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Jennifer Priefer
Paderborn University, Germany, jennifer.priefer@uni-paderborn.de

Lennart Steiger
Paderborn University, Germany, lennartsteiger@gmx.net

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Designing a GIS-AHP-Based Spatial Decision Support System for Discovering and Visualizing Suitable Locations for Electric Vehicle Charging Stations

Jennifer Priefer[1], Lennart Steiger[1]

[1] Paderborn University, Paderborn, Germany
jennifer.priefer@uni-paderborn.de, lennartsteiger@gmx.net

Abstract. With rising interest in electric mobility, the need for Electric Vehicle Charging Stations (EVCS) increases. Since few attempts have been made to address this problem, a visualized Geographic Information System (GIS) approach using geospatial data and a weighted multicriteria analysis considering the proximity to users and the existing energy grid have not been developed yet. Since the visualization of decision problems has been found to be beneficial for decision processes, our goal is to design a Spatial Decision Support System using an AHP approach to support decision-makers to identify suitable locations for EVCS using a GIS to map and visualize the results. We use design science research to design our system as a prototype and find that implementing an AHP approach within a GIS application offers potential to increase added value for decision-making processes.

Keywords: Spatial Decision Support System, Geographic Information System, Analytic Hierarchy Process, Electric Vehicle Charging Stations, Visualization

1 Introduction

The number of Electric Vehicles (EV) on Germany’s roads is already expected to rise to 14 million within the next ten years [1]. To ensure the transition from combustion engines to electric power, a large-scale publicly accessible charging infrastructure is required. Low property ownership rates and a high tenant share in cities even increase the importance of public charging infrastructure, as many residents cannot charge at home [2]. For optimal energy provision to residents, planning public charging infrastructure requires careful placement of Electric Vehicle Charging Stations (EVCS). In the past, site selection was mainly based on economic and technical criteria, but today social and environmental requirements also need to be integrated [3]. Thus, strategies that show how to determine suitable locations for charging stations to further support the development of EV are needed [4].

Spatial Decision Support Systems (SDSS) offer a suitable means for identifying appropriate locations to maximize the use of EVCS [5]. Finding a suitable location for EVCS requires a multicriteria approach [6]. Many criteria, such as environmental, economic, and social impacts, are essential in selecting the location of EVCS [7], and

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qualitative factors should also be included in the decision [8, 9]. In this context, Analytic Hierarchy Process (AHP) combined with Geographic Information Systems (GIS) is a promising approach to identify suitable locations for EVCS [10]. A GIS-AHP approach has already been applied successfully in solar farm siting [10]. In the field of EVCS, geospatial data and AHP have already been combined [11], but the approach and results have never been mapped and visualized within a GIS application, though visualizing decision problems has been found to be beneficial for decision support by emphasizing human visual capabilities [12]. Thus, we posit that integrating AHP in a GIS application is beneficial compared to former approaches and can facilitate decision-making processes.

Therefore, our research goal is to design and develop an AHP-based SDSS integrating geospatial data for determining and visualizing suitable locations for EVCS considering literature-based criteria in combination with expert interviews for criteria weighting. We use the design science research paradigm [13] and follow the first steps of the design science research model by Peffers et al. [14]. Through a prototype, the functionality of the innovative IT artifact is demonstrated by identifying the most suitable locations of EVCS in the city of Paderborn using a GIS application to map and visualize this decision problem.

2 Research Background

Decision Support Systems (DSS) are computer-based systems that enable users to solve semi-structural processes [15] increasingly integrating spatial data, models, and expert knowledge into decision-making processes today. Once spatial data are incorporated into a DSS, it is a Spatial Decision Support Systems (SDSS) for which Geographic Information Systems (GIS) are essential to cover the spatial aspect of the analysis. GIS enable users to generate spatially differentiated decision-making [16] and collect, manage, and analyze geospatial data while considering social structures [17–19]. In the field of location determination, GIS are increasingly used as evaluation and decision-making tools since they offer great potential for understanding complex urban structures.

Spatial decision problems often require evaluating alternatives by considering multiple criteria [20], meaning that GIS are often used in combination with methods for Multi-Criteria Decision-Making (MCDM). The Analytic Hierarchy Process (AHP) is an MCDM procedure [21] that is being used in many fields like evaluating weapon systems or selecting design concepts or projects [22–26]. AHP is used by decision-makers to evaluate alternatives and can include quantitative and qualitative factors [27]. It helps to structure the decision maker's thoughts [28] and aims to identify the preferred alternative and rank the alternatives considering all decision criteria [29]. The advantages of AHP over other multicriteria methods are its flexibility and intuitive usability by decision-makers [30].

Literature reveals several strategies for locating EVCS. Some researchers use GIS in their location analyses to investigate and visualize potential sites by mapping them geographically. Most of the studies are conducted in the energy sector, especially for research in solar plant and wind farm siting [10, 31–34]. For this purpose, they usually use a combined application of GIS and a selected MCDM method. When GIS and AHP are combined, a synergetic effect emerges that contributes to the efficiency and quality of spatial analysis for site selection problems [3]. This approach allows decision-makers to visualize their judgments in a GIS analysis. Thus, the development of an SDSS using a GIS-AHP approach is a promising approach for locating EVCS within an urban environment as it represents an efficient decision technique that applies desired conditions through selection criteria to a spatial decision problem [10]. AHP has already been applied for solar farm siting [10] using a GIS application to determine, map, and visualize suitable locations. Geospatial data and AHP have already been combined within a mathematical model for EVCS location determination [11]. The mapping and visualization within a GIS software has, however, not been performed for this field of application yet though research indicates that the visualization of decision problems adds significant value by taking into account human visual capabilities and thus influences decision-making processes [12].

3 Research Method

Our research objective is to design and develop an AHP-based SDSS integrating geospatial data to determine and visualize suitable locations for EVCS considering literature-based criteria combined with expert interviews for criteria weighting. As our solution classifies as an IT artifact, we aim to design it using design science research as a central research paradigm in IS [13]. Design Science research aims to design IT artifacts [13], which can be constructs, models, methods, and instantiations. For achieving our research goal, we apply the design science research methodology by Peffers et al. [14]. We aim to design an instantiation of a GIS-AHP-based SDSS for determining, mapping, and visualizing suitable locations for EVCS (Figure 1).

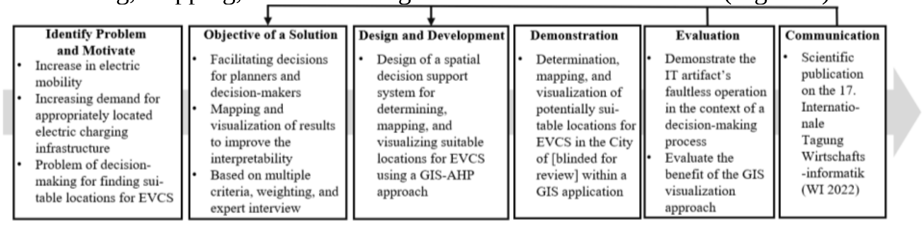

Figure 1. DSRM process based on Peffers et al. [14].

The step *Identify Problem and Motivate* for our research goal has been stated in chapter two. Since there is an increased demand for electric mobility and, thus, for appropriately placed EVCS, our solution aims to solve the problem of finding suitable locations for EVCS by enhancing former approaches with GIS mapping and visualization. Therefore, our *Objective of a Solution* is to facilitate decisions for planners and decision-makers by visualizing suitable locations and thus, improving the interpretability. Our *Design and Development* are based on multiple criteria, the weighting of these criteria and an expert interview to design an SDSS to determine and visualizing suitable locations for EVCS using a GIS-AHP approach. The *Demonstration* of our IT artifact is to determine, map, and visualize potentially suitable locations for EVCS within the city of Paderborn and refer to available spatial data as well as an expert interview. Since the *Evaluation* has not yet been performed, we give an outlook on how to evaluate the IT artifact and the visualization approach using GIS in the context of a decision-making process. The last step is *Communication*, which will be, in our case, the publication on the WI 2022.

4 Results and Discussion

To identify relevant criteria for our analysis, we performed a literature review in the first step. We evaluated the results in a second step utilizing an interview with a leading expert of an innovation department of a local energy operator. After collecting and reviewing the criteria, we can derive an AHP hierarchy model (Figure 2).

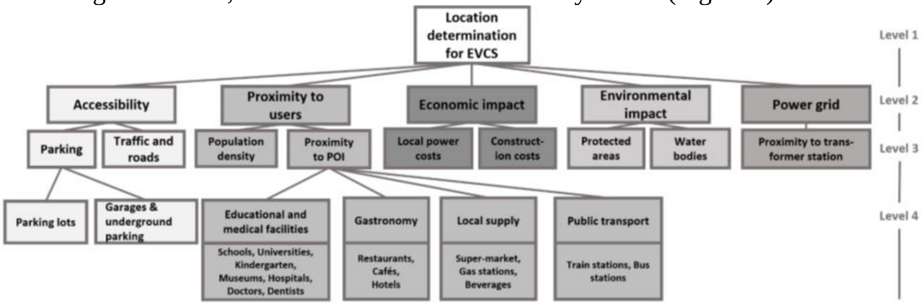

Figure 2. AHP hierarchy model for EVCS location determination following Saaty [21].

First, the charging behavior of EV users is relevant as charging points located in parking garages are most frequently used [35]. Also, the spatial proximity to customers, e.g., close to gas stations, supermarkets, shopping centers, and malls, as well as along major roads and busy highway exits and intersections, is found to be important [36, 37]. Furthermore, aspects like population density, road networks, and environmental impact, as well as ecological criteria like the protection of vegetation and water bodies, should be considered [37, 38]. Besides paying attention to the driving distance between existing EVCS as well as traffic information and travel times [39, 40], Points of Interest (POI) such as hospitals, restaurants, or stores are significant factors for EVCS placements [41]. During the interview, most criteria coincided with those described in the literature. However, according to the expert, the utilization of existing charging stations, the construction costs, and the local population density are essential indicators for placing additional EVCS. However, not all identified criteria have the same priority. Therefore, the next step is to derive the relative weights of the criteria by pairwise comparison using a numerical scale [21]. Since the values are derived from subjective judgments of the decision-makers, it is hardly possible to avoid some inconsistencies. For this reason, the AHP calculates a Consistency Index (CI), which grants experts a slight allowable inconsistency of CI ≤ 0.10.

Table 1. Spatial data with corresponding GIS analyses and classification.

Criteria	**Source**	**Analysis/Calculation**
Accessibility		Weighted *Parking* and *Traffic and roads*
Parking	[42]	Parking space available or not available
Traffic and roads	[44]	Distance: 0m-250m-500m-1000m-2000m
Proximity to users		Weighted *Population density* and *Proximity to POI*
Population density	[45]	Density per district
Proximity to POI		Weighted *Educational and medical facilities*, *Gastronomy*, *Local supply*, and *Public transport*
Educational and medical facilities, Gastronomy, Local supply	[42]	Distance: 0m-75m-150m-225m-300m
Public transport	[42]	Distance: 0m-125m-250m-375m-500m
Environmental impact		Exclude areas from the study area
Protected areas, Water bodies	[43]	Distance: 0m-25m-50m-75m-100m
Power grid		Buffer area
Proximity to transformer stations	[46]	Maximum distance: 2000m

For the GIS part of the IT Artifact, we use geospatial data from different open data portals [42, 43] to map the criteria spatially. To convert all data types to a raster format and harmonize the data, we perform different spatial analyses by using Esri's ArcGIS, a popular GIS application. Table 1 gives an overview of the different analyses and the performed data classification for finding suitable locations. Since GIS analysis depends on data availability, the economic impact must be excluded due to insufficient or unavailable data. To ensure comparability between the different distances and values, since e.g., sometimes a higher distance is beneficial and in other cases it is not, the grid is reclassified by assigning normalized values to the grid. We identified five classes representing areas with characteristics ranging from zero to five, with five being most suitable, one being least suitable, and zero representing unsuitable areas. Our prototype is a real-world IT artifact that is demonstrated based on the study area of Paderborn.

Table 2. Criteria and determined weights from pairwise comparison.

	Accessibility	Proximity to users	Environmental impact	Power grid	Weight
Accessibility	0.35	0.25	0.35	0.58	35.43%
Proximity to user	0.71	0.50	0.35	0.58	49.90%
Environmental impact	0.05	0.07	0.05	0.03	5.07%
Power grid	0.06	0.08	0.15	0.10	9.60%
				CI	0.07

We conducted the pairwise comparison survey with a decision-maker who manages the placement of EVCS at an energy grid operator. The expert has much experience in selecting EVCS locations and follows strategies for future expansion. Priorities were derived based on his judgments and preferences. Table 2 shows the derived weights, where proximity to users is given the highest weighting (49.9%), followed by accessibility (35.43%). Power grid impact is weighted significantly lower at 9.60% but is still ahead of Environmental impact at 5.07%. Subsequently, we combined the geospatial data with the weights to map suitable and unsuitable locations (Figure 3). We find that EVCS have already been located at four of the top eight locations. 42 of the existing 51 EVCS are installed in areas that are at least suitable.

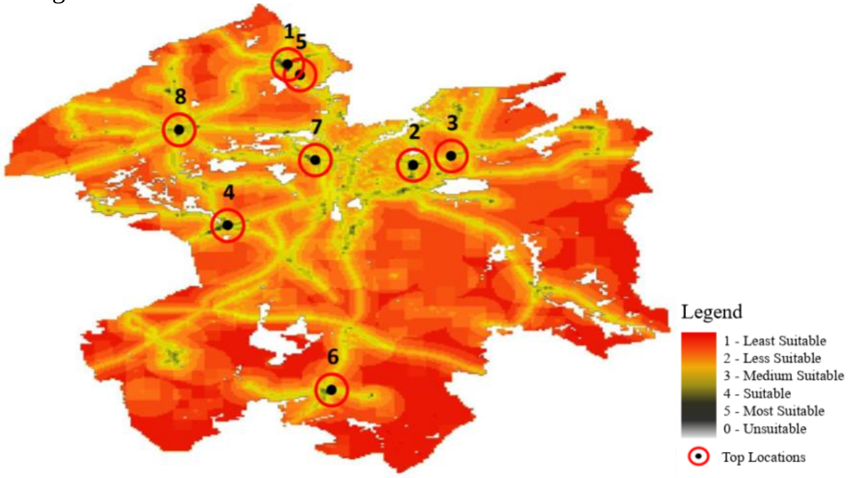

Figure 3. Suitable locations in the study area.

Limitations of our artifact can be identified in the context of data accuracy and installing EVCS at locations that cannot be represented in the form of a GIS layer. However, a diverse selection of criteria was derived from literature, and the existing EVCS within the demonstration area indicate that the IT artifact successfully identified suitable areas. Further, we did not examine any criteria contradiction, what should be included in future research. Another limitation is that only one expert was interviewed. Though a consistency check showed that the judgments are consistent, further research should include more experts to obtain more realistic and accurate results regarding the weights. Furthermore, an evaluation has not yet been performed. A future evaluation of our IT artifact should include implementing the SDSS at an energy grid operator, demonstrating the benefits of the GIS mapping and visualization by comparing existing decision-making processes with our visual approach, e.g., by conducting interviews.

Our IT artifact determines and visualizes suitable locations for EVCS supporting decisions for planning and installation. Therefore, we reached our research goal to design and develop a GIS-AHP-based SDSS for determining, mapping, and visualizing suitable locations for EVCS. Following the DSR Knowledge Contribution Framework [47], our artifact is an *Improvement* since our solution improves existing approaches by using GIS visualization to a known problem. Though we have not been able to evaluate our IT artifact yet and there is a rival artifact locating EVCS in Istanbul [11], we applied a visual approach being the first in this research field to consider human visual capabilities, thus opening entirely new ways to support decision-making processes.

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