (van den Hoed, Helmus, de Vries, & Bardok, 2013).

Fast-charging is an innovation in the charging industry which dramatically reduces charging times. Fast-charging takes 20-30 minutes or less (Sadeghi-Barzani, Rajabi-Ghahnavieh, & Kazemi-Karegar, 2014). The efficiency increase creates a situation where 20 slow-charging stations would be equal to one fast-charging station. Furthermore, the nature of fast-charging is closer to traditional petrol refueling stations. EV users will charge and leave, meaning fast-charging stations will have a high *charge utilization*, and the charging point will not function as a parking space like slow-charging.

Fast-charging will eventually overtake the vast majority of public slow-charging stations and are already record the highest usage frequencies (Morrissey, Weldon, & O'Mahony, 2016). In 2012 there were 4200 fast-chargers installed world-wide and by 2020 it is anticipated that there will be approximately 460,000 installed (Jerram and Gartner, 2012). For the time being, fast-charging is in its infant stages but EV drivers tend to prefer fast-charging points (Neubauer et al. 2012). Priority should therefore be given to developing a highly connected network of strategically located fast-chargers before developing other locations where possible (Morrissey, Weldon, & O'Mahony, 2016). Fast-charging has an opportunity to become the refueling facilities of EVs.

2.3 EV situation in the Netherlands

EVs have recently gained popularity in the Netherlands. The Netherlands boasts the world's second largest EV fleet per capita at 1.7 EVs per 1,000 people (Electric car use by country, 2015). In 2014 the Netherlands experienced a 53% increase in electric vehicles on the road to a total over 46,000 (Electromobility in the Netherlands, 2015) with Tesla model-S as the most sold full EV in the Netherlands (Spoelstra, 2014). Figure 2.1, shows a steady growth of fully electric vehicle registrations from 2010 through 2014. As of September 2015, the total number of registered electric vehicles on Dutch roads reached over 63,600, another 37% increase in just nine months (Electric car use by country, 2015). Taxi services and car sharing services are also shifting toward EVs for their businesses with companies such as *Taxi Electric* and *Car2Go*.

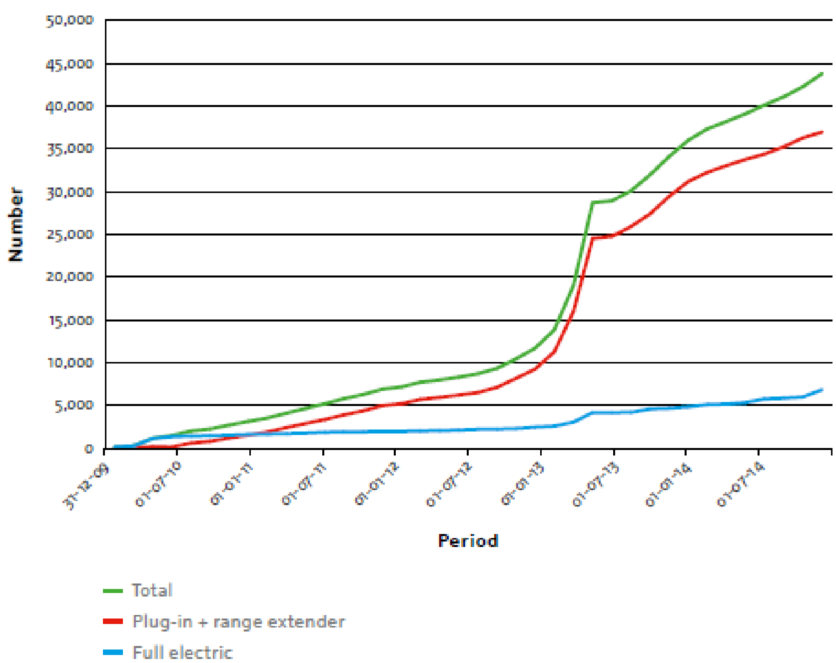


Figure 2.1: Electromobility Growth in Figures (Electromobility in the Netherlands, 2015)

Success of EV growth can partially be attributed to government policies, incentives and goals. The Dutch government offers lucrative tax breaks to EV customers and certain municipalities, such as Amsterdam, offer a cash subsidy for purchasing or leasing an EV. These sorts of policies have made it economical to become an EV driver, which has contributed to such high numbers of EVs on Dutch roads. But the Netherlands is just getting started. *The Dutch government aims to increase the numbers of EVs on the road to 200,000 by 2020, and 1,000,000 by 2025* (Electromobility in the Netherlands, 2015)**.** To meet this ambitious goal, the current number of EVs will have to be quadrupled in the next five years, and increased 20-fold in just 10 years. The EV market in the Netherlands has already experienced five solid years of EV growth and has goals for 10 more years at the same exponential pace.

Charging infrastructure in the Netherlands

It is not surprising that the high number of EVs in the Netherlands has been matched with a public charging infrastructure to provide the fuel of electricity. The Netherlands now has the highest number of charging stations per electric vehicle (Electric car use by country, 2015). The extensive charging network in the Netherlands has insured that EV drivers have a reachable option to refuel, no matter travel behaviors. The charging network has greatly reduced range anxiety. The charging network, while vast, is almost entirely composed of slow-charging points. At the end of 2014 there were 5,400 slow public charging stations, 6,400 slow semi-public charging stations, an estimated 28,000 slow private charging stations, and more than 250 fast-charging stations. Still, in the coming years the Netherlands anticipates substantial growth in the number of charging points in the country (Spoelstra, 2014). Charging station growth in the Netherlands can be seen in table 2.2.

Table 2.2: Charging stations in the Netherlands (Electromobility in the Netherlands, 2015)

	End of 2011	*End of 2012*	*End of 2013*	*End of 2014*
Public (freely accessible 24/7)	1,250	2,782	3,521	5,421
Semi-public (limited public access)	576	829	2,249	6,439
Private	-	4,500 - 5,500	18,000	28,000
Fast-charging stations	14	63	106	254

Slow-charging points are widely accessible in the Netherlands but the turnover rate of EVs charged per day is low. With slow-charging taking 4 - 8 hours per full charge, the maximum turnover rate is, in theory, 3 – 6 EVs per charging point per day. Additionally, slow-charging points in the Netherlands have been combined with parking spaces creating a conflict in the intended service of the space. The function of a slow-charging space is partially to charge the EV and partially to park the vehicle. Nearly 88% of charging transactions in the Netherlands lasted three or more times the theoretical time (Spoelstra, 2014). Slow-charging stations in the Netherlands are being used well beyond their intended use from a charging standpoint.

Slow-charging has played a crucial role in supporting the Dutch EV market but if the Netherlands is to reach their ambitious 2020 and 2025 EV goals, a more efficient charging system that can deliver a higher turnover of fully charged EVs needs to be established. Widespread use of EVs depends mainly on availability of public fast-charging stations (Sadeghi-Barzani, Rajabi-Ghahnavieh, & Kazemi-Karegar, 2014). A single fast-charger has a theoretical turnover rate of 48 - 72 EVs per day, a big improvement on slow-charging. In addition, the cost per EV charging capacity is lowered with fast-charging. In 2014 the number of fast-charging stations in the Netherlands grew from 106 to 254. The majority of these new fast-charging stations can be attributed to the Dutch start-up, Fastned. This company is currently installing an average of one new fast-charging station per week at rest areas along Dutch highways (Electromobility in the Netherlands, 2015). Tesla Motors has also constructed three Supercharger stations in the Netherlands, though these stations only work with Tesla vehicle models. Fast-charging currently controls a small percentage of the charging market in the Netherlands but this service is predicted to grow. The next 10 years will be a time for accelerated growth in the current charging infrastructure (Electromobility in the Netherlands, 2015).

Table 2.3: Fast-charging vs slow-charging

Charging type	*Charge time*	*Maximum turnover per day (EVs)*	*Estimated installation cost (€)**	*Approximate cost per charger capacity (€/EVs per day)*
Slow-charging point	4-8 hours	3 - 6	10,000	1,670 - 3,330
Fast-charging point	20-30 minutes	48 - 72	50,000	694 - 1,042

** Provided by fast-charging experts*

2.4 Urban environments: case study city of Amsterdam

More people in the Netherlands live in an urban environment than in rural areas (Urban population outnumber rural population, 2005). The high density of cities creates a limiting factor: space. A majority of Dutch urban households are unable to charge their EVs at home. Urban environments are important and attractive for placing fast-charging stations since cities have high densities of traffic, population, and most importantly, EV users. Minimal noise pollution, emission pollution, and vibration make EVs optimal for use in densely built urban environments and residential areas (Hatton, Beella, Brezet, & Wijnia, 2009). The majority of fast-charging stations in the Netherlands are not conveniently accessible to people living in Dutch cities because they are being placed along highways. But demand in for charging is clear as slow-charging stations are common in Dutch cities already. The city of Amsterdam has over 1,100 public slow-charging stations as of February, 2015 and the Amsterdam City Council plans for 4,000 stations by 2018 (Charging data Amsterdam Electric, 2015). To further encourage EV use, Amsterdam offers a 5,000€ subsidy per EV from the purchase price, no waiting for a parking permit, has 4 parking garages with free charging, and offers exemption from registration tax and annual circulation taxes (Amsterdam Roundtables Foundation, 2014).

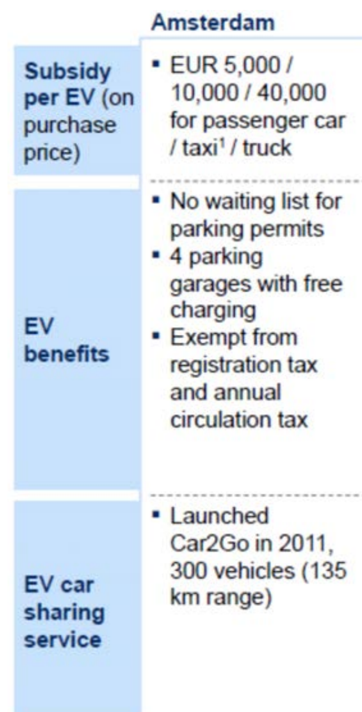


Figure 2.2: EV incentives Amsterdam (Amsterdam Roundtables Foundation, 2014)

The case study city of Amsterdam clearly has a strong demand for public charging but the city is focused on slow-chargers. As EV users grow in cities, the availability of charging stations will become critical. This makes Amsterdam a striking market for public fast-charging stations and an excellent example city. Developing a fast-charging station network in urban environments is an innovation that will improve smart mobility and push the adoption of clean emission, electric vehicles. Furthermore, the uniqueness of the examined urban environment is important to understand for effective decision making.

Stakeholders

The advantages of EV and fast-charging can be appreciated from several aspects and, therefore, includes a variety of stakeholders with their own prerogative. It is important to take each stakeholder's opinion into play to keep a realistic balance. For example, the best choice for investors is not always the best for EV owners and the electric utility (Sadeghi-Barzani, Rajabi-Ghahnavieh, & Kazemi-Karegar, 2014). Stakeholders in fast-charging can include countless private companies that design, engineer, manufacture, and distribute components to build EVs and charging equipment, governments that support innovation and growth, and end users who use EVs daily. An EVCS infrastructure must consider roles of the suppliers, operators, and customers (users) (Hatton, Beella, Brezet, & Wijnia, 2009). This study's objectives focuses on four main stakeholders. These stakeholders jointly and collaboratively explore possible solutions during the modeling process so as to reach consensus (Ssebuggwawo, Hoppenbrouwers, & Proper).

Fast-charging company (Fastned) - A fast-charging company is a commercial entity who finances, designs, and develops fast-charging stations with a business mentality. Fastned is a private Dutch company founded with the goal to build fast-charging infrastructure and to end the dependency on traditional fossil fuel burning vehicles. Fastned's plan, which is referred to as the 'Fastned Freedom Plan', to first develop a 200 station network of fast-charging stations in the Netherlands along highways before rolling out the network throughout Europe. Stations have only been placed along Dutch highways to insure EV users can reach any part of the Netherlands but new station development is being planned in urban environments.

EV Users - An EV user is anyone who owns and operates and EV and can benefit from the placement and use of fast-charging stations. EV users are private citizens who need to charge for personal mobility or businesses who rely on EVs for commercial uses. It is possible that commercial EV ventures develop in the future such as electric car sharing or transportation companies who would have a demand for fast-charging stations.

Local municipality (Amsterdam) **-** The city of Amsterdam has invested heavily in their current charging infrastructure and take pride on their leading role. They will want to insure any placement of fast-charging is well thought-out and can benefit the city while minimizing disruption to the environment and grid impact. Furthermore, the demand for public charging spaces in urban areas will be high because the majority of EV drivers in cities will not be able to recharge their vehicles on private grounds (Kanters, 2013).

Grid Company (Liander) **-** The electricity grid is the energy supplier and connection point for all charging stations. A rapid and significant EV load integration to the power grid is anticipated (Dharmakeerthi, Mithulananthan, & Saha, 2014). Using the grid on a mass scale and a high energy demand are a concerns to the grid company operators, specifically during peak intervals and with fast-charging. Mass charging during a peak demand can have a negative impact on electric grid operations (Sbordone, et al., 2015). Grid companies will prefer fast-charging stations to be located where they have the least impact on the grid and operate responsibly.

2.5 Issue at hand

In the Netherlands, public EV charging infrastructure is growing parallel with the growth of EV adoption. In the next 10 years, EV acceptance is expected to reach the early adopter phase. The current network of slow-charging has a low charge turnover rate and doubles as a parking space, which is not an efficient use of space. With the anticipated exponential growth of the Dutch EV market, cities will have to be prepared to support the demand for electric mobility on a larger scale. Fast-charging has the capacity to charges more EVs in less time than slow-chargers. Complexities of cities make it critical to place a fast and convenient charging infrastructure. A solution is needed to identify ideal locations for fast-charging stations in Dutch urban environments while considering stakeholder objectives.

Chapter 3 Urban modeling and analysis

This section will outline techniques used to solve site selection problems in urban environments and examine past studies showing their relevant applications and tailored usefulness. Literatures over electric vehicles site selection will be dissected in order to reveal: (1) a gap in the current set of knowledge and (2) the reason a GIS-AHP method is the best choice for this application. The outline begins with the different location-allocation methods and goes into details over fundamental differences, analysis procedures, example studies and a summary of the advantages and disadvantages. Next, the selected method of GIS-AHP is explained through literatures and combination synergies. Lastly, there is an identification of what is lacking in past studies and what this one will accomplish.

3.1 Location-allocation

Selecting optimal locations for facilities, no matter the facility's function, is a critical decision for the future success of an organization. A location-allocation model is a method for finding optimal sites for facility locations (Rahman & Smith, 2000). The problem at hand is then a location-allocation problem. The term 'location-allocation' refers to two basic elements of the models: (1) determining the locations of facility outlets and (2) allocating consumers to outlets in order to evaluate the performance of the system (Arentze, Location Allocation Models, 2000).

There are many different approaches to determining the performance of the system; each approach aimed at answering the particular objective of the facility. Objectives are essentially stakeholder interests including consumer, commercial, governmental and community facets. There are a multitude of method types and paired analysis procedures. Procedures apply a mathematical process to find the solution in the defined network or system. In the end, a location-allocation model aspires to represent the reality of a network and make an informed location decision, while satisfying decision maker's goals.

3.2 Network-based optimization

Network-based optimization models operate on the variables and constraints of a specific network. Variables commonly include number of facilities, location of facilities, size of facilities, and proximity distance. Optimization results focus on the network as a whole and how the locations interact with one other and the demand in the system.

A popular method for facility location within a network is the *p*-median model. The *p*-median model aims to maximize the accessibility of a facility by minimizing the total distance needed to travel to the facility location by consumers, or other entities. This model takes a set number of facilities and discrete demand in a network and locates facilities so the weighted travel distance or time between facilities and demand is minimized. Network methods assume that demand will select the nearest facility location. A notable extension of the *p*-median modal is the min-max model. The min-max model has an objective to locate facilities in order to minimize the network's maximum travel distance. The maximum covering model find the location of a given *p*-median number of facilities that maximized the number of consumers covered by the network (Arentze, 2000). This model insures there are no gaps in the facility's coverage and all demand is being met with a set number of facilities. The set-covering model looks to find the minimum number of locations and their respected locations in order to cover all demand, with a specific distance radius. This model is similar to the maximum covering model except the number of facilities is to be minimized. Other location models include: flow capture location model (Tu, Li, Fang, Shaw, & Zhou, 2015), hierarchical clustering analysis, two-stage stochastic program, and agent-based decision support systems (He, Wu, Yin, & Guan, 2013).

3.2.1 Procedure

Evaluating the performance of the network relies on a set of variables and constraints which are to be optimized; either minimized or maximized depending on the objective. Variables and constrains are represented as a mathematical formulas to simulate real-world behaviors. These include *linear programing*, *integer linear programing*, and *non-linear programing* and are referred to as exact methods. Exact methods require a lot of computation and are feasible for relatively small problems only (Arentze, 2000). A heuristic procedure improves the efficiency of problem solving by reducing accuracy. Computation time is lower but the exact solution is not certain. The quicker results of this procedure give the likelihood of full optimization.

3.2.2 Example studies

Network-based location allocation models have been used in a variety of urban facility location applications ranging from healthcare, emergency services, humanitarian logistics, postal services, school location and waste management (He, Kuo, & Wu, 2016). Rahman and Smith (2000) investigated the use of location-allocation models in health service facility development. The most applicable being *p*-median models or covering models. Caunhye et al. (2015) used location-allocation to determine emergency response facilities to radiological incidents in Los Angeles to better understand emergency incidents and future planning.

In the field of charging station location-allocation problems, the majority of previous optimization methods have used mathematical procedures such as: mixed integer programing (MIP) and mixed integer non-liner programing (MINLP). Most models have been used to either maximize coverage of stations and to minimize number of locations based on user demand. The focus of the methods' use could be caused by the infancy of charging station infrastructure and the need to simply have a basic network to support all demand. Sadeghi-Barzani et al. developed a mixed-integer non-linear program (MINLP) to optimize placing and sizing of fast-charging stations in Tehran, Iran. Riemann et al. investigated optimal locations for a specific type of EV charging stations, wireless power transfer facilities. The study used a MINLP that focused on flow-capturing model with stochastic user equilibrium. The goal is was capture as much traffic flow as possible given a set of possible facility locations in a defined network. Results showed how important traffic flow is for site selection and how the new site can dynamically change traffic flow. You and Hsieh took a hybrid heuristic approach to the problem of EV charging station locations. The model aimed to maximize coverage of the charging network based on a trip network and charger types. He et al. (2016) incorporated local supply and demand into three different location models in Beijing, China. The study concluded that *p*-median was more effective than set covering or maximal covering models to address the EVCS location situation because it created more convince for EV users.

3.2.3 Summary

Network-based location-allocation models have been used in numerous facility location applications, including charging stations. In fact, charging station location-allocation models have been nearly exclusively executed with this style of analysis. Network-based approaches depend greatly on the procedure, which uses algorithms to represent the real world and to solve the optimal case. But mathematical models lack the representation of decision makers and cannot include qualitative or subjective variables. In addition, there is need of a designed network with possible facility locations, demand locations and data, and facility effect radius, which is not always available.

3.3 Decision-based optimization

Decision-based optimization focuses on the individual characteristics of the possible alternatives to aid with decision making. With these methods, the term 'optimization' is not easily defined because the 'best' choice is often up to interpretation or individual judgment. Criteria include both qualitative and quantitative data and even expert knowledge into the decision making process.

The basic set of decision-based models are called multi-criteria decision making (MCDM) techniques and are also referred to as multi-criteria evaluation (MCE), or multi-criteria decision analysis (MCDA). MCDM is both an approach and a set of techniques, with the goal of proving an overall ordering of options, from the most preferred to the least preferred option (Dodgson, Spackman, Pearman, & Phillips, 2016). This technique is composed of three basic methods types, quantitative data, qualitative data, and mixed data. Quantitative data methods use criteria scores and weights on a continuous scale, qualitative data methods use an ordinal scale, and mixed data methods is a combination of the two.

The analytic hierarchy process developed by Thomas Saaty is one of the most popular and widely used techniques in decision making (Ssebuggwawo, Hoppenbrouwers, & Proper). AHP is a more specific form of multi criteria decision making (MCDM). Its main feature is that the decision problem is modeled using a hierarchy whose apex is the main objective of the problem and the possible alternatives to be evaluated are located at the base (Sanchez-Lozano, Teruel-Solano, Soto-Elvira, & Garcia-Cascales, 2013). Expert opinions can be captured by a pairwise comparison and converted into criteria weights, used to designate objective importance in the AHP structure. The AHP method has been accepted by the international scientific community as a robust and flexible MCDM tool for dealing with complex decision problems (Sanchez-Lozano, Teruel-Solano, Soto-Elvira, & Garcia-Cascales, 2013).

Other criteria approaches consist of other methods such as the Multi-attribute Utility Theory (MAUT), Multi-attribute Value Theory (MAVT), Elimination and Choice Expressing Reality (ELECTRE) and the Preference Ranking Method for Enrichment Evaluation (PROMETHEE) (Ssebuggwawo, Hoppenbrouwers, & Proper).

3.3.1 Procedure

MDCM requires a list of selection criteria in order to compare the options at hand. Selection criteria are often measured in different units and they can be conflicting in nature. Every criteria is given a weight based on importance to the main objective and a score based on the features of the alternatives. Scores are first standardized on a 0-1 interval and transformed so they follow the same direction. The weights and standardized scores of each criteria are multiplied and summed for every alternative. The end scores reveal the ranking of the proposed alternatives. The higher the alternative score, the more preferable.

3.3.2 Example studies

MCDM technique has been applied in many fields such as railway site selection, wind and solar power station site selection, and waste management site selection (Guo & Zhao, 2015). AHP has been applied to problems involving planning, resource allocation, and business processes.

There has been minimal investigation of using MCDM methods for charging station site selection. Guo and Zhao (2015) optimally selected EV charging stations in a district in Beijing, China. MCDM was shown to be an effective and robust technique for optimal EV site selection. MCDM methods, including AHP, have been suggested to extend the understanding of MCDM in the field of EV charging station site selection.

3.3.3 Summary

MCDM techniques first and foremost work to make complicated decisions simple. Selection criteria often have conflicting objectives and are of unequal importance, which MCDM includes. Qualitative factors can also be included into a decision, and the AHP model goes a step further to incorporate expert judgements. Decision-based optimization is weakened by the lack of relationship between multiple location choices. This means one location has no effect on any others in consideration. Furthermore, the use of expert judgement can be tricky because subjectivity does not guarantee optimization by any means, even if the judgments are consistent.

Table 3.1: Location-allocation model comparison

Model type	Network of locations	Fills gap in knowledge	Geographic solution	Usable with qualitative data	Usable with expert judgement	Ranking of locations
p-median	X	-	X	-	-	-
Max-covering	X	-	X	-	-	-
Set-covering	X	-	X	-	-	-
Agent based models	X	-	X	-	-	-
Multi-criteria decision making	-	-	-	X	-	X
Analytic hierarchy process	-	X	-	X	X	X
GIS-AHP	-	X	X	X	X	X

3.4 GIS-AHP

In the past, site selection was based on limited factors, or by chance and instinct. Now, with more understanding of the built environment, a higher detail of selection criteria are available, which include economic, technical, social, environmental, and governmental aspects. All of these selection factors create a complex, multi-criteria analysis with factors that are often conflicting. There are a number of MCDM methods used to come to a decision with the use of GIS. The use of AHP has been selected in this study because of its advantage in group decision making, integrating expert judgements, and prescribing the best suited choice that will fit the goals of the fast-charging stakeholder. Developing a GIS-AHP tool will be a substantial, powerful, and realistic mechanism to decision makers in the important and complex task of fast-charging station placement in the case study urban environment.

Choosing an optimization model for fast-charging station placement in Dutch urban environments is not a trivial one. The method for this study looks to satisfy the goals of fast-charging decision makers and to fill the missing gaps of past studies and contribute to the scientific community. The duel method of geographic information systems (GIS) and analytic hierarchy process (AHP) has been widely used in site selection applications and is a powerful decision making technique that applies desired conditions though selection criteria to a spatial decision problem. GIS-MCDM have been used in numerous studies of territorial planning such as urban planning and urban infrastructure, and energy (Sanchez-Lozano, Teruel-Solano, Soto-Elvira, & Garcia-Cascales, 2013). Such an application has yet to be used for selection of electric vehicle charging stations.

Sanchez-Lazano et al*.,* used the GIS-AHP method to evaluate solar farm locations in southern-Spain. The method proved to be useful for decision makers and solidified the use of the combined GIS-AHP method as a site selection tool. Rikalovic, Cosic & Lazarevic used a GIS based MCDM method for industrial site selection with multiple, conflicting criteria. The study showed the method was an efficient tool for decision making and can be applied to most site selection subjects. Chaudhary et al. locate fire stations in the city of Kathmandu, Nepal using the GIS-AHP combined method. The application of GIS-AHP would found to have a wide applicability due to is simplicity, ease of use, and great flexibility. Furthermore, it gained the advantage of including expert judgement which would otherwise be disregarded. Akinci et al. analyzed the suitability of new agricultural sites in Turkey, searching for a specific topography. Sener et al. used combination of AHP and GIS in selecting landfill sites in Konya, Turkey. Finally, Mishra et al. used GIS-AHP to find suitable sites for organic farming in the region of northern India.

3.4.1 Drawbacks of the AHP

AHP has received ridicule over its theoretical foundation which has been the subject of some debate. The main doubt with AHP is over the concern of the rank reversal phenomenon. This is the possibility that, simply by adding another option to the list of options being evaluate, the ranking of two other options, not related in any way to the new one, can be reversed (Dodgson, Spackman, Pearman, & Phillips, 2016). This is an important drawback to be aware of when using AHP as an evaluation tool. Furthermore, expert opinion can be double-edged sword; it can both hurt and help the case for the best location depending on the reliability of the judgements. Drawbacks, though minimal, should be noted while using the AHP method in order to truly understand the meaning of results.

3.4.2 Combination synergies

Independently, GIS and AHP are proper tools for a multitude of applications and when combined a synergistic effect occurs, which contributes to the efficiency and quality of spatial analysis for a site selection problem (Rikalovic, Cosic, & Lazarevic, 2014). This method allows decision makers to represent their opinions in a geographic analysis with clear, visual results. The addition of AHP adds value to the original set of GIS data. The use of GIS props up the network and relationship shortcomings of AHP. Therefore, the integration of GIS and AHP methods provides a mechanism to thoroughly explore complicated problems and provides immediate feedback for decision makers (Sener, Sener, Nas, & Karaguzel, 2010). The combination of GIS and MCDM techniques has been increasingly used as an important spatial decision support system for evaluating suitable locations (Uyan, 2013).

3.5 Contributions of this study

Fast-charging has been mainly applied as support for inter-city commuting or cross country trips. Fast-charging stations have been placed in rural locations to link cities and act as backups for EV drivers. Urban environments are prime markets for fast-charging stations. Cities have more people, more EV users, and EV use is an advantage in cities to improve air quality and reduce noise pollution. Most people in Dutch cities do not have access to regular public parking spaces, making home charging difficult for the mass population. In order to sustain EV growth in the Netherlands, fast-charging stations are needed in the most promising locations of dense urban environments. A tool to find locations that fit the needs of all stakeholders is important to the advancement electric mobility, and thus is a benefit for, not only stakeholder, but society in general.

Network-based location-allocation models are a great approach to planning an early charging infrastructure which supports the phase of innovative adopters. EVCS site selection needs this approach to quell range anxiety in environments where public charging coverage is questionable. But this will no longer be the situation for the Netherlands as mass EV adoption unfolds. Now, the focus on a mass-scaled and efficient turnover rate of fully charged vehicles. For fast-charging, it’s now about meeting the quantity of demand and support expected growth.

Selection of charging stations in the past has been based on mathematical approaches. Algorithms have limitations of what they are able to represent: expert opinions and knowledge are left out of the equation. In addition, social and environmental factors are not always easily represented by algorithms. AHP incorporates expert opinion into the decision making process and can use criteria which represent otherwise unquantifiable variables.

Lastly, fast-charging is a new innovation which means has room for development. Research over site selection techniques has been minimal in regards to fast-charging and selection criteria for fast-charging have yet to be fully understood. This study will be the first to apply GIS-AHP approach towards fast-charging site selection.

Chapter 4 Model process

This chapter highlights the processes taken to develop the working GIS-AHP model. The exact results are left for chapter 5. The section beings with an introduction of how the development of the model follows the research process model steps and the literature review stage, and ends with a more detailed review of the process phases.

4.1 Introduction

This model was developed following the research process model (figure 1.1), which begins with a literature review and then is split into two distinct phases. The literature review searched past studies, scientific publications and reports to gain an understanding of the field of location-allocation and EV site selection problems. The literature review highlighted the pros and cons of this study's selected model and helped form a foundation of selection criteria for fast-charging stations. The first phase is the AHP phase where selection criteria are determined, the hierarchy relationship is structured, the pairwise comparison survey is created and distributed, and the pairwise analysis calculates weights for every section criteria layer. The second phase develops the GIS part of the tool where open source data is gathered and organized, GIS layers are created and combined from the data sets and AHP pairwise weights, the case study city of Amsterdam is analyzed, and a sensitivity analysis is performed on the GIS-AHP tool. The model process section will explain the logic behind the model's creation, the steps taken in each phase to derive the expected results, the results themselves and the top 10 locations in the case study city for fast-charging stations.

4.1.1 Area of examination

The area being examined is the urban area of Amsterdam, the capital city of the Netherlands, with 850,000 inhabitants in the city boundary and 1.4 million inhabitants in the urban area. It must be noted that the municipality boundary and the urban area are different. The urban area of examination consists of a rectangular area 17.5 km by 24.4 km that surrounds the entire municipality of Amsterdam and reaches out to the suburbs of the city. The selected coordinates match up with the 2014 Land Use map on the maps.amsterdam.nl website. It is assumed that if this zone is adequate to display all land uses considered important by the city of Amsterdam then it is an adequate examination zone for fast-charging stations affecting the city. Furthermore, the area includes the major highways, living areas, and the international airport. The zone dimension works out to roughly 4875 x 3500 pixels, over 17 million pixels. Each pixel has a resolution of 5 m x 5 m, meaning the examination zone covers 427 km^2.

Alternatives

Alternatives are all of the possible locations available to the decision maker. For a fast-charging site selection problem this means all possible locations that are acceptable for development of fast-charging stations. Each alternative has unique characteristics related to every selection criteria for the site selection problem. Finding the best alternative(s) is the goal for an optimization problem.

Figure 3.1: Area of examination - Amsterdam

4.2 Fast-charging selection criteria

A decision can be separated into decision factors, called selection criteria. Each criterion is a variable that contributes a part towards the final decision. Criteria often differ in their value of importance, called the criteria weight, with the objectives of these criteria often being conflicting. The complexity of conflicting criteria objectives in the decision making process is why MCDM tools are valuable for decision makers.

In the past, site selection was based almost purely on economic and technical criteria but now selection criteria must also satisfy a number of social and environmental requirements, which are enforced by legislations and government regulations (Rikalovic, Cosic, & Lazarevic, 2014). Studies have shed light on what factors make a public EV charging location ideal. These studied have focused on both slow and fast-charging station locations and EV user preferences. It is assumed that EV user behavior and preference for fast-charging will be similar if not equal to slow-charging behaviors. Knowing this, list of selection criteria has been created to get ideas on important and realistic factors for fast-charging locations.

4.2.1 Past studies

Morrissey et al. (2016) looked at the future of fast-charging infrastructure in Ireland and found that car park locations were the most popular and preferred locations for public charging followed by petrol station locations. Shahraki et al. (2015) also considered petrol stations as top candidate locations to build public charging infrastructure when analyzing real world traffic data. Zhang et al. (2015) reiterated the likely placement of fast-charging at existing petrol stations in metropolitan areas and highlighted the possibility for locations like grocery stores, shopping malls, and large department stores. The study also concluded optimal locations were along busy freeway exits and intersections. Shao-yun et al. (2012) researched charging station placement in urban areas and found road network and traffic flow directly affects optimal site locations, along with cost of construction and power loss. Feng et al.

(2015) also used traffic flow rate and included capacity level of the stations as critical criteria. Sadeghi-Barzani et al. (2014) included station development cost, EV energy loss, electric grid loss, and station electrification cost as top decision factors when optimizing fast-charging placement. He et al. (2016) considered the price of electricity, goal destinations and route choices as the most important criterion for EV drivers in metropolitan areas. Chaudhary et al. (2015) listed distance from road and residential population density as important selection criteria. Guo and Zhao (2015) focused on optimal charging station placement with a sustainability perspective and included construction cost, traffic convenience and an environmental impact criteria including destruction degree on vegetation.

Table 4.1: Literature review selection criteria

Selection Criteria	*Source*
Car parks	(Morrissey, Weldon, & O'Mahony, 2016)
Petrol stations	(Morrissey, Weldon, & O'Mahony, 2016), (Shahraki, Cai, Turkay, & Xu, 2015), (Zhang, Schaffer, Brown, & Samuelsen , 2015)
Grocery stores	(Zhang, Schaffer, Brown, & Samuelsen , 2015)
Shopping malls	(Zhang, Schaffer, Brown, & Samuelsen , 2015)
Departments stores	(Zhang, Schaffer, Brown, & Samuelsen , 2015)
Freeway exits and intersections	(Zhang, Schaffer, Brown, & Samuelsen , 2015)
Road network	(Shao-yun, Liang, Hong, & Long, 2012), (Guo & Zhao, 2015)
Traffic flow	(Shao-yun, Liang, Hong, & Long, 2012), (Feng, Yin, & Zhou, 2015)
Construction cost	(Shao-yun, Liang, Hong, & Long, 2012), (Sadeghi-Barzani, Rajabi-Ghahnavieh, & Kazemi-Karegar, 2014), (Guo & Zhao, 2015)
Power loss	(Shao-yun, Liang, Hong, & Long, 2012), (Sadeghi-Barzani, Rajabi-Ghahnavieh, & Kazemi-Karegar, 2014)
Station capacity level	(Feng, Yin, & Zhou, 2015)
EV energy loss	(Sadeghi-Barzani, Rajabi-Ghahnavieh, & Kazemi-Karegar, 2014)
Price of electricity	(He, Wu, Yin, & Guan, 2013)
Destinations	(He, Wu, Yin, & Guan, 2013)
Distance from roads	(Chaudhary, Chhetri, Joshi, Shrestha, & Kayastha, 2015)
Residential population density	(Chaudhary, Chhetri, Joshi, Shrestha, & Kayastha, 2015)
Environmental impact	(Guo & Zhao, 2015)

4.2.2 Finalizing selection criteria

The initial group of selection criteria from the literature review were filtered and changed until a satisfactory set of criteria remained. Many criteria were eliminated because they do not apply or are unimportant in the case study environment. Other criteria were unfeasible to represent in GIS with the current data available. Every finalized selection criteria has a clear objective that contributes to the final goal of fast-charging site selection and is applicable to the case study environment. The objectives have been intentionally connected to stakeholder interests. For example, fast-charging companies would like to place stations in the most accessible and visible locations in order to capture the most customers at their stations. This would make a case for criteria related to accessibility or visibility to include the model. The finalized criteria and objective description is found in the results chapter.

4.3 Phase 1: AHP

The basic theory of AHP may be simplified as a set of independent elements or in this case selection criteria (A_1, A_2,…A_n), which have unique weights (w_1, w_2,…w_n). Decision makers do not know weights in advance but are capable of making a pairwise comparison between the different elements. The results is a square *n* x *n* matrix called the pairwise comparison matrix.

$$A = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix}$$

Figure 4.2: Pairwise matrix (Adamcsek, 2008)

The first step of the AHP process is to define the problem and determine the kind of knowledge sought (Saaty, 2008). The knowledge being sought echoes is the research objective: ideal locations of fast-charging stations in Dutch urban environments. From here, the determination of selection criteria is made from the literature review, elicitation of knowledge with fast-charging experts, and consultation with university supervisors. The selection criteria are structured from the top goal of the decision down to broader objectives. The branching goes on through intermediate levels to the lowest level, which is the set of possible alternatives.

After the structure is completed, the second step makes the pairwise comparison survey and subsequent matrices. The survey, which can be found in the appendix (table A.1), uses a scale of numbers that indicate how many times more important or dominant one element is over another element with respect to the criterion or property with respect to which they are compared (Saaty, 2008). The scale use is the fundamental scale of absolute numbers:

Table 4.2: Fundamental scale of absolute numbers (Saaty, 2008)

Intensity of importance	*Definition*	*Explanation*
1	Equal Importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgement slightly factor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly factor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above non-zero numbers assigned to it when compared with activity *k*, then *j* has the reciprocal value when compared with *i*.	A reasonable assumption

Each matrix compares the set of elements at individual levels, by comparing the row criterion to the criteria in the intersecting column. The example matrix in table 4.3 represents the first level of criteria in the AHP structure. The selection criteria being compared are: proximity of EV users, accessibility for EV users, environmental impact, and grid impact. The first row, proximity of EV users, has values for how important it is compared to the column criteria. It answer the questions: *How many times more, or how strongly more important is the criteria towards an ideal fast-charging location than the criteria on the top?*

A score of 1 can be seen in the first (top left) column of the example matrix, which compares proximity of EV users versus itself. Any criteria compared versus itself will turn out to be just as important, a score of 1. A diagonal symmetry in the matrix can be seen following the self-comparisons from the top left to the bottom right. There is also a noticeable symmetry of the entered values along this same diagonal axis, except the values are reciprocals of one another. One always enters the whole number in its appropriate position and automatically enters its reciprocal in the transpose position (Saaty, 2008). The next score (one cell to the right) has a value of 1/7 and is compared to accessibility for EV users. This means that proximity of EV users is very strongly less important than accessibility for EV users, or as the transposition, accessibility for EV users is very strongly more important than proximity to EV users.

Table 4.3: Example pairwise matrix

Example pairwise matrix	*Proximity to EV users*	*Accessibility for EV users*	*Environmental impact*	*Grid impact*
Proximity to EV users	1	1/7	1	1/2
Accessibility for EV users	7	1	6	3
Environmental impact	1	1/6	1	1
Grid impact	2	1/3	1	1

The pairwise comparison survey was completed by two top decision makers who are directing fast-charging station and network development. They have experience in selecting and developing fast-charging station locations and have strategies of how they want to select future sites. In step 3, the matrices and results of the pairwise survey are placed in an Excel spreadsheet to find the resulting selection criteria weights for each expert opinion and to check for judgement consistency. It is important to check for a consistency of judgements amongst the respondents. The consistency ratio needs to be checked at each level of the hierarchy. The threshold of consistency is a CR < 0.10, giving experts a small allowable error in judgement. If a matrix is not consistent, the judgement needs to be re-evaluated to improve consistency to an acceptable threshold. This is done with the *Consistency Index (CI)* and the *Consistency Ratio* (CR) calculated by:

$$CI = (\lambda_{max} - n)/(n-1), \;\; CR = CI/RI(n)$$

Where RI is the *Random Index* calculated as an average of a randomly generated pairwise matrix of the same order (Ssebuggwawo, Hoppenbrouwers, & Proper) and can be seen below:

Table 4.4: Random index table

n	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Random Index	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.51

Calculating weights is the first step to determining λ_{max} , which is the principle eigenvalue of the matrix in question. The matrix must be normalized, taking the sum of each column and dividing each cell by its related column's total. The weight per element is then the average of cells in each row. Table 4.5 is the normalized matrix of the first example matrix with respective column sums (11.0, 1.64, 9.0, and 5.5).

Table 4.5: Normalized example matrix

Normalized Matrix	*Proximity to EV users*	*Accessibility for EV users*	*Environmental impact*	*Grid impact*	*Weight*
Proximity to EV users	0.09	0.09	0.11	0.09	*9.5%*
Accessibility for EV users	0.64	0.61	0.67	0.55	*61.4%*
Environmental impact	0.09	0.10	0.11	0.18	*12.1%*
Grid impact	0.18	0.20	0.11	0.18	*16.9%*

Next the CI and CR matrix are calculated. Here, the weights for each column element are multiplied by the comparison matrix values. Then the row sums are calculated. Next, the sum to weight ratio is calculated for each row. Finally, the average of the sum/weights ratio is calculated to find the value of λ_{max}. Below, the example continues for this step:

Table 4.6: CI and CR example matrix

CI and CR	*Proximity to EV users*	*Accessibility for EV users*	*Environmental impact*	*Grid impact*	*Sum*
Proximity to EV users	0.09	0.09	0.12	0.08	*0.39*
Accessibility for EV users	0.66	0.61	0.73	0.51	*2.52*
Environmental impact	0.09	0.10	0.12	0.17	*0.49*
Grid impact	0.19	0.20	0.12	0.17	*0.69*

Table 4.7: CI and CR example values

Sum/Weight	*Count (n)*	4
4.09	Lambda max (λ_{max})	4.0643
4.09	CI	0.0214
4.02	RI	0.9000
4.05	CR	0.0238

The example matrix shows that the CI is below the 10% threshold and judgement values are consistent for this particular matrix. This same process is repeated for the other matrices and survey sets.

4.3.1 Combining judgments

Consistent pairwise comparison matrices were combined using the Aggregation of Individual Judgements (AIJ) technique. Under this technique, the group becomes the 'new individual' rather than a collection of independent individuals (Ssebuggwawo, Hoppenbrouwers, &

Proper). The crux of this technique is using a geometric mean method, which is used in averaging ratio sensitive data. Instead of finding the numerical average between two numbers, this finds the ratio average. This is done by taking the product of the scores to the power of (1/n). In this instance, the geometric mean method takes the square root of the product of each decision maker's judgement, since there are two opinions being combined. The combined values are deemed consistent if the original comparison matrix is consistent. The end results of the aggregated pairwise comparison provide the weights to each layer, designating the importance of each layer in the view of an expert individual.

4.4 Phase 2: GIS

Phase 2 is about developing the GIS part of the tool which will determine top locations for fast-charging stations. This phase involves establishing critical datasets from open sources, creating GIS layers that accurately represent the situation in the case study environment, combining selection criteria layers following the AHP structure, analyzing the case study city, and testing the sensitivity of the tool. Weights from the AHP pairwise comparison are used when combining the criteria layers; incorporating phase 1 into the tool and creating the GIS-AHP synergy. It is important to insure data is realistic, as up-to-date as possible, and represent the criteria adequately. Data was transformed between vector and raster forms, scaled so values are comparable, and processed to become compatible in the Easy AHP add-on. Manipulation is necessary because data was available in many different file formats. Effort was taken to conform layers to be consistent.

4.4.1 Establishing datasets

Finding reliable and accurate data was one of the most important and difficult steps in development analytical tool. All data was found using open sources, meaning they are available to the general public. Data is easy to access but also has limited flexibility. Data that exactly fit the needs of the criteria is not always available, leaving area for improvement. Overall, more than 22 GB of data and 3000 files took part in creating the GIS-AHP tool.

Sources

PDOK (Publieke Dienstvarlening op de Kaart) is the central facility for geo-datasets in the Netherlands. This service offers free access to digital geographical datasets and aims for the most actual and reliable information for both public and private sectors. PDOK meets national and international standards making the data sets vast, reliable, and trustworthy. Other than the quality and quantity of information, PDOK covers the entirety of the Netherlands, making it flexible to all urban environments in the country. A plethora of information was extracted from PDOK, specifically the Top10NL map.

NDW (Nationale Databank Wegverkeersgegevens) is an organization best known for its enormous database of real-time and historic traffic data within the Netherlands. The information is used to optimize traffic management and provide users with the best information. NDW works with the central government, urban regions, and main municipalities in the country so the data is reliable and available for all urban environments in the country. Information over the road network and road categorization was found with this source.

The city of Amsterdam has several interactive maps and its own form of open geo data on their municipal website, maps.amsterdam.nl. This site offers information specifically on the city of Amsterdam and has a limited but specific set of data compared to PDOK. Information from this source cannot be applied to other cities within the Netherlands. Though, this is where specific and more unique open source information was found about the case study city, like environmental data.

Hoogspanningnet.com is a website devoted to grid information for the Benelux area. They have created a Google Earth map of all high voltage lines throughout the country with their voltage level and connecting substations. This source provided important information over grid substations and the electric grid network in the Netherlands, reaching all urban environments in the country.

4.4.2 Preparing spatial analysis

GIS layers were created in a unique way depending on which format or file type the data was in and the objective of the layer. All layers needed to be converted into raster data to be combined. Layers also must have the same scale for their values, same dimensions, same resolution (pixel size) and be set in the same coordinate reference system (CRS). This process insures the layers perfectly overlap in QGIS and each criteria layer has comparable values before weights are taken into consideration. The following sections present the process for the suitability analysis, heatmap layers, buffer layers, grid layers, and the combination of layers. Details over the decay kernel formulas reveal the precision in each layer.

Suitability analysis

The suitability analysis layer removes unsuitable areas from the area of examination. This layer narrows down the possible locations to only worthy areas making the tool more realistic and makes for an easier analysis of the final objective layer. A variety of vector, raster and other processing tools were used in QGIS to create the suitability layer. Map features like buildings, roads, water areas, and protected green area are examples of unsuitable spaces for development. Unsuitable features are then combined into one layer. The process of creating the analysis can be seen in Figure 4.3.

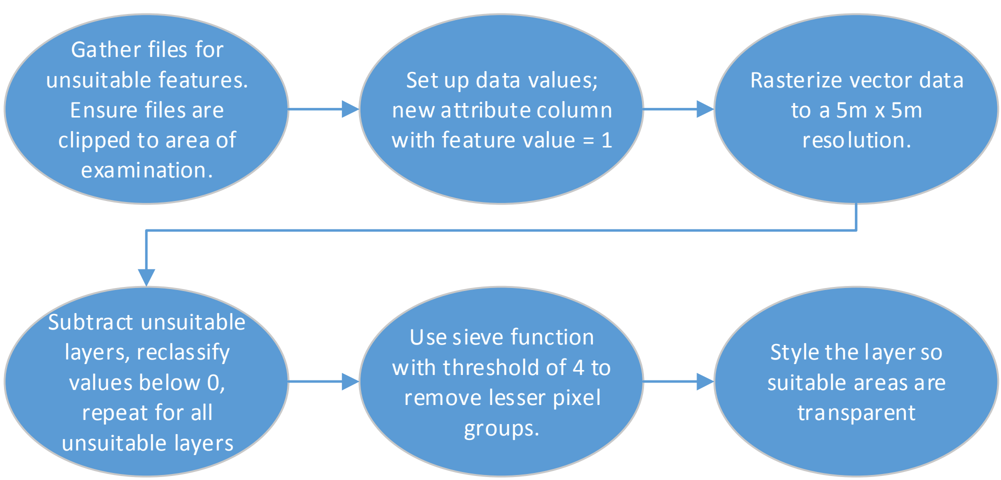


Figure 4.3: Suitability analysis process

Heatmaps

The heatmap function provides an immediate visual summary of information and allows the viewer to understand complex data sets (Kong, Zhang, & Stonebraker, 2015). An advantage of using heatmaps in this study is the ability to process a set of points into a raster data file based on density and their distance of effect. The heatmap tool in QGIS gives each point an proximity distance which decays as the distance increases. The data is output as a raster map. There is an advanced option where the cell sizes can be determined. This was set to a project default of 5m x 5m. The kernel shape determines the decay curve from the center point to the end points of the radius. Three kernel formulas were used: quartic (biweight), triangular, and uniform.

Kernel formulas

Quartic (biweight) – Quartic is the QGIS default setting for kernel shape and is commonly used in probability density functions. The estimation density of this function is smooth and non-liner. This is applied to layers which are scored based on preferences. The mathematical function and curve can be seen below:

$$K(u) = \frac{15}{16}(1 - u^2)^2$$

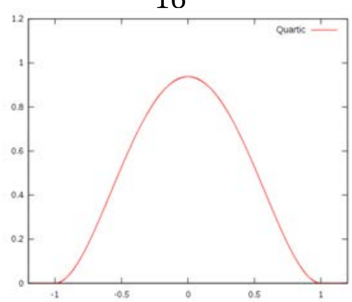


Figure 4.4: Quartic (biweight) kernel graph

Triangular- The triangular kernel represents densities that decrease equally as the distance decreases. This is applied to layers where each unit of distance has a liner effect on the preference value.

$$K(u) = (1 - |u|)$$

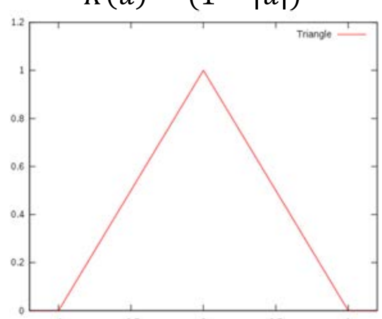


Figure 4.5: Triangular kernel graph

Uniform - The uniform kernel holds a constant value over the proximity distance. There is no decay from the center point to the end of the area of effect.

$$K(u) = u$$

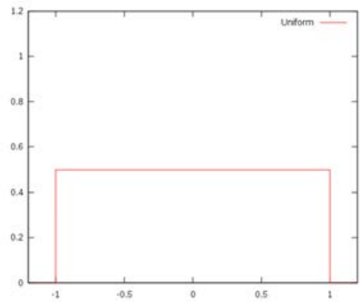


Figure 4.6: Uniform kernel graph

With the correct specification, the heatmap layer can be created through the following process:

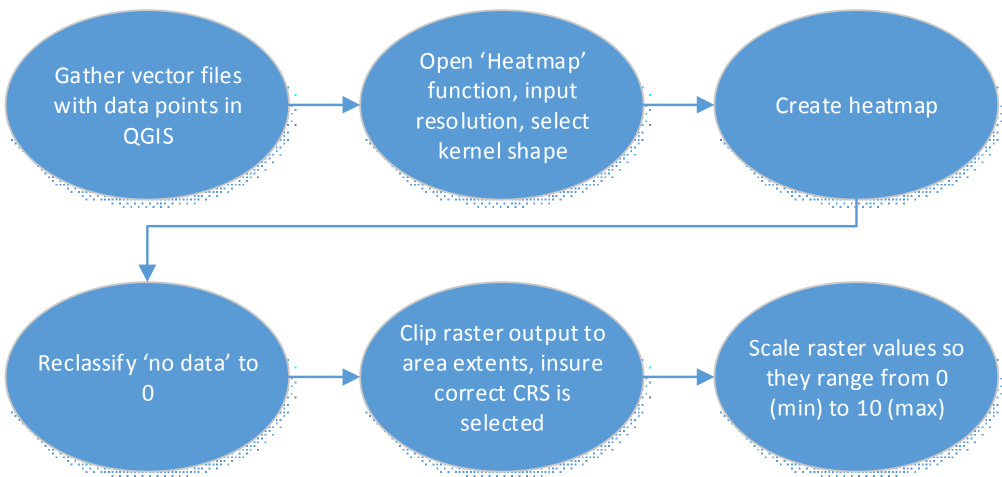


Figure 4.7: Heatmap layer process

Buffer layers

Buffering is a vector geoprocessing tool used to create a uniform value around map features: points, lines, or polygons. Buffering is another process useful in proximity analysis. Much like the heatmap tool, the buffer can be given a proximity distance value which extends the effect area in all directions based on the value. This creates a uniform kernel that can be applied to lines, polygons and points. Buffer layers are created with the following steps.

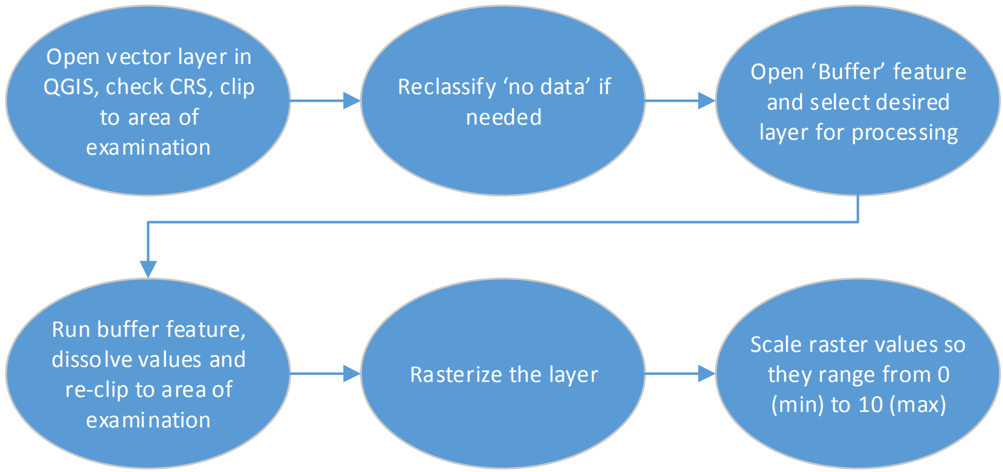


Figure 4.8: Buffer layer process

Grid layers

Certain data sets are available in the format of grids, like a checkerboard, which hold values per area of observation. This is similar to the pixels in raster data but on a larger scale and in vector format. Grid datasets need little change, only to represent their values in raster form. Though, some creativity was taken to conform them to the standards of the study:

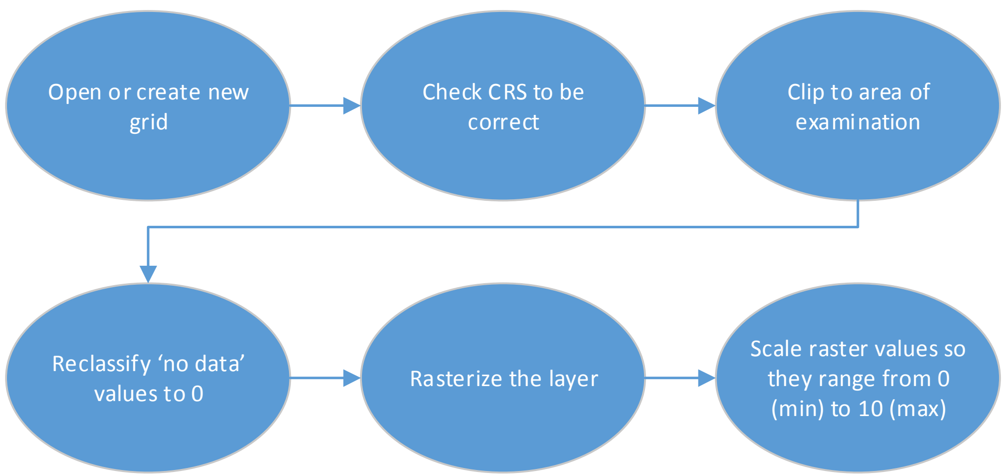


Figure 4.9: Grid layer process

Each time a heatmap or buffer layer is created, it needs a value for the proximity distance. The value determines how far the map features will extend and is a critical input towards to overall function of the GIS-AHP analysis. The reason behind layers' selected proximity distance can be found in chapter 5.

4.4.3 Combining AHP layers

After all selection criteria layers have been created and made comparable, the criteria layers can be combined into a final layer which satisfies the research objective. The Easy AHP add-on is a free tool which provides Analytic Hierarchy Process and Weighted Liner Combination analysis in QGIS. The interface makes it easy to select input layers, input AHP matrix values, confirm consistency of the values and weight percentages, and combine them into a master layer. The output is then a single raster GIS layer from the weighted and 'stacked' input layers. Figure 4.10 shows how each unique layer will be combined.

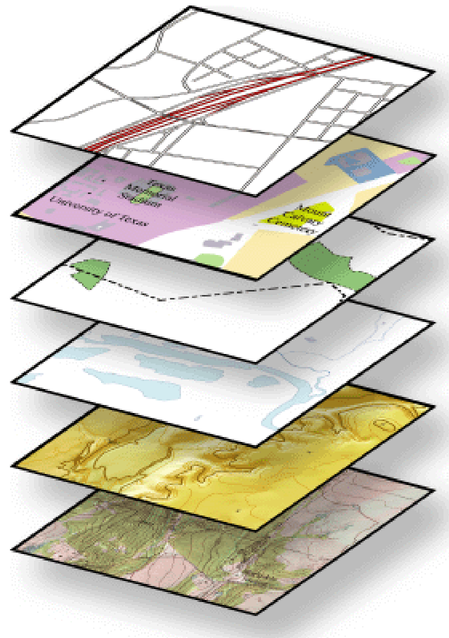


Figure 4.10: 'Stacked' GIS layers

4.4.4 Sensitivity analysis

It is important to re-evaluate the layer combination process to see how the results change when the criteria weights change. To do this, the final objective layer is recombined but setting all layers at an equal level of importance, like expert knowledge is not playing a role. Layers carry the same weight at a local level. The sensitivity analysis is an indication of the GIS-AHP tool's level of certainty. If the analysis shows the tool is sensitive to expert knowledge in the results, then the tool is considered robust. It is good to see a shift in fast-charging locations if decision makers change their development strategy. The sensitivity analysis results can be found in chapter 5.

Chapter 5 Model results

This section shows the results of the GIS-AHP tool for locating ideal fast-charging locations in the city of Amsterdam including the results of the steps leading up to the research objective. First, the finalized selection criteria are described with their respected objective goals and layer proximity distance reasoning. Next, the AHP pairwise comparison results are shown and discussed. Finally, the top 10 fast-charging station locations are listed with scores and defendable reasons for their selection.

5.1 Finalized selection criteria

Evaluation of the literature review, elicitation of knowledge with fast-charging experts, and consultation with university supervisors led to a list of finalized selection criteria which are most important for an ideal fast-charging location. Representing stakeholder objectives was a key part of the final selection.

5.1.1 Level 2 layers

Accessibility for EV users - The objective is to make stations conveniently available to EV users. This criteria insures that stations can be easily accessed through the available road infrastructure, focuses on being adjacent to main roadways and capturing high rates of traffic flow. The goal is to place fast-charging stations where EV users can enter the station, charge, and exit without troubles.

Environmental impact - The objective is to reduce development impact on nature and the surrounding ecosystems. This criteria includes the perspective for locations that have the lowest impact on protected species.

Proximity of EV users - The objective is to place stations near EV users' homes, work, and common trip destinations. This criteria insures that the charging station is located closely to EV user's trip origins and trip destinations. This criteria considers two customer types: private EV users and commercial business that use EV's on a daily basis. The goal is to place fast-charging stations as close to as many trip starting points, mid points, and end points as possible.

Grid impact - The objective is to reduce impact on the electricity grid network. Fast-charging can cause a large impact, especially during peak hour usage. GIS data shows transformer station locations where voltage is reduced from 50 kV down to a more workable 10 kV. Fast-charging stations require a 10kV grid connection. The closer to the 50 kV/10 kV sub stations means less energy loss from the substation to the fast-charging station. Furthermore, there is a higher chance that a 10 kV connection is more readily accessible to make development of the station more cost effective.

5.1.2 Level 3 layers

Road capacity level - The objective is to place fast-charging near high traffic flows. It makes sense to place stations where customers are most likely to drive. Roads with higher vehicle capacity will give accessibility to fast-charging stations because more EVs per day pass by the location. Additionally, higher capacity roads are used for longer, faster journeys creating a demand for fuel. The goal is to place fast-charging stations where they can capture the highest flow-rate of cars as possible within reasonable distance of important roads.

Distance from main road - The objective is to make stations easily accessible to EV users and to created higher visibility of the station to drivers. The criteria insures fast-charging stations are placed where EV users can quickly enter the station from an adjacent roadway, fuel, and merge back into traffic with minimal effort. The goal is to place stations adjacent to important roadways.

Protected flora and fauna - The objective is to reduce impact on nature and the surroundings. This layer specifically looks at the number of protected species per km^2 in the area of examination. The goal is to develop fast-charging on locations that have the least impact on local species.

Residential population density – This criteria objective is to place fast-charging stations in the denser residential areas to be near people's homes, which are starting and ending points for private EV users. The goal is to be located in areas of the city that have the highest population as possible.

Proximity of facilities - The objective is to place stations near EV user's trip destinations. This criteria includes common destinations where EV users will frequently drive to and from. People are likely to fast-charge at convenient, familiar, and daily-use location. The goal is to locate the station near as many daily-use facilities as possible.

Proximity of commercial EVs - The objective is to place fast-charging stations near commercial and business EV demand. There are several businesses that rely on public charging infrastructure to fuel their EV's. Being closely located to these customers will encourage fast-charging over slow-charging to improve efficiency in their operations. The goal is to be as close to as many commercial EV users as possible.

Proximity of slow-chargers - The objective is to place stations near private EV demand and slow-charging proximity is a good indication. In Amsterdam, slow-chargers are placed by user demand and requests. This means the current slow-charging infrastructure identifies places where EV users want to charge and where they live or work. The goal is to locate fast-charging stations as close to as many slow-chargers as possible.

Distance from grid substations – Grid sub-stations transform voltage levels to more useable levels. The closer to sub stations means less energy loss to supply the electricity and more grid support nearby. The goal is to be closer to grid substations to reduce fast-charging impact on the electrical grid.

5.1.3 Level 4 layers

Proximity of petrol stations - The objective is to place stations near common facilities. Petrol stations are familiar refueling points and can help make the transition from ICEs to EV's. Additionally, petrol stations have already been placed in top locations for capturing ICE customers. The goal is to place fast-charging near as many petrol stations as possible.

Proximity of shopping centers - The objective is to place stations near common trip destinations. Shopping areas are a common destination point where a high number of people travel. The goal is to place fast-charging to as many shopping areas as possible.

Proximity of recreation & entertainment - The objective is to place stations near EV user's trip destinations, one common being recreation and entertainment areas. Recreation and entertainment zones are an end destination for EV users that considers areas of sporting, leisure, and nature areas. The goal is to be as close to as many recreation and entertainment areas as possible.

Proximity of parking garages - The objective is to place stations near EV user's trip destination. Parking garages are places with high density of vehicles, and therefore a destination point for EV users. Past literatures have shown these can be preferable points for EV charging. The goal is to be as close to parking garages as possible.

Proximity of taxi points - The objective is to place stations near current commercial EV demand. Taxi services are beginning to turn to EVs, for example, Electric Taxi is a taxi service with a full fleet of Tesla Model S's. Electric taxis have a potential to use fast-charging to refuel between destinations. Taxi points are designate areas where taxis begin customer trips and return for more customers. The goal is to be located close to taxi points within the city.

5.1.4 Layer proximity

A proximity distance is needed when creating the 11 base criteria layers. Layer processing tools such as heatmaps and buffers make use of proximity distances to show their effect on the urban environment. A proximity distance is how far the criteria are assumed to cover and changes based on the objective of the individual criteria.

Heatmap proximity

(Very low distance: 500m)
Proximity of slow-charging – Funke et al. (2015) defines core cities as cities above 100,000 inhabitants and assumes 500m is a sufficient proximity distance in core cities for slow-charging.

Proximity of shopping centers - People will generally prefer a distance of at least 500m to a shopping area. It is assumed 500m is sufficient to capture EV users to and from shopping areas.

Proximity of recreation and entertainment - Like shopping centers, 500m is convenient for customers entering or leaving this mid-destination point.

(Low distance: 1000m)
Proximity of taxi points – Cities are pushing green taxi adoptions with subsidies. At these points taxis pick up customers from highly populated areas, often areas with shopping or entertainment nearby. 1000m is an assumption that is convenient for electric taxis to charge before going to the taxi stand to pick up customers. Taxi companies will likely have their own charging points, so a further distance may encourage them to charge at those points.

(Medium distance: 1500m)
Petrol stations – It is assumed that the reach of petrol stations is approximately 1500m.

(High distance: 2000m)
Proximity of parking garages – Parking garages have a higher distance due to the demand for parking in cities. Parking is cities can be a struggle, which is why parking garages exist – to provide parking on a mass scale. Furthermore, parking garages are placed in areas with high parking demand. It is assumed that 2000m is sufficient for representing parking garage proximity.

(Very high radius: 4000m)
Distance from grid substations – Electricity loss does not work on preference but is dependent on the distance. Each station has a high proximity distance to reach a large amount of the city per station. It is assumed that a proximity distance is 4000m is adequate.

Buffer Distances

Distance from main roads – 100m is the maximum distance to place a fast-charger from the main road, according to fast-charging decision makers. The closer to the road the more preferable. Ideally, the station would be in a location where an EV user can directly drive in to the station, charge, and continue back on their route. Furthermore, a location directly adjacent to a road provides visibility and advertising.

Road capacity level – Road capacity was buffered 500 meters to represent the effect of the road. The buffering reveals intersections by overlapping proximities. 500m was considered a reasonable effect area for important roads.

Grid dimensions

Residential population density –The grid dimensions of 500m x 500m were given in the original set of data. Each grid square represents 250 m^2 of the examination area.

Protected flora and fauna –The grid dimensions of 1000m x 1000m were given in the original set of data. Each grid square represents 1 km^2 of the examination area.

Table 5.1: Proximity distances and dimensions

Criteria layer	*Distance and dimensions*	*Kernel shape*	*Processing type*
Proximity of slow-charging	500m	Quartic	Heatmap
Proximity of shopping centers	500m	Quartic	Heatmap
Proximity of recreation and entertainment	500m	Quartic	Heatmap
Proximity of taxi points	1000m	Quartic	Heatmap
Proximity of petrol stations	1500m	Quartic	Heatmap
Proximity of parking garages	2000m	Quartic	Heatmap
Distance from grid substations	4000m	Triangular	Heatmap
Distance from main roads	100m	Uniform	Buffer
Road capacity level	500m	Uniform	Buffer
Residential population density	500m x 500m	Uniform	Grid
Protected flora and fauna	1000m x 1000m	Uniform	Grid

5.2 AHP structure

The finalized criteria are organized in a relationship hierarchy based on stakeholder objectives and urban relationships. The AHP structure describes the relationships of each criteria with the final objective to find ideal charging stations in Amsterdam. The second level, represented in green, highlight main criteria of the study. From here, sub-criteria branch off, which are represented by base GIS layers. Some of these have sub-criteria of their own.

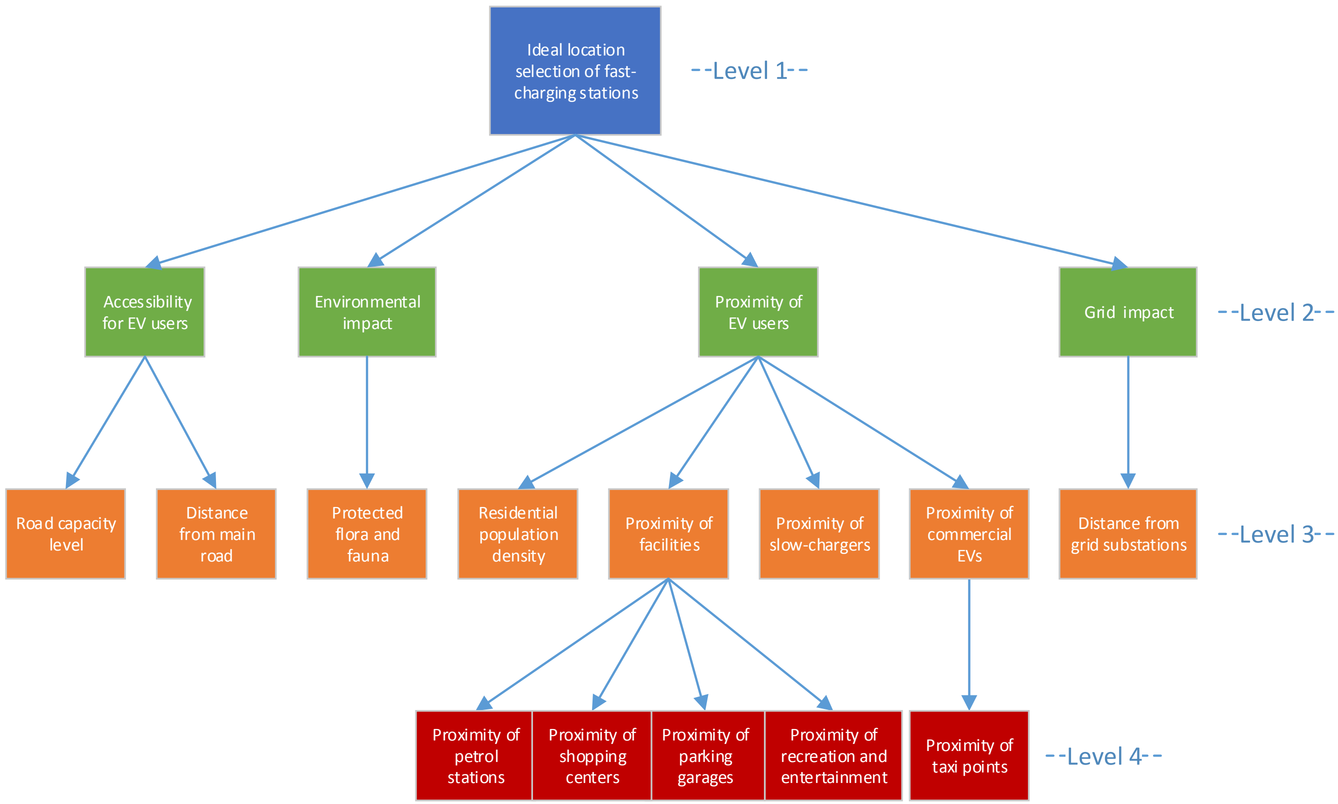


Figure 5.1: Selection criteria AHP structure with levels

5.2.1 Pairwise comparison

Pairwise comparison results were calculated from the expert survey and pairwise comparison matrices. Judgements were under the consistency index threshold, though, for each decision maker there was one matrix that needed to be re-evaluated due to inconsistency. After the fix, all pairwise comparisons were deemed consistent. With the individual pairwise comparisons evaluated and consistent, the judgements can be combined to find the global and local weights for each selection criteria. Global weight is the criteria weight on the final objective and local weigh is weight the criteria has on the related 'parent' criteria.

Accessibility was a unanimous priority with a global weight of 63.5%. There is a need to be as close to as much traffic flow as possible and this is clear with experts. The other three main criteria shared the remaining weight somewhat evenly. Locations near roadways of high importance are most critical and will receive higher preference scores. High scores are also driven away from the denser areas of the city because proximity to EV users is viewed as less important and busy roads are not near high population areas.

Table 5.2: Pairwise comparison weights

Level 2	*Local weight*	*Level 3*	*Local weight*	*Global weight*	*Level 4*	*Local weight*	*Global weight*
Accessibility for EV users	63.5%	Road capacity level	66.7%	42.3%	-	-	-
		Distance from main road	33.3%	21.2%	-	-	-
Environmental impact	13.5%	Protected flora and fauna	100.0%	13.5%	-	-	-
Proximity of EV users	13.0%	Residential Population Density	46.2%	6.0%	-	-	-
		Proximity of facilities	27.1%	3.5%	Proximity of petrol stations	59.8%	2.1%
					Proximity of shopping centers	17.9%	0.6%
					Proximity of recreation and entertainment	13.3%	0.5%
					Proximity of parking garages	9.0%	0.3%
		Proximity of commercial EVs	18.9%	2.5%	Proximity of taxi points	100.0%	2.5%
		Proximity of slow-chargers	7.9%	1.0%	-	-	-
Grid impact	10.0%	Distance from grid substation	100.0%	10.0%	-	-	-

5.3 GIS layers

Each selection criteria was represented by a GIS layer. Following the model process transforms datasets into map layers. The first layer created was the suitability layer, which removes all unworthy alternatives from the selection process. Then all base criteria were created representing the fast-charging situation in the case study city. Finally, layers were combined to reach the apex of the AHP structure.

5.3.1 Suitability analysis

To construct the suitability analysis, data was gathered to represent the map features which are unsuitable for fast-charging development. Factors that are considered unsuitable are:

Buildings – All buildings in the city of Amsterdam appear as a vector layer. Buildings occupy the land area, making it unavailable to build upon.

Water areas – Areas such as rivers, lakes, ponds, and canals are all areas that are unsuitable to place a fast-charging station.

Roads – Though roads are very important to this study, it is not possible to place a station in the road areas themselves.

Protected green space – Protected areas are considered off limits for development reasons. These areas are not available for placement of fast-charging stations.

Distance (100m) from important roads – Fast-charging experts voiced the importance to place near busy roads. There is no desire to develop stations on neighborhood roadways or locations far from important roads, so there is no reason to include them in the analysis. The maximum distance to build from a main road is 100 meters away.

The area of examination compared to the suitability analysis is below:

Figure 5.2: Area of examination

Figure 5.3: Suitability analysis

Layer combinations

Accessibility for EV User is a combination of the two sub-layers, road capacity level and Distance from main road. The combined pairwise comparison gave a local weight of 67% to Road capacity level and a local weight of 33% to distance from main road. This combined layer holds 63.5% of the importance to the final objective layer making it a heavily important factor in determining fast-charging locations. 'Child' selection criteria layers can be found in the appendix (figures A.2 – A.13).

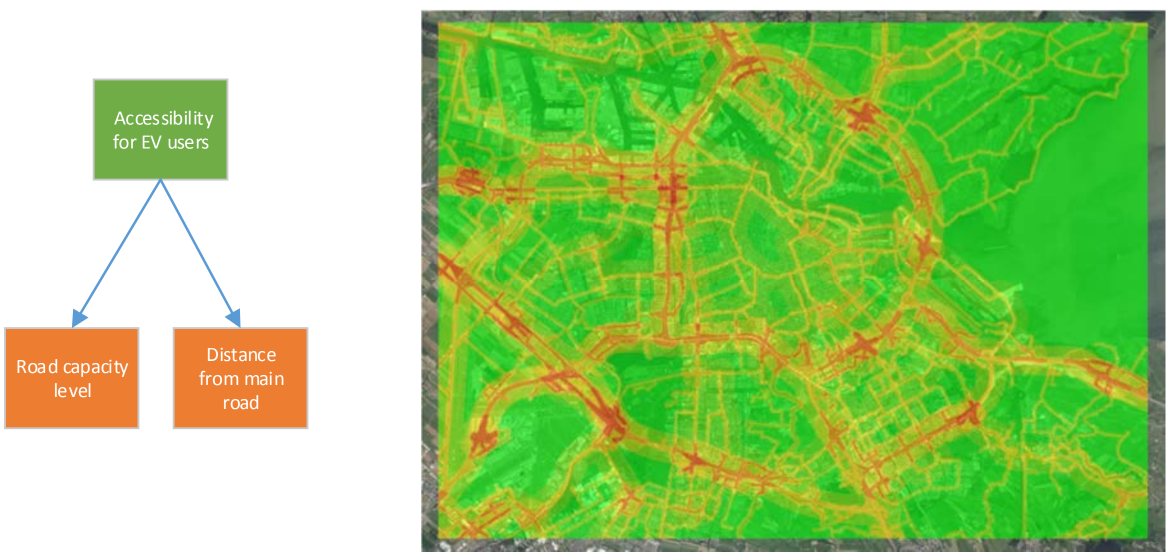


Figure 5.4: Accessibility for EV users and AHP section

Environmental Impact is directly related to the sub-criteria, Protected Flora and Fauna. No combination is needed for this criteria. Environmental impact holder 13.5% of the importance for the final layer.

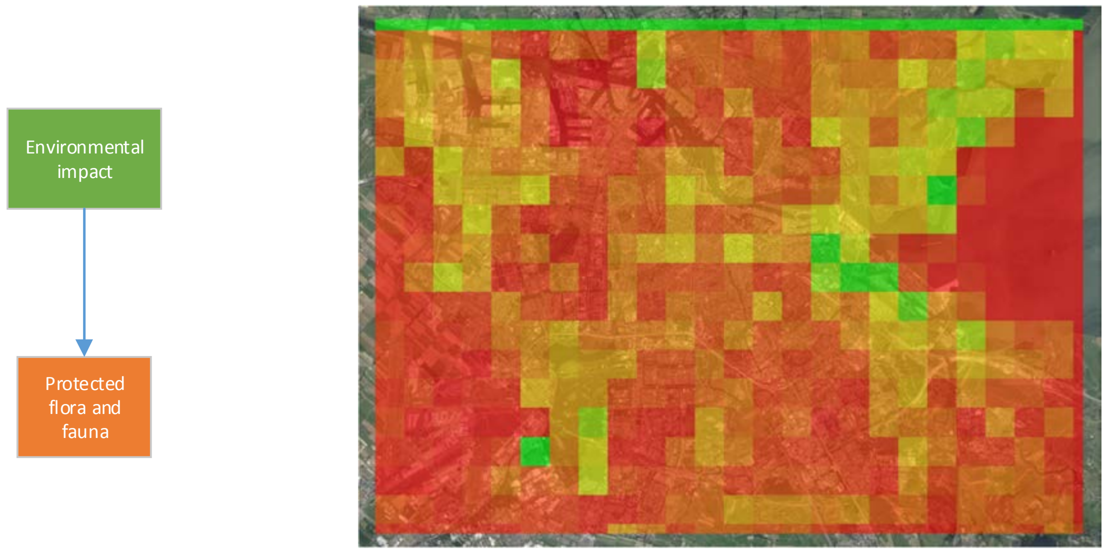


Figure 5.6: Environmental impact layer and AHP section

Proximity of EV users is a combination of residential population density (45.2%), proximity of facilities (27.1%), proximity of commercial EVs (18.9%), and proximity of slow-chargers (7.9%). Proximity of facilities is a combination of four sub-criteria, proximity of petrol stations, shopping centers, recreation and entertainment, and taxi points. Proximity of EV users has 13% of the importance toward the final objective layer. 'Child' selection criteria layers can be found in the appendix (figures A.2 – A.13).

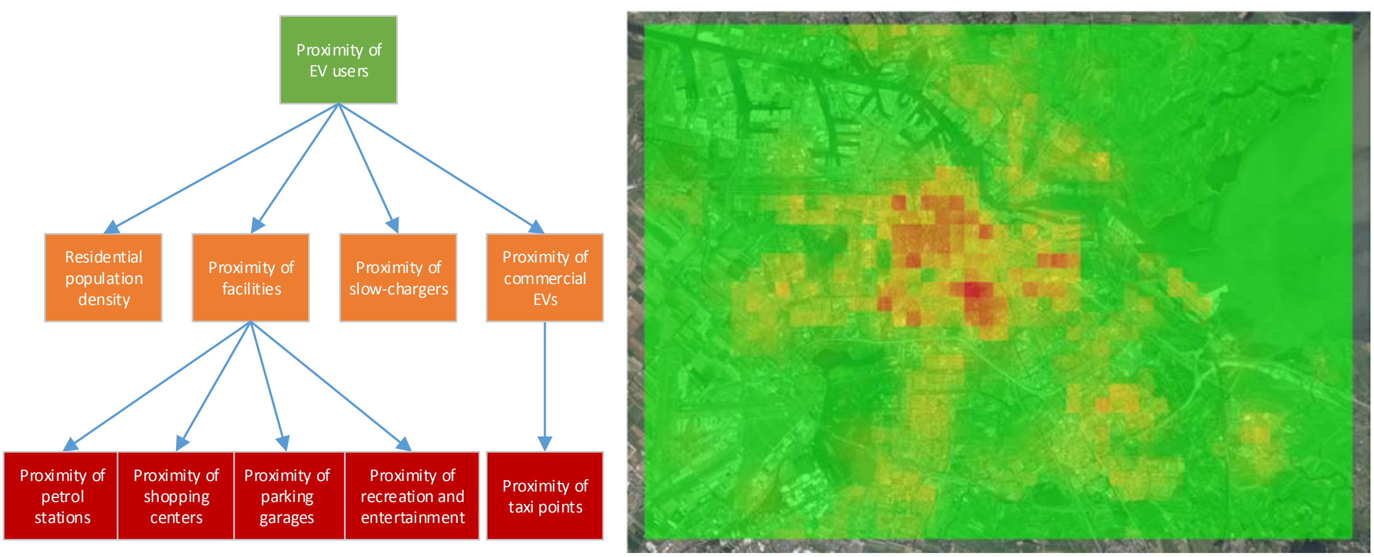


Figure 5.75: Proximity of EV users layer and AHP section

Grid impact requires no combination and is directly the distance from grid substations layer. Grid impact makes up 10% of the importance toward the final objective criteria layer.

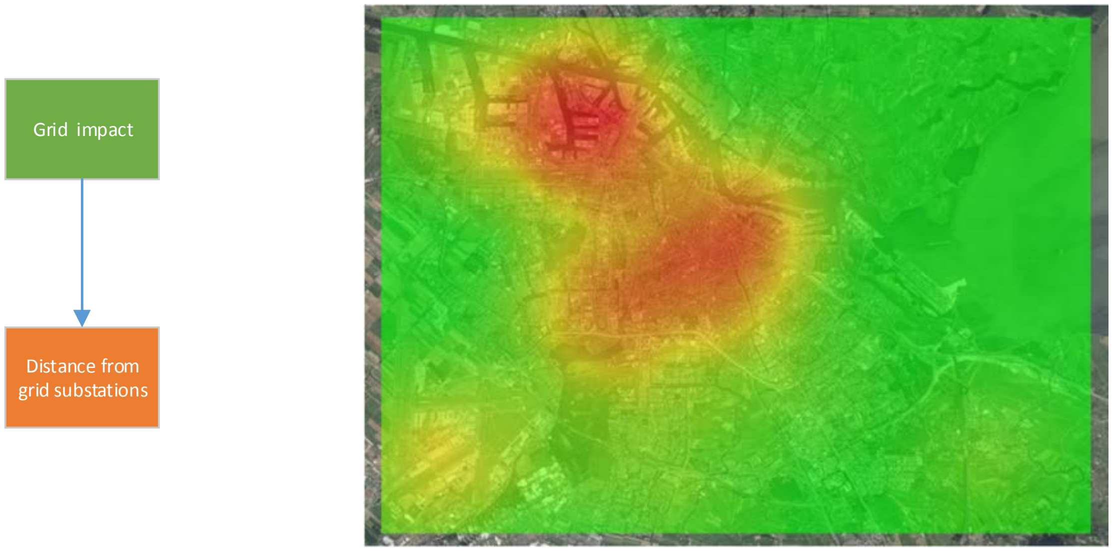


Figure 5.8: Grid impact layer and AHP section

The final objective layer is a combination of the four main criteria on level 2 of the AHP structure. Weights give their respective layer more or less overall score depending on the percentage. Analyzing the final layer will provide the top location in the city of Amsterdam for fast-charging locations. Below the image with the final objective layer results and the layer with the suitability overlay can be seen:

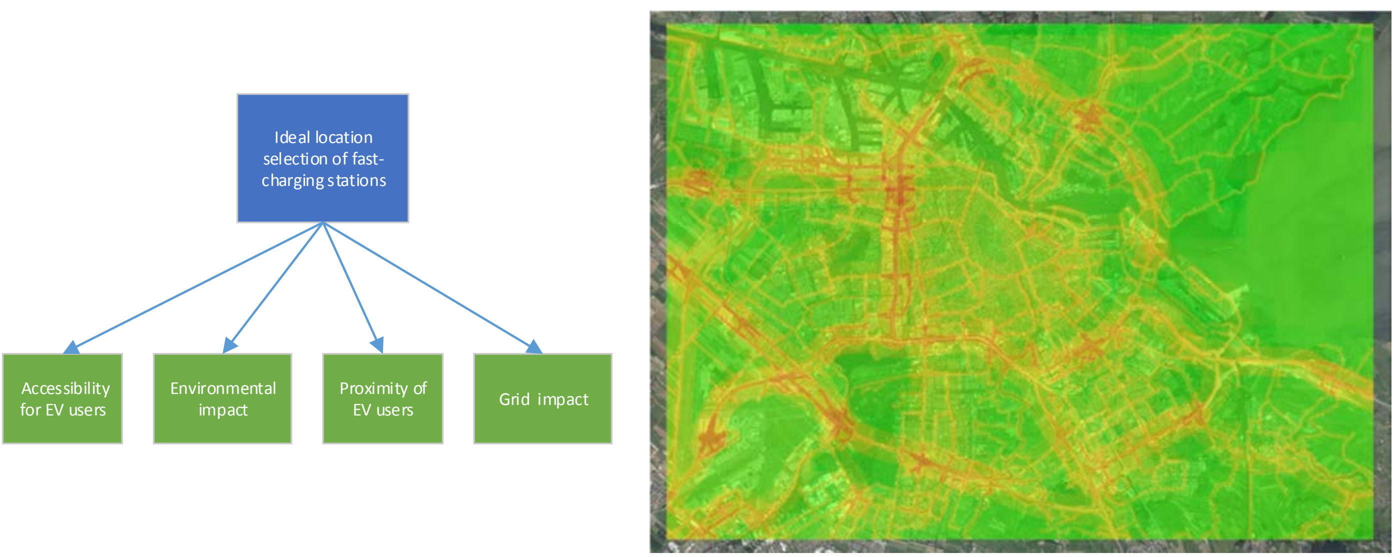


Figure 5.9: Final objective layer and AHP section

5.4 Analysis of Amsterdam

Even with the suitability analysis removing high percentage of unsuitable location, there are still vast amount of location alternatives. QGIS has a tool which allows the user to identify features of a certain layer. This was used with the final objective layer to find the location scores, but on a more precise level. Band rendering under the layer properties is used to classify value into a desired color scheme. For this study the scale (Figure 5.10) goes from green, which is a low score, to yellow, which is a medium score, to red, which is a high score. Band rendering then changes the layer scores to an easily identifiable color gradient scheme. This scale was applied to selection criteria layers to visualize the city scores per criteria layer. Band rendering can be focused on a more specific range, such as scores above 8 to highlight areas that only meet these specifications. Scores below a certain level are filtered out and leaves only top locations highlighted. Placing the suitability layer over the final objective layer then narrows down the locations to a reasonable amount. The approach was taken to find ideal fast-charging locations in the city of Amsterdam.

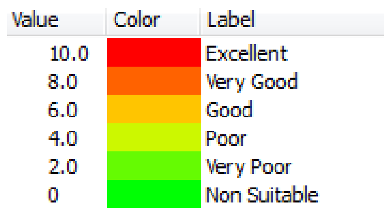


Figure 5.10: Band rendering scale

5.4.1 Number of stations and station coverage

The determined number of fast-charging stations to be located is based on the goal of decision makers. This study takes the top 10 locations as an example to satisfy plans of the supporting company, Fastned. The number of locations is ultimately up to the goals of the decision maker and how many are practical to develop. Another approach would be to place enough stations to cover the demand of the whole urban environment or to minimize travel distance to demand. In order to insure stations are not located in clustered groups, stations are not placed within a 3000 meters of one another. The assumed radius was approved by decision makers as realistic. It is important to compare scores and construction feasibility of the potential sites and not just rely entirely on the highest score, especially when the score difference is minimal. One of the most important rules governing the use of GIS for spatial decision support systems that GIS themselves do not make decisions – people do (Rikalovic, Cosic, & Lazarevic, 2014).

5.4.2 Top 10 fast-charging locations in Amsterdam

Top 10 fast-charging locations were determined based on the score in the final objective layer and the available alternatives in the suitable zones. A zoomed in view with the satellite map of the area reiterates a location is acceptable for station development. Below is examination are of Amsterdam with the top 10 ranked station locations throughout the urban environment. A reasonable distribution can been seen. Locations follow the intent of decision makers by occupying locations adjacent to busy highways and intersections.

Figure 5.10: Top 10 fast-charging locations in Amsterdam

Individual locations

Location 1 **-** The top ranked fast-charging location in the city is located in the west of the city center, just outside of the ring, near the intersection of highway A10 and Haarlemmerweg and the intersection of the A5 and A10 highways. It is also close to the Sloterdijk train station. From a closer examination, there are four potential locations within 3000m of one another, all with high scores. Only one location can be selected in this area to avoid clustering. The choice is made by a closer examination of the four sub areas according to their score and location characteristics.

The first sub-area, and top overall location in the city of Amsterdam, has a score of 8.40 out of 10 and is along Radarweg, next to Amsterdam Sloterdijk Station and the "Grand Café Hermes". This area is within 500 meters of both A5, A10, Haarlemmerweg, and is directly adjacent to Radarweg. The second sub-area has an overall score of 8.20 out of 10 and is equidistant from A5 and Haarlemmerweg. This area is within 500 meters of both exits of A5, Haarlemmerweg, and is directly adjacent to Seinweg. Furthermore, there is adequate space and undeveloped land to place a fast-charging station. The third sub-area has an overall score of 8.35 out of 10 and is along Haarlemmerweg. This area is within 500 meters of the A10 exit, and is directly adjacent to Haarlemmerweg. Further examination of the location shows complexity with bike paths, nearby railways bridges, and an unknown water ditch. This adds to the construction uncertainty of the location. The fourth sub-area has an overall score of 8.3 out of 10 and is along A10. Further examination of the location shows the accessibility is along a bridged highway stretch and is not feasible for this reason. The top sub-area is the first sub-area. This was chosen from the four possible locations because the score was the highest in the area and there is plenty of land space to place a fast-charging station while the other locations are more constrained and risky.

Table 5.3: Location 1 scores

Final objective score	8.4
Accessibility for EV users	10
Environmental impact	8.5
Grid impact	8
Proximity to EV users	1

Figure 5.12: Location 1 placement (map, score & earth views)

Location 2 - The second best location in the city is located in Amsterdam Zuid, south and west of the city center, just inside the ring, across from the Olympic Stadium. The overall score of this location is a 7.40 out of 10. The area is 500 meters from the highway A10 (east-west) and is directly adjacent to Amstelveenseweg. The plot is in a busy area with minimal space and trees, but enough for the dimensions of a fast-charging station. There is also conflict with a bike lane so extra precautions need to be taken. This location is less accessible but gains makes up with proximity of EV users. There is a petrol station across the street, and recreation and parking garage nearby.

Table 5.4: Location 2 scores

Final objective score	7.4
Accessibility for EV users	8.3
Environmental impact	7
Grid impact	7.3
Proximity to EV users	3.3

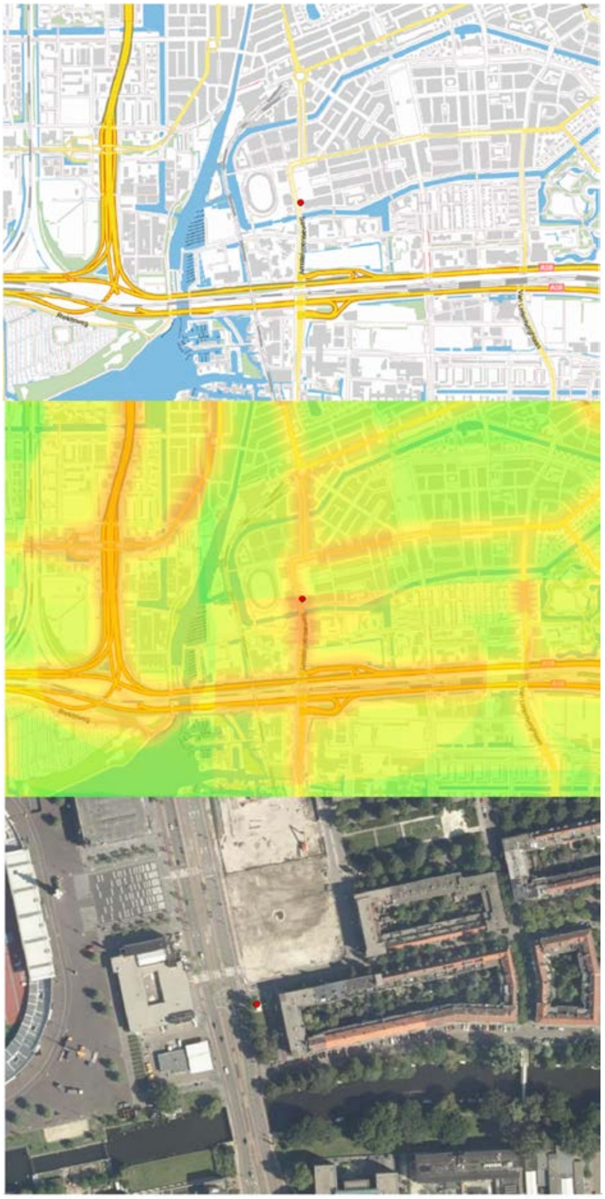


Figure 5.13: Location 2 placement (map, score & earth views)

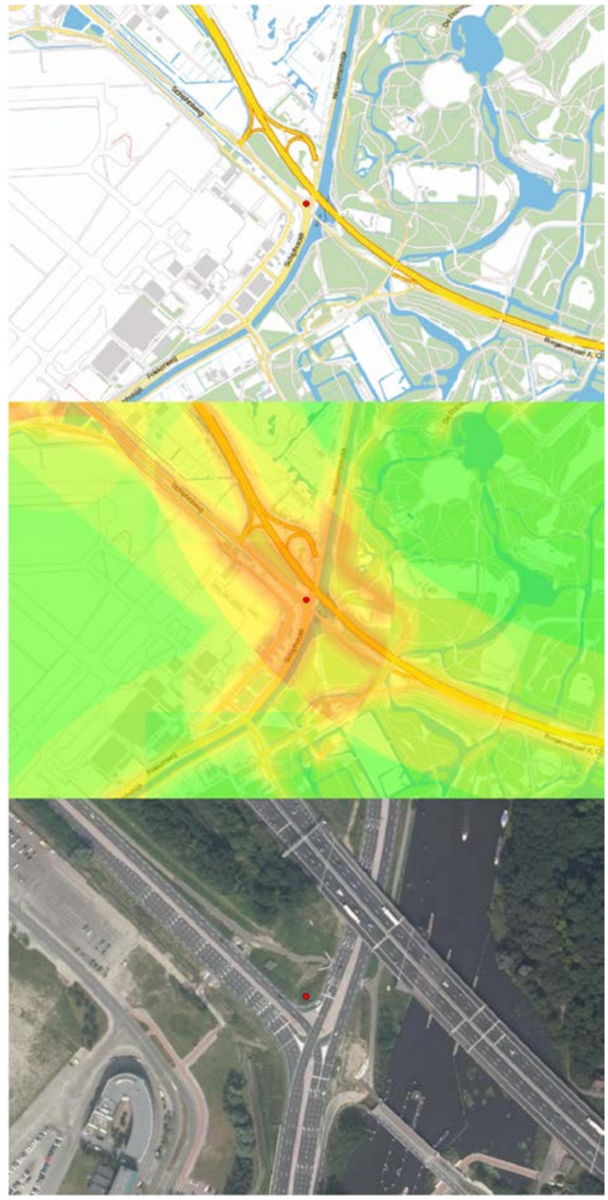


Figure 5.14: Location 3 placement (map, score & earth views)

Location 3 - Location 3 has an overall score of 7.18 and it located along A9 and Schipholweg near Schiphol Airport. This is well outside of the ring, and is technically not located in the municipality of Amsterdam. Though, this may be a good location next to the airport as many destinations are to and from the airport. This location is in a busy intersection and has high visibility from the A9 highway.

Table 5.5: Location 3 scores

Final objective score	7.18
Accessibility for EV users	8.9
Environmental impact	9.5
Grid impact	2.5
Proximity to EV users	1

Location 4 - The fourth location, with an overall score of 7.0, is in Amsterdam-Noord, north of the city center and the IJ River. The location is near the intersection of A10 and Nieuwe Leeuwarderweg. Further examination of the area shows that the top scored area may not be feasible because it is next to a highway exit ramp. There would then need to be an additional entry/exit ramp to insure safe entry and exits from the charging station. Another option is to place the station 100 meters down the way, to a location that is less dangerous and can support traffic from both directions. There are other locations in the area that may be more realistic to build upon. This is ultimately up to the decision making team.

Table 5.6: Location 4 scores

Final objective score	7
Accessibility for EV users	8.6
Environmental impact	9.5
Grid impact	1.1
Proximity to EV users	1.4

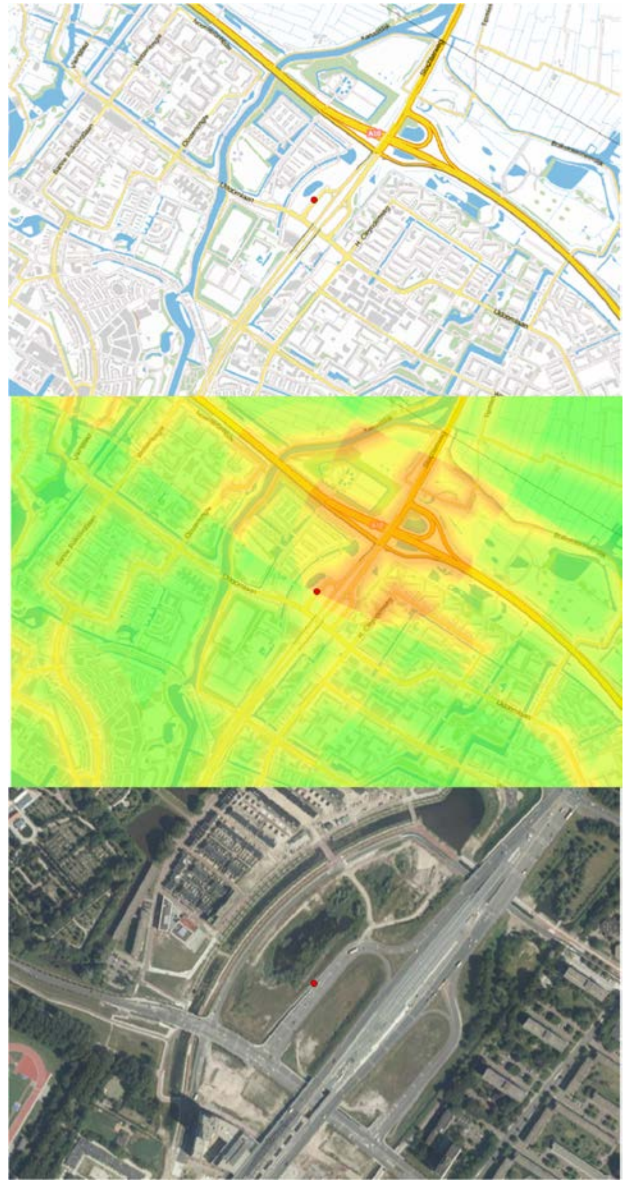


Figure 5.15: Location 4 placement (map, score & earth views)

Location 5 - Location 5 has an overall score of 7.0 and is located along the main traffic exchange of Schiphol Airport. Main roads include the A4 and A5 highways, and the Ceintuurbaan Zuid road leading to the airport. The airport is a common destination for the residents of Amsterdam and commercial EV users (taxis) so this can be a highly used station location.

Table 5.7: Location 5 scores

Final objective score	7
Accessibility for EV users	8
Environmental impact	10
Grid impact	4.6
Proximity to EV users	0.6

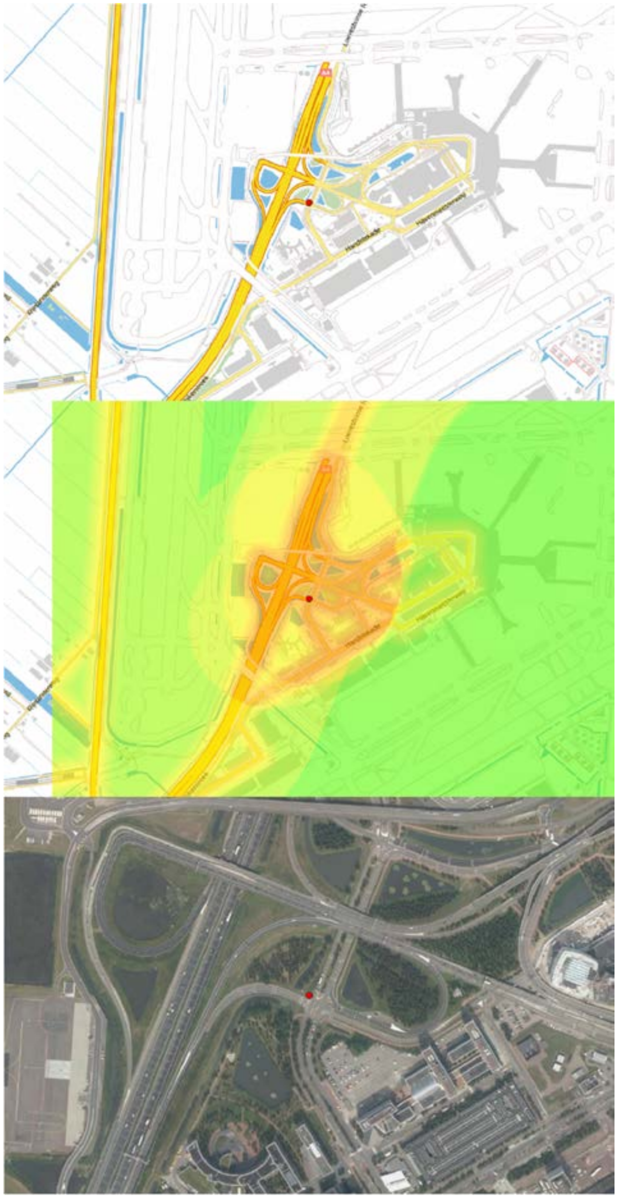


Figure 5.16: Location 5 placement (map, score & earth views)

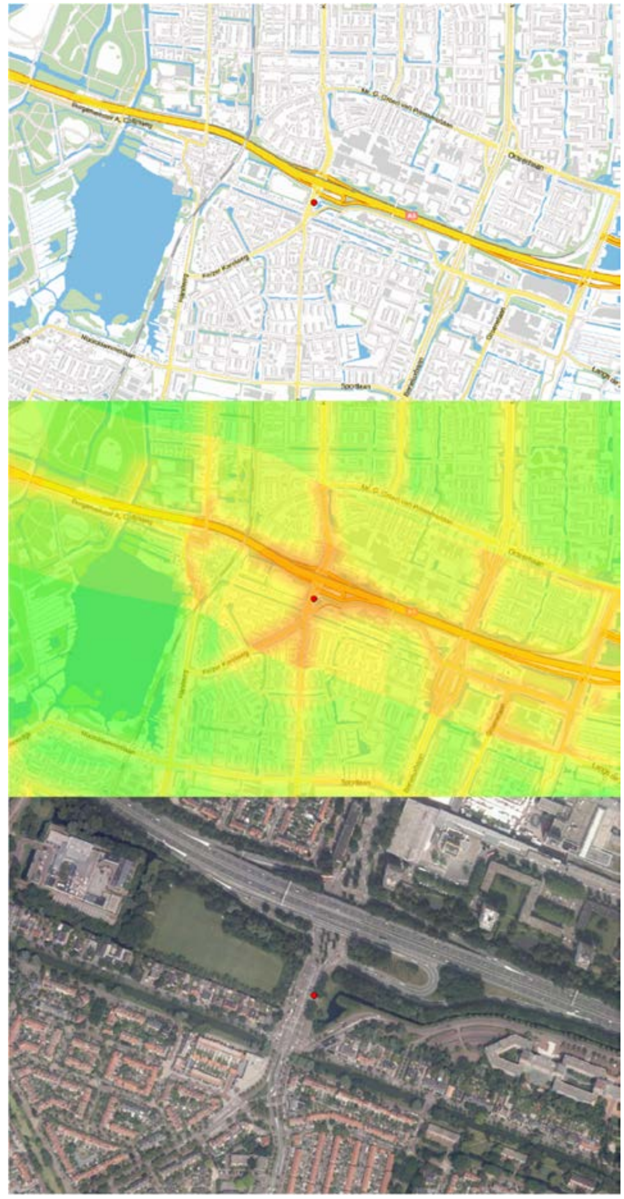


Figure 5.17: Location 6 placement (map, score & earth views)

Location 6 - With a score of 7.0, is located on the intersection of A9 and Keizer Karelweg. This area is located in the sub-urban area of Amstelveen. The location is closer to the A9 highway exit and directly adjacent to the busy road of Keizer Karelweg. There are open plots where a fast-charging station can be built, though some additional merge ways will need to be added. It should be noted that the location is more located in a denser populated area than the Schiphol locations.

Table 5.8: Location 6 scores

Final objective score	7
Accessibility for EV users	8.3
Environmental impact	9.5
Grid impact	2.4
Proximity to EV users	1.3

Figure 5.18: Location 7 placement (map, score & earth views)

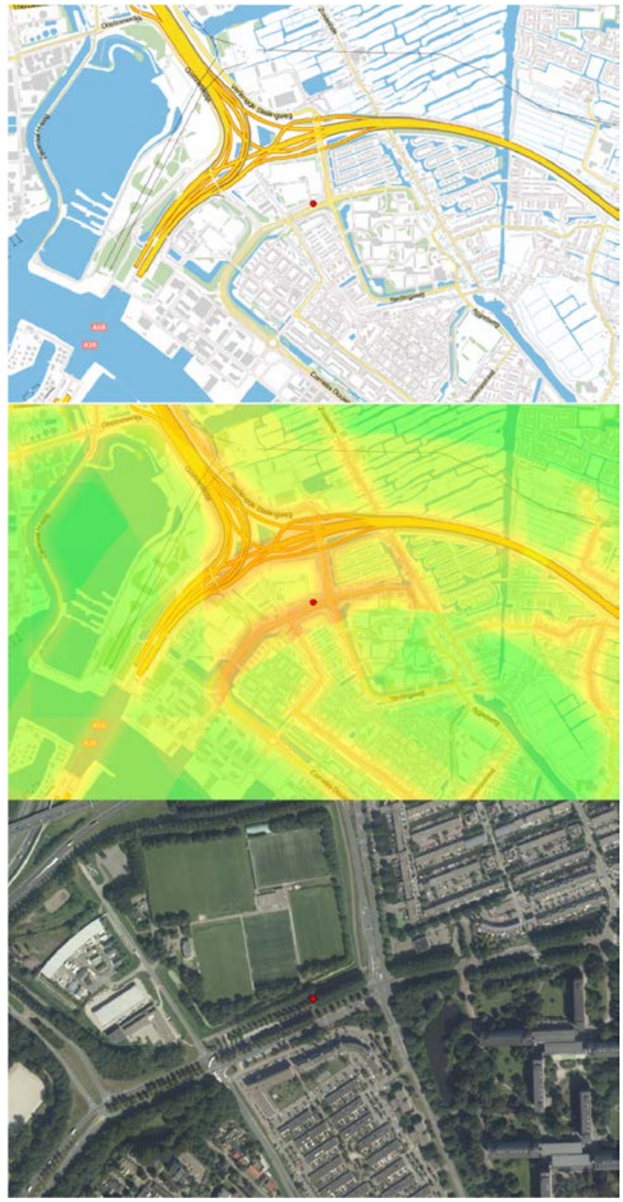


Figure 5.19: Location 8 placement (map, score & earth views)

Location 7 - With a score of 6.95, location 7 is located near the village of Halfweg. The location is just after an exit along the A200 highway, and is in between the A9 and A5 highways. This location is also technically outside of the municipality of Amsterdam, and is on the cusp of being considered rural. The score is high because of the connecting roads and proximity to other highways. Furthermore, this is a good refueling point for people leaving or entering the city limits. In addition, there is a carpark area across the street.

Table 5.9: Location 7 scores

Final objective score	6.95
Accessibility for EV users	8.6
Environmental impact	9.5
Grid impact	1.45
Proximity to EV users	0.65

Location 8 – With a score of 6.80, location 8 is located in the north along Molenaarsweg, is within 500 meters of the E35 and A10 connections, and is adjacent to Molenaarsweg, a fairly busy road. There is also an intersection of Molenaarsweg and Stellingweg, which connects to the highways. Stellingsweg could be more preferable as it is closer to the highway, but the adjacent water ditch creates a tight space. The location is also near a recreational sports complex. The location is somewhat difficult to build on considering a tunnel bike paths and tight space from a nearby water ditch. The location would also need work preparing the land by removing trees and leveling the land.

Table 5.10: Location 8 scores

Final objective score	6.8
Accessibility for EV users	8.3
Environmental impact	8.5
Grid impact	1.8
Proximity to EV users	1.85

Location 9 – With a score of 6.75, location 9 is located after the A9 exit and Amsterdamse Baan. The location is in between Schipholweg, A4 and A5 highways. It could be considered a rural area but this means there is more room to develop. It is also just north of Schiphol Airport, which may be redundant with the other two locations near the Airport, one being along the A9 highway.

Table 5.11: Location 9 scores

Final objective score	6.75
Accessibility for EV users	8.6
Environmental impact	9.5
Grid impact	0.3
Proximity to EV users	0.2

Location 10 – with a score of 6.76, location 10 is located in Amsterdam Zuidoost off of the A9 exit toward Loosdrechtdreet. The location is off of the busy highway, A9, and a provincial highway and is an entrance point the south-east part of the city. It is also next to a recreational area, decent distance from shopping areas, and a metro stop.

Table 5.12: Location 10 scores

Final objective score	6.76
Accessibility for EV users	8.9
Environmental impact	7
Grid impact	0.4
Proximity to EV users	1

Figure 5.20: Location 9 placement (map, score & earth views)

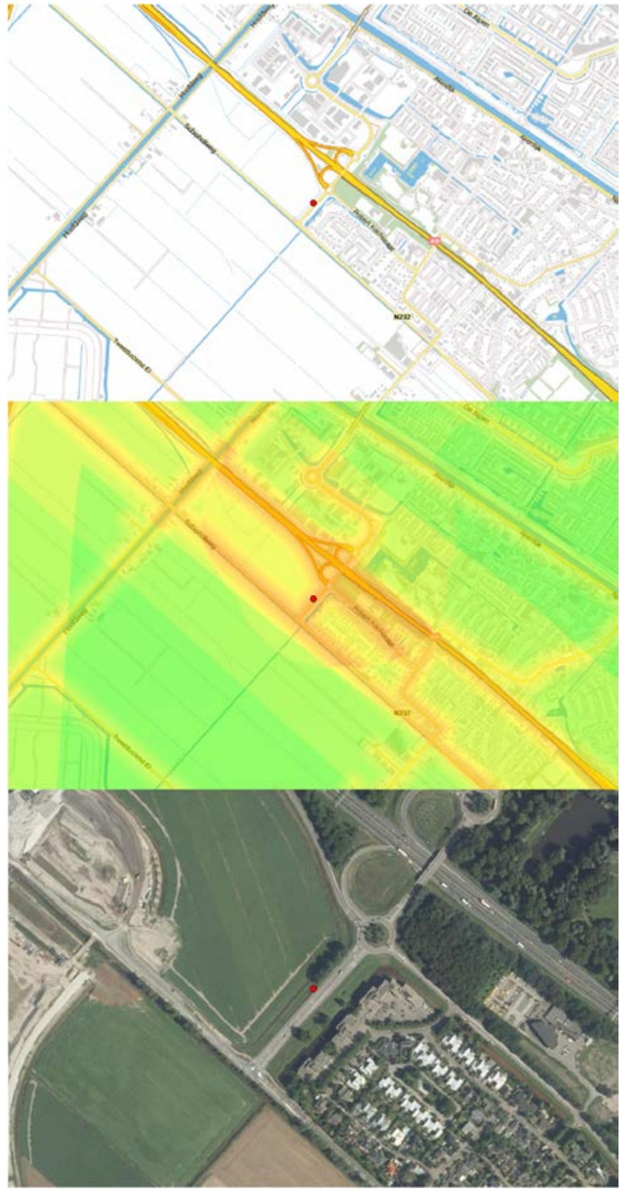


Figure 5.21: Location 10 placement (map, score & earth views)

Sensitivity Analysis

The sensitivity analysis is a combination of the criteria layers made with equal weights to analyze the GIS-AHP tool's sensitivity to expert judgment. Creating equal weights will show the analysis results as if expert judgement plays no role in the decision making process. The results will depend entirely on the normalized score of each GIS layer and how they are summed for each alternative.

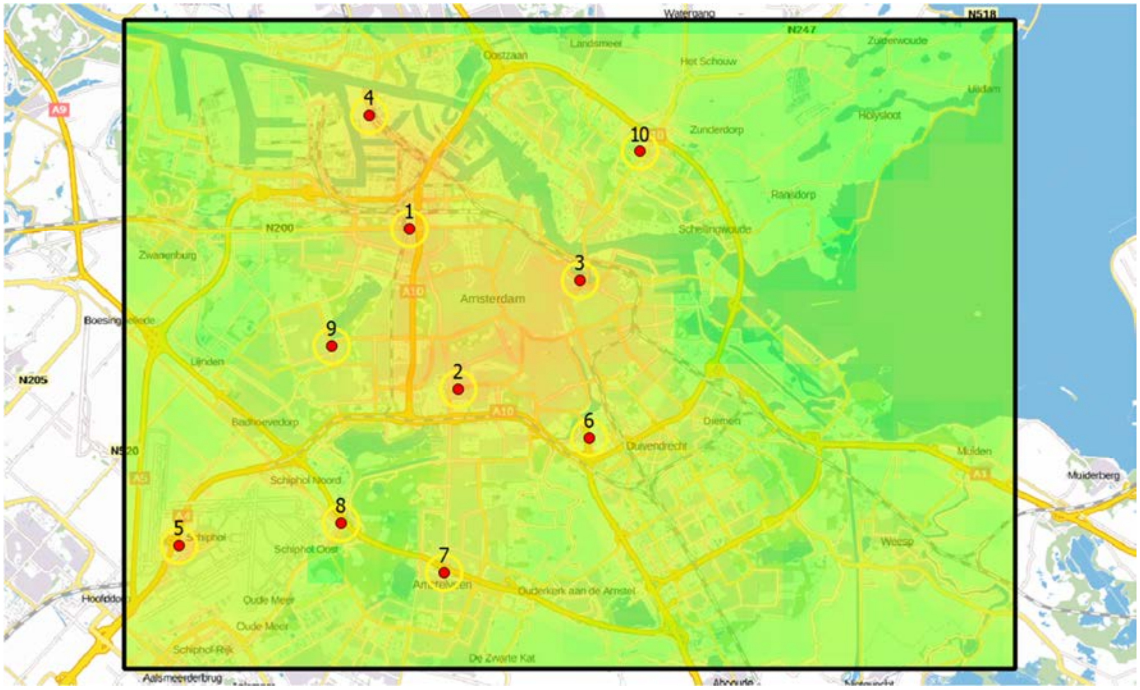


Figure 5.22: Sensitivity analysis with top locations

Scores become more balanced compared to the study results. This falls in line with the weights becoming more balanced. The average score per alternative is higher when compared to the objective layer with expert opinion weights. The overall maximum location score falls from an 8.43 to a 7.0 with the sensitivity analysis. This is explained again by the evenly divided layer weights, but also by the conflict of the layers. Being closer to important roads means moving away from EV user populations and the city center. In the sensitivity analysis there is a location movement toward the city center because proximity of EV users has more influence on the final objective layer. There are high scores recorded inside the city center, but most are unsuitable for development due to space limitations or permanent structures.

Table 5.13: Sensitivity analysis vs expert judgements

Score comparisons	*With expert judgement*	*Sensitivity analysis*
Maximum score	8.43	7.00
Minimum score	0.00	0.00
Average score	2.68	3.14
Standard deviation	1.50	1.20

The top 3 locations in the sensitive analysis cover the entirety of the city center with a location in the west, south, and east of the city. Locations 1, 2 5, 7, 8 and 10 from the sensitivity analysis are in locations also found in the final objective layer, though, not necessarily with the same ranking.

Chapter 6 Discussion

This chapter opens a discussion for the results found in the case city of Amsterdam. The patterns and observations of the top 10 locations are shown, followed by limitations of the study and recommended extensions of the study.

6.1 Location patterns and observations

Placement of fast-charging stations clearly follows the city ring and the busy highways. Locations that are in a 500 meter proximity of multiple important roadways are most prized. The preference of decision makers is clear: accessibility is top priority. Ideal locations will be developed near the highest capacity roadways and directly adjacent to a roadway where EV customers can easily enter a station and exit when their charge is complete.

The top location in the city of Amsterdam is unanimous choice with a score of 8.4 out of 10. This location is the most accessible centered between two busy highways and a busy regional way. The score was boosted even further with its low impact on the environment and low grid impact. This location, like all others, has a noticeably low score for proximity of EV users. There is a clear contradiction between the selection criteria of accessibility proximity of EV users, and accessibility clearly wins.

Locations 2 is also located between two highways and along a prime city road. This location is in a denser area with more housing and recreational areas, and is next to a petrol station, which gives it the highest score of any location for proximity of EV users. Being within the city ring and near many important roadways makes it an excellent location for fast-charging. Space limitation is a drawback with choosing a location in a denser area. The suitability analysis shows that the plot of land would be large enough to build on, but more development is needed to work with landscape and bike paths.

Locations 3 through 10 are all very closely scored and their rankings differ by only a margin of 0.5 points. Because of overwhelming preference to high capacity roads and intersections, locations tend to move toward sub-urban areas that are outside the municipality of Amsterdam boundary in order to satisfy the demand for traffic flow. This then leads to locations 3, 5, 6, 9 being selected in a repetitive area, along highway A9 and near Schiphol Airport. Location 7 is also arguably in a rural area on the outskirts of the analyzed area. Though these areas capture high traffic flows and are highly accessible, it is questions if they really constitute a solution to urban demand. Out of the 10 top locations in Amsterdam, 5 are within the city limits and 5 are outside.

6.2 Limitations

Limitations are when steps in the research are not able to reach their full potential due to an uncontrollable barrier. Limitations in this study were due to the accuracy of available information, inability to sufficiently represent selection criteria, and drawbacks with the selected model.

6.2.1 Information

Open source data was exclusively used in this study. Not all data sets were equal in the way they were able to represent criteria objectives. Data accuracy varied by: (1) the relevancy of the data, (2) the GIS layout of data, (3) the data units (4) the assumed proximity distances and

(5) barrier of development. The most up-to-date data was used but in some cases this was up to two years old. Today's reality could be a much different scenario from two years ago. The GIS layers were represented as heatmaps, buffer sets, and grid layouts due to the data type. Ideally, they would all be conformed to one feature type to make a more exact analysis. Not all criteria were able to be shown as accurate as hoped. For example, road capacity level shows the importance of the roads based on the NWB, but a more accurate data set would be traffic flow rate of vehicles per unit of time, though, this data is not available. Lastly, the proximity distances are defended but can be improved as more is discovered about fast-charging user behaviors and preferences in urban environments. In addition, there are tangibility barriers to the development of stations which are unknown. Even if a location is desired, actual purchasing of the land plots is not always possible. Furthermore, permitting, designing, and construction is a long process before the stations is fully developed.

6.2.2 Selection criteria

Additional selection criteria layers were planned to be included but data was not available to adequately support them. Solar potential, land cost, and distance from 10kV grid lines were criteria which are important to fast-charging locations but were unable to be represented in GIS. Data is either not open to the public use or is nonexistent. Criteria, like land cost, are frequently in fluctuation making them hard to capture. Perhaps as more open data is made available these criteria can be included in the analysis.

6.2.3 Selected method

MCDM models are limited by analyzing each alternative individually. There is no relationship between the networks of location choices. This makes the first ideal location a strong decision but the following locations less defendable. For example, the top locations could be determined based on their scores, but in the case study they, at times, clustered in one area. A decision maker would not want to place all facilities in one place; facilities should work together in a network.

The GIS-AHP model is greatly influenced by expert knowledge. This makes AHP a double-edged sword in the sense that knowledge can be helpful if accurate and harmful if inaccurate. The pairwise comparison tests for consistency amongst judgements, but there is still an area of uncertainty in the procedure. The tool works to represent an organization's vision, which is why the locations are labeled 'ideal' over the term 'optimal'. Another concern with the AHP model is the case of the rank reversal phenomenon.

6.3 Recommended extensions

The GIS-AHP method can also be improved by the use of additional criteria, or additional expert opinions. New criteria may be proven important to the success of fast-charging locations as the service is further understood and as more data becomes available. Other stakeholder opinions can be included in the AHP pairwise comparison including; EV users, the municipally, or the grid company.

Extending the understanding of ideal fast-charging locations with other techniques is certainly possible. *P*-median and max coverage are two widely known models and are popular with optimizing locations within a defined network. *P*-median can insure the network of fast-chargers are being optimized by minimizing travel distances from EV users. *P*-median can work well in urban environments to improve convenience of the stations by planning a network. Max-coverage would make sure a network is in place to service the entire urban environment. Other MCDM methods and combination methods can extend understanding of location-allocation uses. Additionally, the combination with fuzzy set theorem could reduce some of the ambiguity involved with criteria weights.

Chapter 7 Conclusion

Electric vehicles show great promise to enhance modern mobility by quelling concerns over exhaust pollution, and improving energy efficiency and safety. In the Netherlands the electric vehicle market has passed the innovator's adoption phase and reached the early adoption phase. This pattern of EV acceptance will continue exponentially as the Netherlands plans for 1 million EVs on the road by 2025. The Netherlands has set an impressive foundation for EV acceptance by placing a vast network of public slow-charging points and offering lucrative financial incentives to EV users. But the inefficiencies of slow-charging points are obvious and will not support a mass-scale number of EVs. In dense urban environments where space is limited, EVs have the highest acceptability and need a reliable, efficient, and intelligent charging infrastructure. Fast-charging, with the capability to fully charge an EV in 20 minutes or less, is a prime upgrade to the Dutch charging infrastructure. An upgrade to the charging infrastructure will support EV adoption and make a strong push for solving society's modern mobility issues.

Selecting locations for fast-charging stations is incredibly important, especially in the early stages of consumer adoption and the beginning phase of commercial viability. Urban environments have unique characteristics which contribute to the complexity of location-allocation and decision making. Previous studies have selected models which lack the input of expert knowledge and are subject to complex algorithms. A synergistic method of GIS-AHP has been selected to make sense of complex urban factors and to implement expert knowledge towards a geographic solution for fast-charging site selection. This study will fill a gap in knowledge by being the first of its kind to use a GIS-AHP approach for fast-charging site selection.

Eleven selection criteria were finalized from a literature review, elicitation of knowledge with fast-charging experts, and consultation with university supervisors. Selection criteria were organized in a relationship hierarchy based on stakeholder objectives, with the final objective of ideal locations for fast-charging as the structure's apex. GIS layers represent selection criteria, and were created through open source GIS datasets and the software QGIS. The final objective layer is a combination of all 11 criteria layers, each with a unique weight devised from a pairwise comparison and expert judgements. Accessibility for EV users, a combination of road capacity level and distance from main road, was the dominant criteria layer with 63.5% of the global importance, followed by environmental impact at 13.5%, proximity of EV users at 13.0%, and grid impact at 10.0%.

The most ideal location in the city of Amsterdam, with a final objective score of 8.40 out of 10, is located in the west of the city, next to Sloterdijk Station and adjacent to Radarweg. The location's proximity to two busy highways, two regional roadways, and multiple busy intersections gave it the top score. The second most ideal location, with a score of 7.40, is south of the main city center across from the Olympic stadium. This location is also near a busy highway intersection and is along a busy city road but gained an advantage for its score in proximity of EV users. Location 3 through 10 had close scores and were placed throughout the examination area, mostly along intersections of important roads and near Schiphol Airport. The sensitivity analysis shows that the GIS-AHP tool is heavily influenced by expert knowledge and the pairwise comparison weights. Without expert opinions, the locations shift toward the city center and areas a higher proximity of EV users. There is a clear conflict with accessibility and proximity of EV users.

The use of GIS-AHP for fast-charging site selection is a robust location-allocation approach and can be applied to urban environments. Incorporating expert opinion into GIS layer weights provides a business-conscious boost over past location-allocation studies and aids decision makers with a user-friendly and visual geographic solution. Fast-charging locations placement is a critical decision that will have an impact on the future of charging infrastructure and EV acceptance. This study has developed a useful tool to analyze urban environments and bring fast-charging to the public in the most effective and responsible way.

References

Adamcsek, E. (2008). *The Analytic Hierarchy Process and its Generalizations.* Thesis, Eotvos Lorand University.

Amsterdam Roundtables Foundation. (2014). *Electric vehivles in Europe: gearing up for a new phase?*

Arentze, T. (2000). Location Allocation Models. 1-23.

Arentze, T., & Borgers, A. (2003). *Introduction to Multi-criteria Evaluation.* Eindhoven University of Technology, Urban Planning Group.

Caunhye, A. M., Li, M., & Nie, X. (2015). A location-allocation model for casualty response planning during catastrophic radiological incidents. *Socio-Economic Planning Sciences, 50*, 32-44.

Cavadas, J., Correia, G. H., & Gouveia, J. (2015). A MIP model for locating slow-charging stations for electric vehicles in urban areas accounting for driver tours. *Transportation Research Part E, 75*, 188-201.

Charging data Amsterdam Electric. (2015, Feburary). Amsterdam.

Chaudhary, P., Chhetri, S. K., Joshi, K. M., Shrestha, B. M., & Kayastha, P. (2015). Application of an Analytic Hierarchy Process (AHP) in the GIS interface for suitable fire site selection: A case study of Kathmandu Metropolitan City, Nepal. *Socio-Economic Planning Sciences*, 1-12.

Dharmakeerthi, C. H., Mithulananthan, N., & Saha, T. K. (2014). Impact of electric vehicle fast charging on power system voltage stability. *Electrical Power and Energy Systems, 57*, 241-249.

Dodgson, J., Spackman, M., Pearman, A., & Phillips, L. (2016, June 8th). *Communities and Local Government* . Retrieved from The National Archives: http://webarchive.nationalarchives.gov.uk

Electric car use by country. (2015, November 15). Retrieved from Wikipedia: https://en.wikipedia.org/wiki/Electric_car_use_by_country#Global_outlook

(2015). *Electromobility in the Netherlands.* Utrecht: Netherlands Enterprise Agency.

Feng, H., Yin, Y., & Zhou, J. (2015). Deploying public charging stations for electric vehicles on urban road networks. *Transportation Research Part C, 60*, 227-240.

Funke, S. A., Gnann, T., & Plotz, P. (2015). *Addressing the Different Needs for Charging Infrastructure: An Analysis of Some Criteria for Charging Infrastructure Set-up.* Karlsruhe, Germany: Pringer International Publishing Switzerland.

Guo, S., & Zhao, H. (2015). Optimal site selection of electric vehicle charging station by using fuzzy TOPSIS based on sustainability perspective. *Applied Energy, 158*, 390-402.

Hatton, C. E., Beella, S. K., Brezet, J. C., & Wijnia, Y. C. (2009). Charging Sations for Urban Settings the design of a product platform for electric vehicle infrastructure in Dutch cities. *EVS24 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium*, (pp. 1-13). Stavanger, Norway.

He, F., Wu, D., Yin, Y., & Guan, Y. (2013). Optimal deployment of public charging stations for plug-in hybrid electric vehicles. *Transportation Research Part B, 47*, 87-101.

He, S. Y., Kuo, Y.-H., & Wu, D. (2016). Incorporating institutional and spatial factors in the selection of the optimal locations of public electric vehicle charging facilities: A case study of Beijing, China. *Transportation Research, 67*(Part C), 131-148.

Kanters, G. F. (2013). *Spatial modelling to allocate locations for public charging stations.* Eindhoven, Netherlands.

Kim, S., Yang, D., & Soora, R. (2015). Understanding charging patterns of electric vehicles on public charging infrastructure. *BIVEC/GIBET Transport Research Day 2015*.

Kong, N., Zhang, T., & Stonebraker, I. (2015). Evaluation of web GIS functionality in academic libraries. *Applied Geography, 60*, 288-293.

Langezaal, M. (2015, October 5). The Fastned Freedom Plan. Netherlands.

Lee, J., & Park, G.-L. (2015). Dual battery management for renewable energy integration in EV charging stations. *Neurocomputing*, 181-186.

Mobility and Transport. (2012). Transport: Electric vehicles - European commission. Retrieved from ec.europa.eu

Morrissey, P., Weldon, P., & O'Mahony, M. (2016). Future standard and fast charging infrastructure planning: An analysis of electric vehicle charging behavior. *Energy Policy, 89*, 257-270.

Open Geo Data. (2016). Retrieved from City of Amsterdam: http://maps.amsterdam.nl/open_geodata/

Publike Dienstverlening op de Kaart. (2016). Retrieved from PDOK: https://www.pdok.nl/

Rahman, S.-u., & Smith, D. K. (2000). Use of location-allocation models in health service development planning in developing nations. *European Journal of Operational Research, 123*, 437-452.

Rikalovic, A., Cosic, I., & Lazarevic, D. (2014). GIS Based Multi-Criteria Analysis for Industrial Site Selection. *Procedia Engineering, 69*, 1054-1063.

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *Int. J. Services Sciences, 1*(1), 83-98.

Sadeghi-Barzani, P., Rajabi-Ghahnavieh, A., & Kazemi-Karegar, H. (2014). Optimal fast charging station placing and sizing. *Applied Energy, 125*, 289-299.

Sanchez-Lozano, J. M., Teruel-Solano, J., Soto-Elvira, P. L., & Garcia-Cascales, M. S. (2013). Geographical Information Systems (GIS) and Multi-Criteria Decision Making (MCDM) methods for evaluation of solar farms locations: Case study in south-eastern Spain. *Renewable and Sustainable Energy Reviews, 24*, 554-556.

Sbordone, D., Bertini, I., Di Pietra, B., Falvo, M., Genovese, A., & Martirano, L. (2015). EV fast charging stations and energy storage technologies A real implementation in the smart micro grid paradigm. *Electric Power Systems Research, 120*, 96-108.

Schroeder, A., & Traber, T. (2012). The economics of fast charging infrastructure for electric vehicles. *Energy Policy, 43*, 136-144.

Sener, S., Sener, E., Nas, B., & Karaguzel, R. (2010). Combining AHP with GIS for landfill site selection: A case study in the Lake Beysehir catchment area (Konya, Turkey). *Waste Management, 30*, 2037-4046.

Shahraki, N., Cai, H., Turkay, M., & Xu, M. (2015). Optimal locations of electric public charging stations using real world travel patterns. *Transportation Research Part D, 41*, 165-176.

Shao-yun, G., Liang, F., Hong, L., & Long, W. (2012). The Planning of Electric Vehicle Charging Stations in the Urban Area. *EMEIT*, (pp. 1598-1604).

Speidel, S., & Braunl, T. (2014). Driving and charging patterns of electric vehicles for energy usage. *Renewable and Sustainable Energy Reviews, 40*, 97-110.

Spoelstra, J. C. (2014). *Charging behaviour of Dutch EV drivers.* Utrecht University, Science and Innovation Management , Utrecht.

Ssebuggwawo, D., Hoppenbrouwers, S., & Proper, E. (n.d.). *Group Decision Making in Collaborative Modeling.* Radboud University , Institue of Computing and Information Sciences, Nijmegen.

Tesla Motors. (2013, August 13). Tesla Model S Achieves Best Safety Rating of Any Car Ever Tested. Palo Alto, CA, USA.

Tu, W., Li, Q., Fang, Z., Shaw, S.-l., & Zhou, B. (2015). Optimizing the locations of electric taxi charging stations: A spatial-temporal demand coverage approach.

Urban population outnumber rural population. (2005, February 21). Retrieved from Statistics Netherlands: http://www.cbs.nl/en-GB/menu/themas/dossiers/nederland-regionaal/publicaties/artikelen/archief/2005/2005-1651-wm.htm

Uyan, M. (2013). GIS-based solar farms site selection using analytic hierarchy process (AHP) in Karapinar region, Konya/Turkey. *Renewable and Sustainable Energy Reviews, 28*, 11-17.

van den Hoed, R., Helmus, J. R., de Vries, R., & Bardok, D. (2013). Data analysis on the public charge infrastructure in the city of Amsterdam. *ECS27 Symposium*, (pp. 1-10). Barcelona, Spain.

Wang, Y.-W., & Lin, C.-C. (2013). Locating multiple types of recharging stations for battery-powered electric vehicle transport. *Transportation Research Part E, 58*, 76-87.

Zhang, L., Schaffer, B., Brown, T., & Samuelsen , G. S. (2015). The optimization of DC fast charging deployment in California. *Applied Energy, 157*, 111-122.

Glossary

Analytic hierarchy process (AHP) – A structured technique for analyzing and organizing complex decisions based on mathematics and psychology.

Buffer - A geoprocessing tool which extends constant coverage in all directions of a feature depending on the proximity value.

Capacity utilization – the time a charging point is occupied by an EV divided by the total time the charge point was available.

Charge utilization - the time an EV is actually charging divided by the time the car is connected.

Clip – A GIS process which creates a new shape based on the area of the input layer that is overlapped by the clipping layer.

Consistency index (CI) – A calculation of a pairwise matrix used to find consistency ratio.

Consistency ratio (CR) - A measurement of a set of judgments for error and changes in judgment.

Electric vehicle (EV) – Vehicles powered by an electric motor and a rechargeable electric battery.

Electric vehicle charging stations (EVCS) – One or more charging point used to refuel EVs with electricity.

Fast-charger – Any charger with a 43 kW power level or higher.

Geographic information system (GIS) – A system designed to capture, store, manipulate, analyze, manage and present all types of spatial and geographical data.

GIS Layer – A specific set of GIS data representing one facet of the real world.

Heatmap – A geographical representation of data where the individual points create a color coded density map.

Kernel function - A weighting function used in estimating density and creating a corresponding distribution.

Multi-criteria decision making (MCDM) – Used in structuring and solving decision and planning problems involving multiple criteria.

No data – Refers to the absence of data for a particular variable value.

Pairwise comparison – A process used to compare entities in pairs to judge the level of preference between the pairs.

Proximity distance – A distance value which defines the effect area of a particular feature.

Range anxiety – Fear of running out of battery range before reaching the end destination or a recharging point.

Reclassify – Process used to reassign values to another set of values.

Raster data – A matrix of cells or pixels organized in a grid where each cell contains a value representing information.

Rasterize – A conversion into pixels that can be displayed on a screen, typically from vector data.

Slow-charger – Any charger with a power level lower than 43 kW.

Vector data – A representation of the world using points, lines, and polygon features.

Appendix

Figure A.1: (from left to right) CHAdeMO adapter, CCS "Combo" adapter, AC "Mennekes" adapter

Table A.1: Pairwise survey

AHP Level	Item	Scale									Scale								Item
		Extreme Importance		*Very Strong Importance*		*Strong Importance*		*Moderate Importance*		*Equal Importance*	*Moderate Importance*		*Strong Importance*		*Very Strong Importance*		*Extreme Importance*		
Level 1	**Proximity to EV Users**	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Accessibility for EV Users**
	Proximity to EV Users	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Environmental Impact**
	Proximity to EV Users	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Grid Impact**
	Accessibility for EV Users	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Environmental Impact**
	Accessibility for EV Users	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Grid Impact**
	Environmental Impact	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Grid Impact**
Level 2	**Distance from Main Road**	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Road Capacity Level**
Level 2	**Proximity of Facilities**	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Residential Population Density**
	Proximity of Facilities	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Proximity of Slow Chargers**
	Proximity of Facilities	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Proximity of Commercial Evs**
	Residential Population Density	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Proximity of Slow Chargers**
	Residential Population Density	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Proximity of Commercial Evs**
Level 3	**Proximity of Slow Chargers**	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Proximity of Commercial Evs**
	Proximity of Petrol Stations	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Proximity of Shopping Centers**
	Proximity of Petrol Stations	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Proximity of Parking Garages**
	Proximity of Petrol Stations	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Proximity of Recreation**
	Proximity of Shopping Centers	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Proximity of Parking Garages**
	Proximity of Shopping Centers	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Proximity of Recreation**
	Proximity of Parking Garages	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**Proximity of Recreation**

Table A.2: Pairwise results expert #1

Tier 1	*COMPARE ROW TO COLUMN								Random Index
Comparison Matrix 1	Proximity to EV Users	Accessibility for EV Users	Environmental Impact	Grid Impact				2	0
Proximity to EV Users	**1**	1/4	1	4				3	0.58
Accessibility for EV Users	4	**1**	6	8				4	0.9
Environmental Impact	1	1/6	**1**	3				5	1.12
Grid Impact	1/4	1/8	1/3	**1**				6	1.24
Sum	*6.25*	*1.54*	*8.33*	*16.00*				7	1.32
								8	1.41
Normialized Matrix	Proximity to EV Users	Accessibility for EV Users	Environmental Impact	Grid Impact	Weight			9	1.45
Proximity to EV Users	0.16	0.16	0.12	0.25	17.3%			10	1.51
Accessibility for EV Users	0.64	0.65	0.72	0.50	62.7%				
Environmental Impact	0.16	0.11	0.12	0.19	14.4%				
Grid Impact	0.04	0.08	0.04	0.06	5.6%				
					100.0%				
CI and CR	Proximity to EV Users	Accessibility for EV Users	Environmental Impact	Grid Impact	Sum	Sum/Weight	Count (m)	4	
Proximity to EV Users	0.17	0.16	0.14	0.22	0.70	4.03	Lamda max (x)	4.087975044	
Accessibility for EV Users	0.69	0.63	0.86	0.45	2.63	4.19	CI	0.029325015	
Environmental Impact	0.17	0.10	0.14	0.17	0.59	4.09	RI	0.9	
Grid Impact	0.04	0.08	0.05	0.06	0.23	4.03	CR	0.03258335	
Tier 2									
Comparison Matrix 2	nce from renewable energy so	Distance from grid substation							
Distance from renewable energy sources	**1**	1/7							
Distance from grid substation	7	**1**							
Sum	8.00	1.14							
Normialized Matrix	nce from renewable energy so	Distance from grid substation	Weight						
Distance from renewable energy sources	0.13	0.13	12.5%						
Distance from grid substation	0.88	0.88	87.5%						
CI and CR	nce from renewable energy so	Distance from grid substation	Sum	Sum/Weight	Count (m)	2			
Distance from renewable energy sources	0.13	0.13	0.25	2.00	Lamda max (x)	2	*2 x 2 always		
Distance from grid substation	0.88	0.88	1.75	2.00	CI	0	consistant		
					RI	1.12			
					CR	0			
Comparison Matrix 3	Proximity to EV Users	Accessibility for EV Users	Weight						
Distance from main road	**1**	1/4	20.0%						
Traffic flow rate	4	**1**	80.0%						
Comparison Matrix 4	Distance from facilities	Residential population density	Distance from slow chargers	Distance from commercial Evs					
Distance from facilities	**1**	1	5	4					
Residential population density	1	**1**	5	5					
Distance from slow chargers	1/5	1/5	**1**	1					
Distance from commercial Evs	1/4	1/5	1	**1**					
Sum	*2.5*	*2.4*	*12.0*	*11.0*					
Normialized Matrix	Distance from facilities	Residential population density	Distance from slow chargers	Distance from commercial Evs	Weight				
Distance from facilities	0.41	0.42	0.42	0.36	40.1%				
Residential population density	0.41	0.42	0.42	0.45	42.4%				
Distance from slow chargers	0.08	0.08	0.08	0.09	8.5%				
Distance from commercial Evs	0.10	0.08	0.08	0.09	9.0%				
CI and CR	Distance from facilities	Residential population density	Distance from slow chargers	Distance from commercial Evs	Sum	Sum/Weight			
Distance from facilities	0.40	0.42	0.42	0.36	1.61	4.01	Count (m)	4	
Residential population density	0.40	0.42	0.42	0.45	1.70	4.01	Lamda max (x)	4.006232674	
Distance from slow chargers	0.08	0.08	0.08	0.09	0.34	4.01	CI	0.002077558	
Distance from commercial Evs	0.10	0.08	0.08	0.09	0.36	4.00	RI	0.9	
							CR	0.002308398	
Comparison Matrix 5	Proximity to EV Users	Accessibility for EV Users	Weight						
Cost of land parcel	**1**	1/5	16.7%						
Distance from grid mid-connection	5	**1**	83.3%						
Comparison Matrix 6	Solar energy potential	Protected flora and fauna	Weight						
Solar energy potential	**1**	1	50.0%						
Protected flora and fauna	1	**1**	50.0%						
Tier 3									
Comparison Matrix 7	Distance from petrol stations	Distance from shopping centers	Distance from parking garages	Distance from recreation					
Distance from petrol stations	**1**	3	4	5					
Distance from shopping centers	1/3	**1**	5	6					
Distance from parking garages	1/4	1/5	**1**	1					
Distance from recreation	1/5	1/6	1	**1**					
Sum	*1.8*	*4.4*	*11.0*	*13.0*					
Normialized Matrix	Distance from petrol stations	Distance from shopping centers	Distance from parking garages	Distance from recreation	Weight				
Distance from petrol stations	0.56	0.69	0.36	0.38	49.9%				
Distance from shopping centers	0.19	0.23	0.45	0.46	33.3%				
Distance from parking garages	0.14	0.05	0.09	0.08	8.8%				
Distance from recreation	0.11	0.04	0.09	0.08	8.0%				
CI and CR	Distance from petrol stations	Distance from shopping centers	Distance from parking garages	Distance from recreation	Sum	Sum/Weight			
Distance from petrol stations	0.50	1.00	0.35	0.40	2.25	4.51	Count (m)	4	
Distance from shopping centers	0.17	0.33	0.44	0.48	1.42	4.26	Lamda max (x)	4.223969261	
Distance from parking garages	0.12	0.07	0.09	0.08	0.36	4.06	CI	0.07465642	
Distance from recreation	0.10	0.06	0.09	0.08	0.32	4.06	RI	0.9	
							CR	0.082951578	
Comparison Matrix 8	Car2Go routes	AH delivery routes	Electric Taxi routes	PostNL routes					
Car2Go routes	**1**	1	1/4	1					
AH delivery routes	1	**1**	1/5	1					
Electric Taxi routes	4	5	**1**	6					
PostNL routes	1	1	1/6	**1**					
Sum	*7.0*	*8.0*	*1.6*	*9.0*					
Normialized Matrix	Car2Go routes	AH delivery routes	Electric Taxi routes	PostNL routes	Weight				
Car2Go routes	0.14	0.13	0.15	0.11	13.3%				
AH delivery routes	0.14	0.13	0.12	0.11	12.6%				
Electric Taxi routes	0.57	0.63	0.62	0.67	62.0%				
PostNL routes	0.14	0.13	0.10	0.11	12.1%				
CI and CR	Car2Go routes	AH delivery routes	Electric Taxi routes	PostNL routes	Sum	Sum/Weight			
Car2Go routes	0.13	0.13	0.16	0.12	0.53	4.01	Count (m)	4	
AH delivery routes	0.13	0.13	0.12	0.12	0.50	4.01	Lamda max (x)	4.015518334	
Electric Taxi routes	0.53	0.63	0.62	0.72	2.51	4.04	CI	0.005172778	
PostNL routes	0.13	0.13	0.10	0.12	0.48	4.01	RI	0.9	
							CR	0.005747531	

Table A.3: Pairwise results expert #2

Tier 1								n	Random Index
Comparison Matrix 1	Proximity to EV Users	Accessibility for EV Users	Environmental Impact	Grid Impact				2	0
Proximity to EV Users	**1**	1/7	1	1/2				3	0.58
Accessibility for EV Users	7	**1**	6	3				4	0.9
Environmental Impact	1	1/6	**1**	1				5	1.12
Grid Impact	2	1/3	1	**1**				6	1.24
Sum	*11.00*	*1.64*	*9.00*	*5.50*				7	1.32
								8	1.41
Normialized Matrix	Proximity to EV Users	Accessibility for EV Users	Environmental Impact	Grid Impact	Weight			9	1.45
Proximity to EV Users	0.09	0.09	0.11	0.09	9.5%			10	1.51
Accessibility for EV Users	0.64	0.61	0.67	0.55	61.4%				
Environmental Impact	0.09	0.10	0.11	0.18	12.1%				
Grid Impact	0.18	0.20	0.11	0.18	16.9%				
					100.0%				
CI and CR	Proximity to EV Users	Accessibility for EV Users	Environmental Impact	Grid Impact	Sum	Sum/Weight	Count (m)	4	
Proximity to EV Users	0.09	0.09	0.12	0.08	0.39	4.09	Lamda max (x)	4.0643	
Accessibility for EV Users	0.66	0.61	0.73	0.51	2.52	4.09	CI	0.0214	
Environmental Impact	0.09	0.10	0.12	0.17	0.49	4.02	RI	0.9000	
Grid Impact	0.19	0.20	0.12	0.17	0.69	4.05	CR	0.0238	
Tier 2									
Comparison Matrix 2	nce from renewable energy so	Distance from grid substation							
Distance from grid substation	5	**1**							
Sum	5.00	1.00							
Normialized Matrix	nce from renewable energy so	Distance from grid substation	Weight						
Distance from grid substation	1.00	1.00	100.0%						
Comparison Matrix 3	Proximity to EV Users	Accessibility for EV Users	Weight						
Distance from main road	**1**	1	50.0%						
Traffic flow rate	1	**1**	50.0%						
Comparison Matrix 4	Distance from facilities	Residential population density	Distance from slow chargers	Distance from commercial Evs					
Distance from facilities	**1**	1/5	4	1/2					
Residential population density	5	**1**	5	1					
Distance from slow chargers	1/4	1/5	**1**	1/5					
Distance from commercial Evs	2	1	5	**1**					
Sum	*8.3*	*2.4*	*15.0*	*2.7*					
Normialized Matrix	Distance from facilities	Residential population density	Distance from slow chargers	Distance from commercial Evs	Weight				
Distance from facilities	0.12	0.08	0.27	0.19	16.4%				
Residential population density	0.61	0.42	0.33	0.37	43.2%				
Distance from slow chargers	0.03	0.08	0.07	0.07	6.4%				
Distance from commercial Evs	0.24	0.42	0.33	0.37	34.1%				
CI and CR	Distance from facilities	Residential population density	Distance from slow chargers	Distance from commercial Evs	Sum	Sum/Weight			
Distance from facilities	0.16	0.09	0.25	0.17	0.68	4.11	Count (m)	4	
Residential population density	0.82	0.43	0.32	0.34	1.91	4.43	Lamda max (x)	4.194690164	
Distance from slow chargers	0.04	0.09	0.06	0.07	0.26	4.07	CI	0.064896721	
Distance from commercial Evs	0.33	0.43	0.32	0.34	1.42	4.16	RI	0.9	
							CR	0.072107468	
Comparison Matrix 6	Solar energy potential	Protected flora and fauna	Weight						
Protected flora and fauna	1	**1**	**100.0%**						
Tier 3									
Comparison Matrix 7	Distance from petrol stations	Distance from shopping centers	Distance from parking garages	Distance from recreation					
Distance from petrol stations	**1**	5	7	5					
Distance from shopping centers	1/5	**1**	1	1/3					
Distance from parking garages	1/7	1	**1**	1/3					
Distance from recreation	1/5	3	3	**1**					
Sum	*1.5*	*10.0*	*12.0*	*6.7*					
Normialized Matrix	Distance from petrol stations	Distance from shopping centers	Distance from parking garages	Distance from recreation	Weight				
Distance from petrol stations	0.65	0.50	0.58	0.75	62.0%				
Distance from shopping centers	0.13	0.10	0.08	0.05	9.1%				
Distance from parking garages	0.09	0.10	0.08	0.05	8.1%				
Distance from recreation	0.13	0.30	0.25	0.15	20.7%				
CI and CR	Distance from petrol stations	Distance from shopping centers	Distance from parking garages	Distance from recreation	Sum	Sum/Weight			
Distance from petrol stations	0.62	0.45	0.57	1.04	2.68	4.32	Count (m)	4	
Distance from shopping centers	0.12	0.09	0.08	0.07	0.37	4.03	Lamda max (x)	4.122167052	
Distance from parking garages	0.09	0.09	0.08	0.07	0.33	4.05	CI	0.040722351	
Distance from recreation	0.12	0.27	0.24	0.21	0.85	4.09	RI	0.9	
							CR	0.045247056	

Table A.4: Combined judgements

Comparison Matrix 1	Proximity to EV Users	Accessibility for EV Users	Environmental Impact	Grid Impact
Proximity to EV Users	**1**	1/7	1	1/2
Accessibility for EV Users	7	**1**	6	3
Environmental Impact	1	1/6	**1**	1
Grid Impact	2	1/3	1	**1**

AG1						
*weighted geometric mean method	1.00	0.19	1.00	1.41		
	5.29	1.00	6.00	4.90		
	1.00	0.17	1.00	1.73		
	0.71	0.20	0.58	1.00		
	8.00	1.56	8.58	9.05		
WG1					Weight	
*row geometric mean method	0.13	0.12	0.12	0.16	**12.98%**	Proximity to EV Users
	0.66	0.64	0.70	0.54	**63.59%**	Accessibility for EV Users
	0.13	0.11	0.12	0.19	**13.50%**	Environmental Impact
	0.09	0.13	0.07	0.11	**9.93%**	Grid Impact
					100.00%	**9.93%**
						9.93%

Comparison Matrix 2		
Distance from grid substation	**100%**	*no other criteria

Comparison Matrix 3	Proximity to EV Users	Accessibility for EV Users
Distance from main road	**1**	1
Traffic flow rate	1	**1**

AG3				
*weighted geometric mean method	1	0.5		
	2	1		
	3	1.5		
WG3			Weight	
*row geometric mean method	1/3	1/3	**33.33%**	Distance from main road
	2/3	2/3	**66.67%**	Traffic flow rate

Comparison Matrix 4	Distance from facilities	Residential population density	Distance from slow chargers	Distance from commercial Evs
Distance from facilities	**1**	1/5	4	1/2
Residential population density	5	**1**	5	1
Distance from slow chargers	1/4	1/5	**1**	1/5
Distance from commercial Evs	2	1	5	**1**

AG4	1.00	0.45	4.47	1.41		
*weighted geometric mean method	2.24	1.00	5.00	2.24		
	0.22	0.20	1.00	0.45		
	0.71	0.45	2.24	1.00		
	4.17	2.09	12.71	5.10	Weight	
					27.07%	Distance from facilities
WG4	0.239993383	0.213525492	0.351909363	0.277433038	**46.16%**	Residential population density
*row geometric mean method	0.536641517	0.477457514	0.393446629	0.438660149	**7.89%**	Distance from slow chargers
	0.053664152	0.095491503	0.078689326	0.08773203	**18.88%**	Distance from commercial Evs
	0.169700948	0.213525492	0.175954682	0.196174783		

Comparison Matrix 5	Proximity to EV Users	Accessibility for EV Users	Weight
Cost of land parcel	**1**	1	**50.0%**
Distance from grid mid-connection	1	**1**	**50.0%**

AG5				
*weighted geometric mean method	1	0.447213595		
	2.236067977	1		
	3.236067977	1.447213595		
WG5				
*row geometric mean method	1/3	1/3	**30.90%**	Cost of land parcel
	2/3	2/3	**69.10%**	Distance from grid mid-connection

Comparison Matrix 6	Solar energy potential	Protected flora and fauna	Weight	*Same for both
Solar energy potential	**1**	1	**50.0%**	
Protected flora and fauna	1	**1**	**50.0%**	

Comparison Matrix 7	Distance from petrol stations	Distance from shopping centers	Distance from parking garages	Distance from recreation
Distance from petrol stations	**1**	5	7	5
Distance from shopping centers	1/5	**1**	1	1/3
Distance from parking garages	1/7	1	**1**	1/3
Distance from recreation	1/5	3	3	**1**

AG5	Distance from petrol stations	Distance from shopping centers	Distance from parking garages	Distance from recreation		
*weighted geometric mean method	1.00	3.87	5.29	5.00	Distance from petrol stations	
	0.26	1.00	2.24	1.41	Distance from shopping centers	
	0.19	0.45	1.00	0.58	Distance from parking garages	
	0.20	0.71	1.73	1.00	Distance from recreation	
	1.65	6.03	10.26	7.99	Weight	
WG5					**59.78%**	
*row geometric mean method	0.61	0.64	0.52	0.63	**17.94%**	
	0.16	0.17	0.22	0.18	**8.97%**	Distance from petrol stations
	0.11	0.07	0.10	0.07	**13.32%**	Distance from shopping centers
	0.12	0.12	0.17	0.13		Distance from parking garages
						Distance from recreation

Comparison Matrix 8		
Electric Taxi routes	**100%**	*no other criteria

Comparison Matrix 1	Proximity to EV Users	Accessibility for EV Users	Environmental Impact	Grid Impact
Proximity to EV Users	**1**	1/4	1	4
Accessibility for EV Users	4	**1**	6	8
Environmental Impact	1	1/6	**1**	3
Grid Impact	1/4	1/8	1/3	**1**

Comparison Matrix 2	Distance from renewable energy sources	Distance from grid substation
Distance from renewable energy sources	**1**	1/7
Distance from grid substation	7	**1**

Comparison Matrix 3	Proximity to EV Users	Accessibility for EV Users
Distance from main road	**1**	1/4
Traffic flow rate	4	**1**

Comparison Matrix 4	Distance from facilities	Residential population density	Distance from slow chargers	Distance from commercial Evs
Distance from facilities	**1**	1	5	4
Residential population density	1	**1**	5	5
Distance from slow chargers	1/5	1/5	**1**	1
Distance from commercial Evs	1/4	1/5	1	**1**

Comparison Matrix 5	Proximity to EV Users	Accessibility for EV Users	Weight
Cost of land parcel	**1**	1/5	16.7%
Distance from grid mid-connection	5	**1**	83.3%

Comparison Matrix 7	Distance from petrol stations	Distance from shopping centers	Distance from parking garages	Distance from recreation
Distance from petrol stations	**1**	3	4	5
Distance from shopping centers	1/3	**1**	5	6
Distance from parking garages	1/4	1/5	**1**	1
Distance from recreation	1/5	1/6	1	**1**

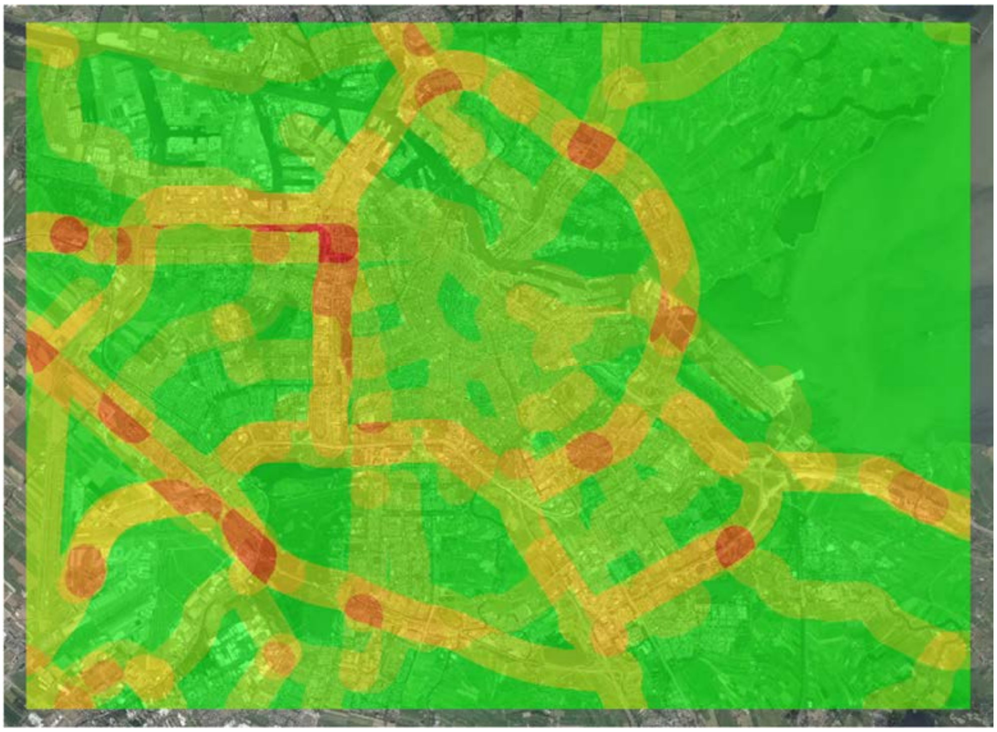


Figure A.2: Road Capacity Level layer

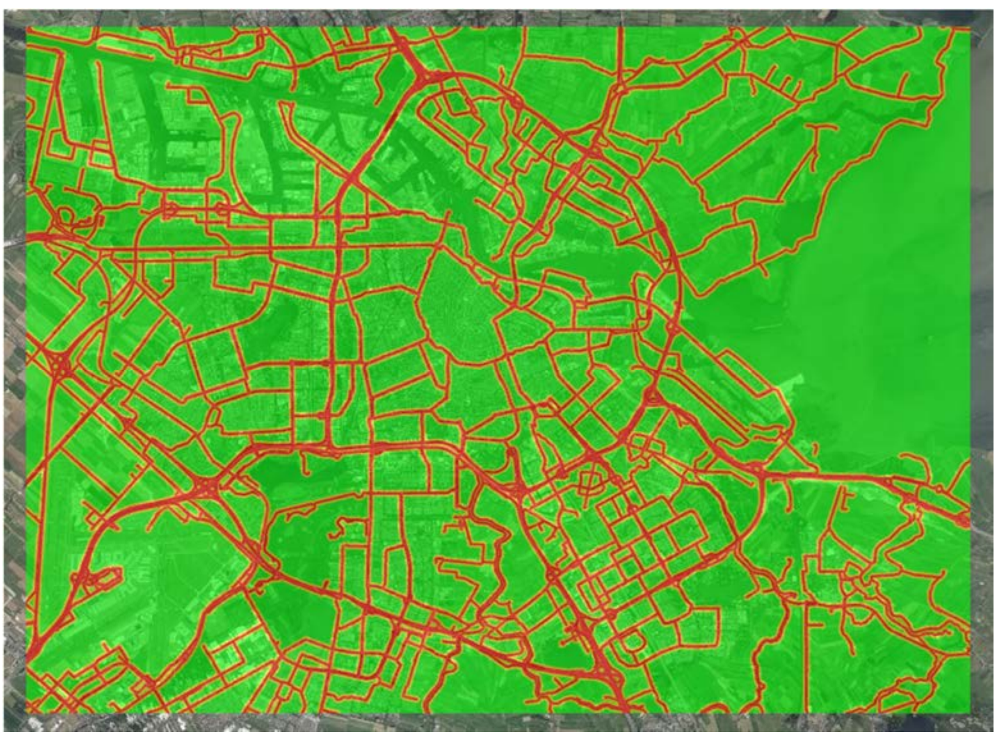


Figure A.3: Distance from Main Road layer

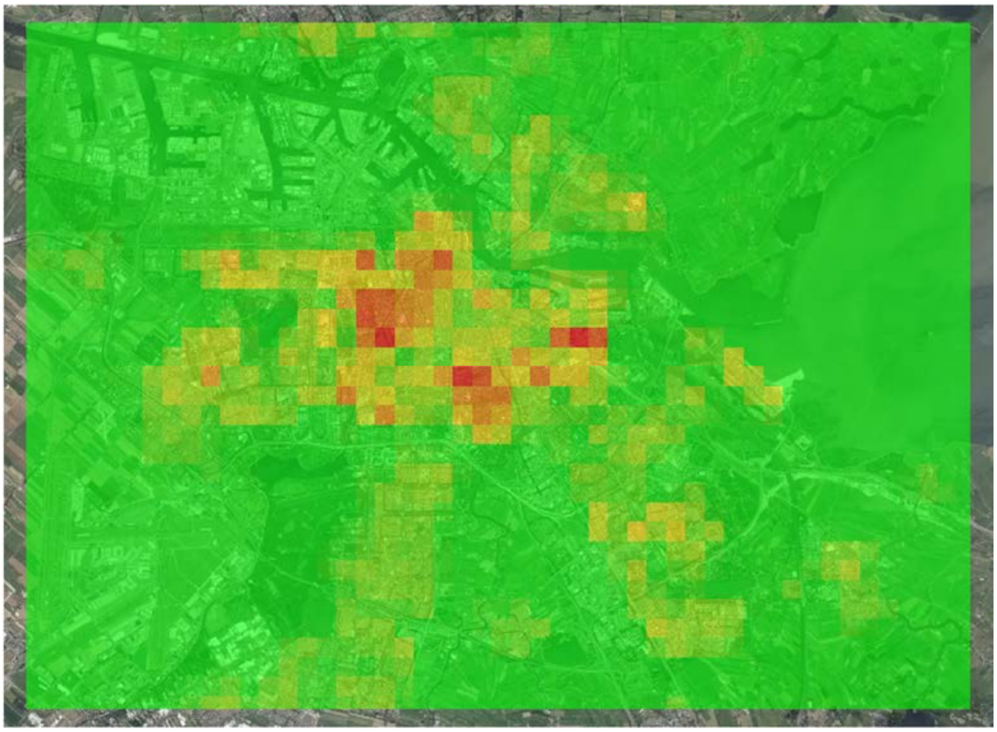


Figure A.56: Residential Population Density layer

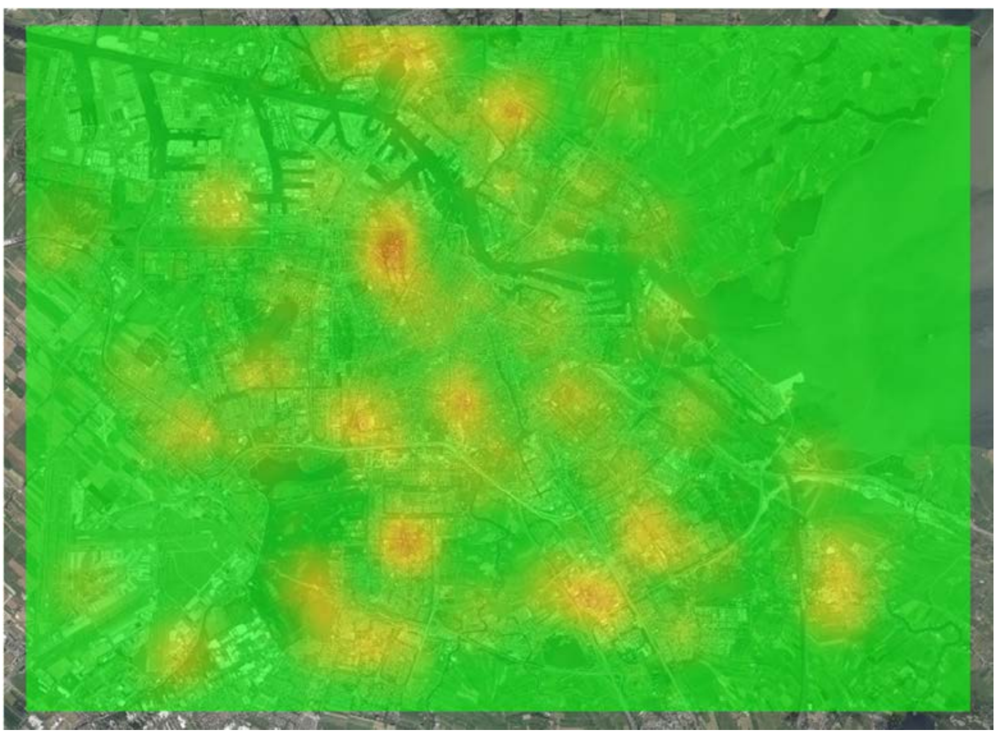


Figure A.6: Proximity of Facilities layer

Figure A.77: Proximity of Commercial EVs layer

Figure A.88: Proximity of Slow Chargers layer

Figure A.9: Proximity to Petrol Stations layer

Figure A.109: Proximity to Shopping Centers layer

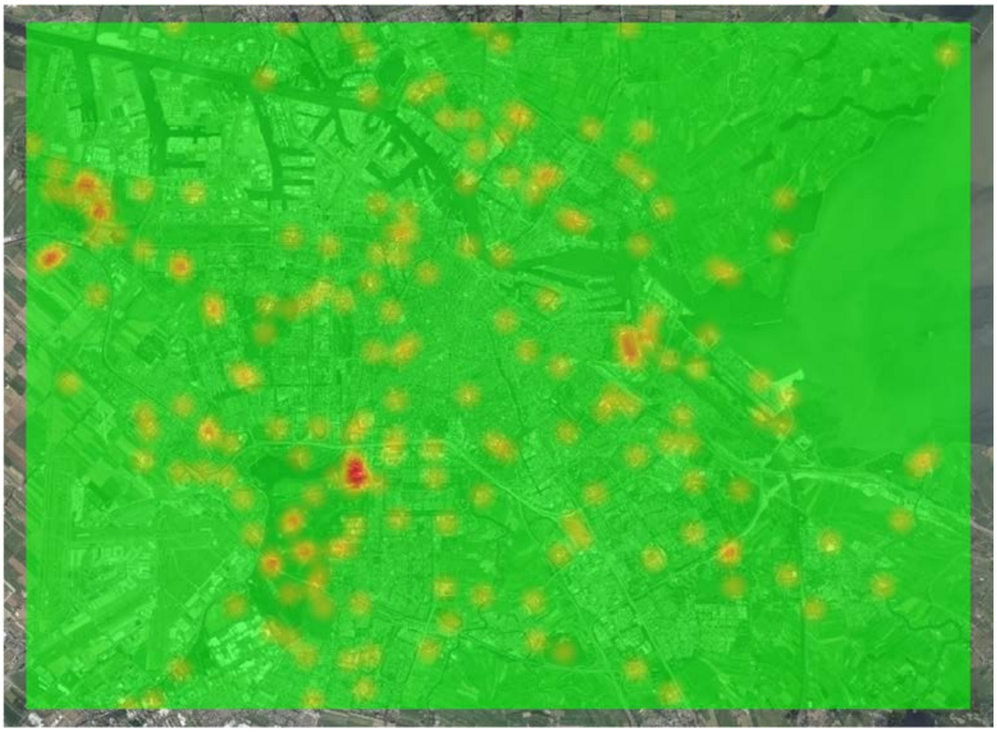


Figure A.11: Proximity to Parking Garages layer

Figure A.1210: Electric Taxi Points

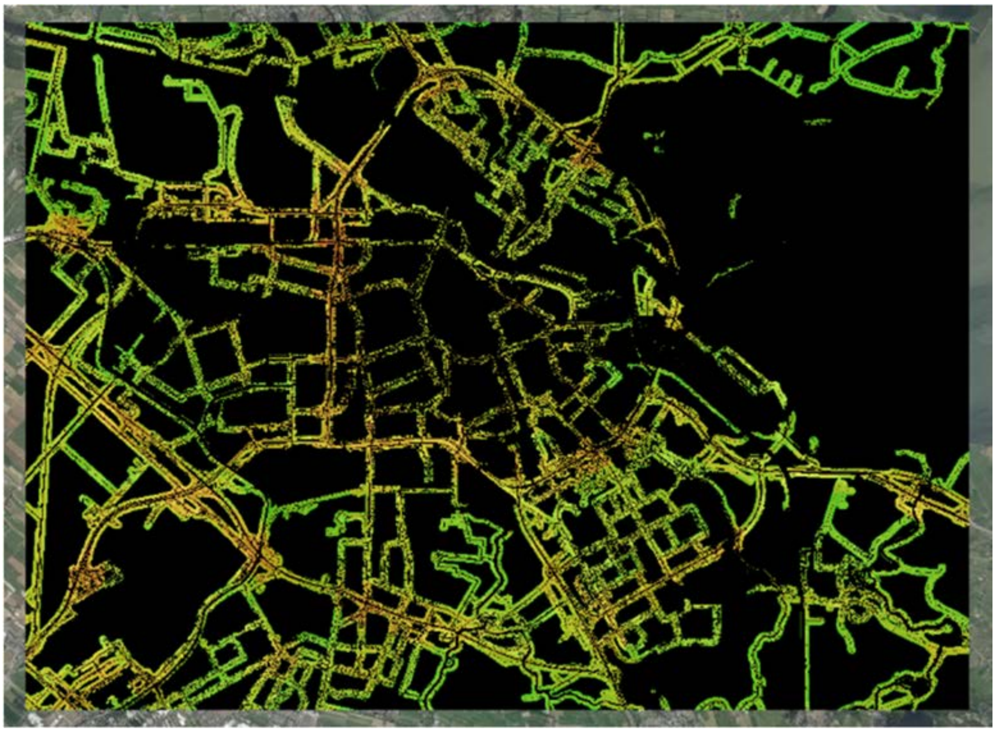


Figure A.1311: Final objective layer w/ suitability analysis

Summary

Introduction

This study uses a geographical information system (GIS) based analytic hierarchy process (AHP) approach for selecting ideal locations for fast electrical vehicle charging stations in Dutch urban environments. The synergies of a GIS-AHP tool allow for effective decision making while considering multiple, and often conflicting urban factors. Expert knowledge is used to judge the importance of selection criteria, resulting in criteria weights for created GIS layers. GIS layers are combined following the AHP structure to reach the final objective layer. The case study city of Amsterdam is taken as an example. An analysis of the top 10 site selections and their urban characteristics are presented. The sensitivity analysis proves the tool is effective at incorporating expert knowledge into the tool. The working GIS-AHP tool has proven to be flexible and powerful for decision makers and will act as evidence that a selected fast-charging station location is truly ideal based off of urban characteristics. This study has been the first of its kind to use a GIS-AHP approach towards location-allocation for electric vehicle fast-charging stations.

Method

There are many different approaches to determining the performance of the system; each approach aimed at answering the particular objective of the facility. Objectives are essentially stakeholder interests including consumer, commercial, governmental and community facets. In the end, a location-allocation model aspires to represent the reality of a network and make an informed location decision, while satisfying decision maker's goals.

Table 1: Gap in knowledge

Model type	Network of locations	Fills gap in knowledge	Geographic solution	Usable with qualitative data	Usable with expert judgement	Ranking of locations
p-median	X	-	X	-	-	-
Max-covering	X	-	X	-	-	-
Set-covering	X	-	X	-	-	-
Agent based models	X	-	X	-	-	-
Multi-criteria decision making	-	-	-	X	-	X
Analytic hierarchy process	-	X	-	X	X	X
GIS-AHP	-	X	X	X	X	X

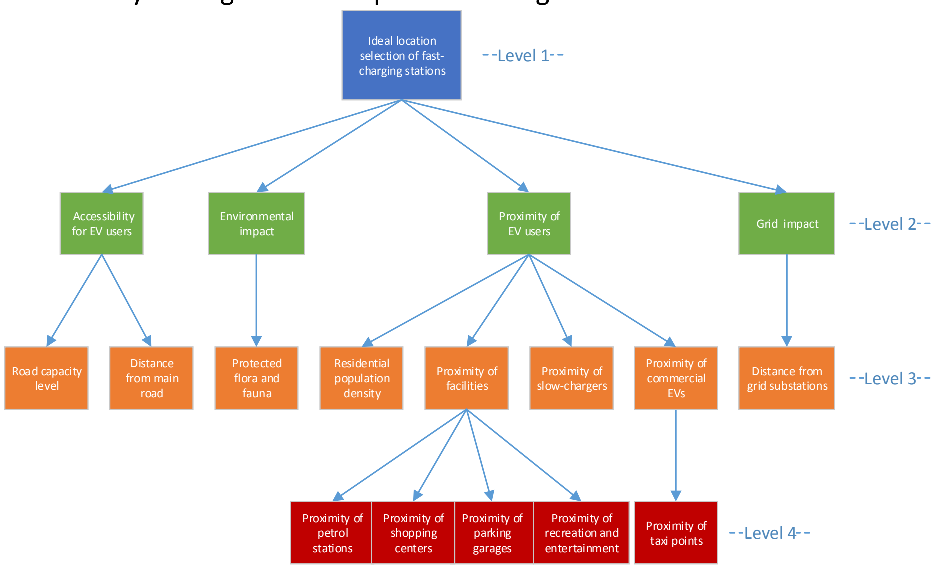
GIS-AHP

Independently, GIS and AHP are proper tools for a multitude of applications and when combined a synergistic effect occurs, which contributes to the efficiency and quality of spatial analysis for a site selection problem (Rikalovic, Cosic, & Lazarevic, 2014). This method allows decision makers to represent their opinions in a geographic analysis with clear, visual results. The addition of AHP adds value to the original set of GIS data. The use of GIS props up the network and relationship shortcomings of AHP. Therefore, the integration of GIS and AHP methods provides a mechanism to thoroughly explore complicated problems and provides immediate feedback for decision makers (Sener, Sener, Nas, & Karaguzel, 2010). The combination of GIS and MCDM techniques has been increasingly used as an important spatial decision support system for evaluating suitable locations (Uyan, 2013).

Results

AHP structure

The finalized criteria are organized in a relationship hierarchy based on stakeholder objectives and urban relationships. The AHP structure describes the relationships of each criteria with the final objective to find ideal charging stations in Amsterdam. A pairwise comparison from provided criteria layer weights from expert knowledge.



GIS layers

Each selection criteria was represented by a GIS layer. The first layer created was the suitability layer, which removes all unworthy alternatives from the selection process. Then all base criteria were created representing the fast-charging situation in the case study city. Finally, layers were combined to reach the apex of the AHP structure. To construct the suitability analysis, data was gathered to represent the map features which are unsuitable for fast-charging development. Factors that are considered unsuitable are: *Buildings, water areas*, r*oads, protected green space*, d*istance (100m) from important roads*.

Layer combinations

Accessibility for EV User is a combination of the two sub-layers, road capacity level and distance from main road. The combined pairwise comparison gave a local weight of 67% to road capacity level and a local weight of 33% to distance from main road. This combined layer holds 63.5% of the importance to the final objective layer making it a heavily important factor in determining fast-charging locations. Environmental impact is directly related to the sub-criteria, protected flora and fauna. No combination is needed for this criteria. Environmental impact holder 13.5% of the importance for the final layer. Proximity of EV users is a combination of residential population density (45.2%), proximity of facilities (27.1%), proximity of commercial EVs (18.9%), and proximity of slow-chargers (7.9%). Proximity of facilities is a combination of four sub-criteria, proximity of petrol stations, shopping centers, recreation and entertainment, and taxi points. Proximity of EV users has 13% of the importance toward the final objective layer. Grid impact requires no combination and is directly the distance from grid substations layer. Grid impact makes up 10% of the importance toward the final objective criteria layer. GIS results can be seen below:

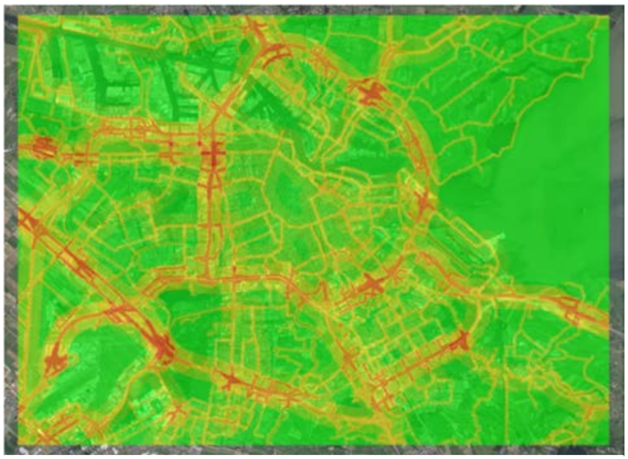


Figure 1: Accessibility for EV users

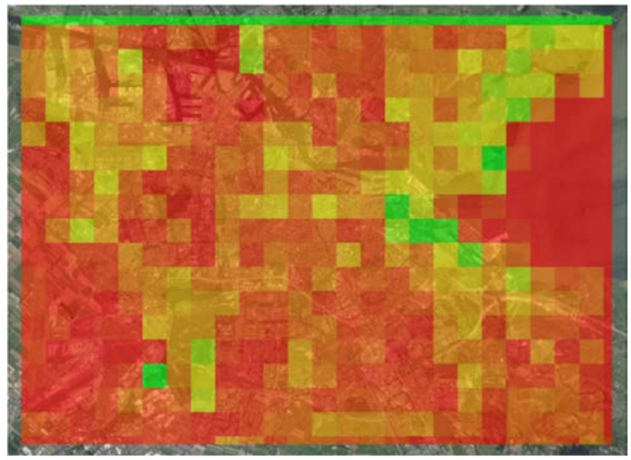


Figure 2: Environmental impact

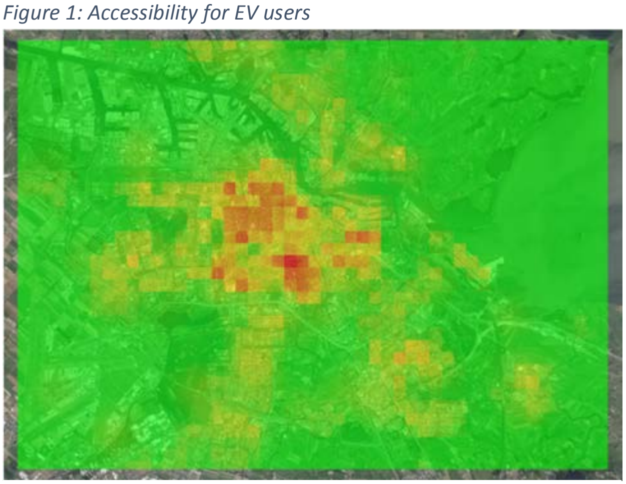


Figure 312: Proximity of EV users

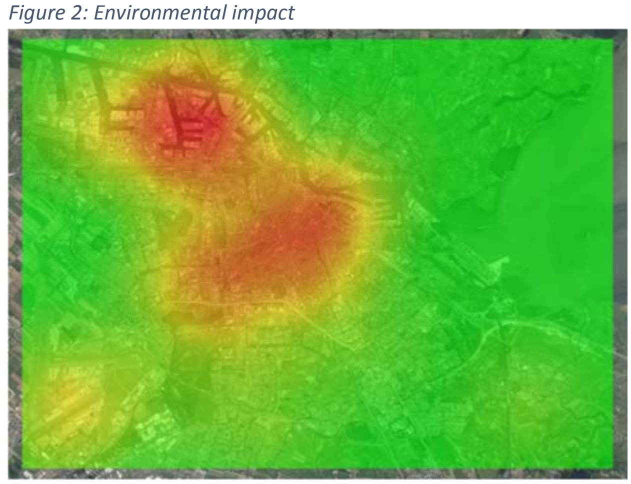


Figure 4: Grid impact

The final objective layer is a combination of the four main criteria on level 2 of the AHP structure. Weights give their respective layer more or less overall score depending on the percentage. Analyzing the final layer will provide the top location in the city of Amsterdam for fast-charging locations. Figure 5 is the final objective layer.

Figure 5: Final objective layer

Analysis of Amsterdam
Top 10 fast-charging locations were determined based on the score in the final objective layer and the available alternatives in the suitable zones. A zoomed in view with the satellite map of the area reiterates a location is acceptable for station development. Figure 6 shows Amsterdam with the top 10 ranked station locations throughout the urban environment. Locations follow the intent of decision makers by occupying locations adjacent to busy highways and intersections.

Figure 613: Top 10 locations in Amsterdam

Conclusion
Electric vehicles show great promise to enhance modern mobility by quelling concerns over exhaust pollution, and improving energy efficiency and safety. In the Netherlands the electric vehicle market has passed the innovator's adoption phase and reached the early adoption phase. This pattern of EV acceptance will continue exponentially as the Netherlands plans for 1 million EVs on the road by 2025. Fast-charging, with the capability to fully charge an EV in 20 minutes or less, is a prime upgrade to the Dutch charging infrastructure. An upgrade to the charging infrastructure will support EV adoption and make a strong push for solving society's modern mobility issues. Previous studies have selected models which lack the input of expert knowledge and are subject to complex algorithms. A synergistic method of GIS-AHP has been selected to make sense of complex urban factors and to implement expert knowledge towards a geographic solution for fast-charging site selection. This study will fill a gap in knowledge by being the first of its kind to use a GIS-AHP approach for fast-charging site selection.

Eleven selection criteria were finalized and organized in a relationship hierarchy based on stakeholder objectives, with the final objective of ideal locations for fast-charging as the structure's apex. GIS layers represent selection criteria, and were created through open source GIS datasets and the software QGIS. The final objective layer is a combination of all 11 criteria layers, each with a unique weight devised from a pairwise comparison and expert judgements. Accessibility for EV users, a combination of road capacity level and distance from main road, was the dominant criteria layer with 63.5% of the global importance, followed by environmental impact at 13.5%, proximity of EV users at 13.0%, and grid impact at 10.0%.

The most ideal location in the city of Amsterdam, with a final objective score of 8.40 out of 10, is located in the west of the city. The location's proximity to two busy highways, two regional roadways, and multiple busy intersections gave it the top score. The second most ideal location, with a score of 7.40, is south of the main city center across from the Olympic stadium. This location is also near a busy highway intersection and is along a busy city road but gained an advantage for its score in proximity of EV users. Location 3 through 10 had close scores and were placed throughout the examination area, mostly along intersections of important roads. The sensitivity analysis shows that the GIS-AHP tool is heavily influenced by expert knowledge and the pairwise comparison weights. Without expert opinions, the locations shift toward the city center and areas a higher proximity of EV users. There is a clear conflict with accessibility and proximity of EV users.

The use of GIS-AHP for fast-charging site selection is a robust location-allocation approach and can be applied to urban environments. Incorporating expert opinion into GIS layer weights provides a business-conscious boost over past location-allocation studies and aids decision makers with a user-friendly and visual geographic solution. Fast-charging locations placement is a critical decision that will have an impact on the future of charging infrastructure and EV acceptance. This study has developed a useful tool to analyze urban environments and bring fast-charging to the public in the most effective and responsible way.

References

Adamcsek, E. (2008). *The Analytic Hierarchy Process and its Generalizations.* Thesis, Eotvos Lorand University.

Amsterdam Roundtables Foundation. (2014). *Electric vehivles in Europe: gearing up for a new phase?*

Arentze, T. (2000). Location Allocation Models. 1-23.

Arentze, T., & Borgers, A. (2003). *Introduction to Multi-criteria Evaluation.* Eindhoven University of Technology, Urban Planning Group.

Charging data Amsterdam Electric. (2015, Feburary). Amsterdam.

(2015). *Electromobility in the Netherlands.* Utrecht: Netherlands Enterprise Agency.

Guo, S., & Zhao, H. (2015). Optimal site selection of electric vehicle charging station by using fuzzy TOPSIS based on sustainability perspective. *Applied Energy, 158*, 390-402.

Rikalovic, A., Cosic, I., & Lazarevic, D. (2014). GIS Based Multi-Criteria Analysis for Industrial Site Selection. *Procedia Engineering, 69*, 1054-1063.

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *Int. J. Services Sciences, 1*(1), 83-98.

Sener, S., Sener, E., Nas, B., & Karaguzel, R. (2010). Combining AHP with GIS for landfill site selection: A case study in the Lake Beysehir catchment area (Konya, Turkey). *Waste Management, 30*, 2037-4046.

Uyan, M. (2013). GIS-based solar farms site selection using analytic hierarchy process (AHP) in Karapinar region, Konya/Turkey. *Renewable and Sustainable Energy Reviews, 28*, 11-17.