“Optimizing electric vehicles charging for enhancing environmental sustainability and reducing carbon emissions of freight transport: case of Czech Republic”

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OPTIMIZING ELECTRIC VEHICLES CHARGING FOR ENHANCING ENVIRONMENTAL SUSTAINABILITY AND REDUCING CARBON EMISSIONS OF FREIGHT TRANSPORT: CASE OF CZECH REPUBLIC

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Abstract

The limited infrastructure of charging stations, which is crucial in route planning and total journey time and creates uncertainty in efficiency and operating costs, calls for new economic and statistical methods in sustainability development and environmental economics. This paper aims to examine the challenges of integrating electric vehicles into freight transport to improve distribution logistics' environmental sustainability, which represents one of the pathways for reducing environmental risk.

The analysis results underscore the inadequacy of the truck charging station network in the Czech Republic. This insufficiency presents an opportunity to enhance environmental sustainability and reduce carbon emissions through strategic analysis and optimizing charging station locations. The difficulty of identifying optimal locations for these stations, given truck availability, requires using multi-criteria decision-making techniques such as the Analytical Network Process (ANP).

Municipalities with limited access to existing logistics facilities were considered during the simulation. This way, 15 new locations were identified for municipalities with insufficient distance to a charging station.

By implementing the ANP method, the study contributes to a more environmentally sustainable transportation infrastructure, highlighting the potential for significant reductions in carbon emissions through improved charging station networks. These results apply to other countries and can provide novel insights on optimizing charging station locations for sustainable economic development and reducing freight transport's carbon emissions and environmental risks.

Keywords electric vehicles, environmental risks, location model, infrastructure planning, freight transport, sustainable development, Czech Republic

JEL Classification C61, Q50, Q55, R41

INTRODUCTION

Recently, electric mobility and the deployment of electric freight transport have become one of the key priorities of transforming transport solutions on the path to sustainable economic development and reducing environmental hazards. One of the main objectives of distribution logistics is to deliver goods at the required time and to the required quality while maximizing vehicle utilization and reducing the negative impact on the environment by reducing CO_2 emissions (Rajkoomar et al., 2022; Li & Zhou, 2021). With the development of alternative powertrains for passenger vehicles, especially in the field of electric power, it is possible to consider applications in freight transport, specifically for distribution logistics and urban logistics (Kozlovskyi et al., 2019;

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Strielkowski et al., 2019; Pan et al., 2021). In view of the potential for expansion, a freight distribution network methodology in which vehicles use alternative fuel sources can be considered. Traffic restrictions and low-emission zones are limiting factors for vehicles using conventional fuels.

In electric vehicle (EV) usage, a multi-level distribution model that combines multiple optimization options can be used. As a result, the main problems to be addressed can be identified (Cattaruzza et al., 2017). Urban areas aim to reduce harmful emissions and noise caused by traditional vehicles running on fossil fuels (Aijaz & Ahmad, 2022; Simionescu et al., 2022). But at the same time, reducing the road throughput, which will negatively affect the battery capacity, should be considered. Therefore, delivery times considering possible road constraints also need to be considered (Mancini, 2017). These constraints lead logistics companies to consider whether alternative fuel or fuel-cell electric vehicles can be used efficiently. The main prerequisite to increase efficiency is not only the ideal vehicle route but also customer behavior, which can influence the order mix and increase the efficiency of the vehicle (Husinec et al., 2020).

1. LITERATURE REVIEW

Selecting the right locations for electric truck charging stations can help to permanently reduce carbon emissions and promote the use of renewable energy generation (Phadke et al., 2019; Fan et al., 2023; Zhu et al., 2023; Rapson & Muehlegger, 2023). For example, locating the charging station close to a large logistics facility can both minimize the distance traveled to the charging station (reducing energy consumption) and could use the roof area for the installation of solar panels, thus increasing the use of renewable energy and reducing the environmental impact (Ali & Naushad, 2022; Barman et al., 2023). An optimized network of charging points can also be beneficial in terms of social sustainability. One aspect one should consider is the overall health of the community. By moving freight out of urban areas, one can ultimately see an improvement in air quality, a reduction in noise, and an overall improvement in the quality of life (Minet et al., 2020; Kinsella et al., 2023). The area of potential use of the vehicles is limited by insufficient or completely missing infrastructure of truck charging stations and by the time needed to charge the batteries. The main reason for the introduction of electromobiles is their minimal environmental impact (Behnke & Kirschstein, 2017). A study on the use of the energy network shows the vehicles' benefits in charging at night when electric vehicles are mainly charged (Montoya et al., 2017). Night charging helps balance voltage in the energy network by consuming surplus production.

Along with the development of electric vehicles, people should develop a smart energy network that will provide energy for these vehicles in the future (Huang et al., 2016). Improving the efficiency of a vehicle is related to increasing the efficiency of the network; thereby, it is possible to achieve a significant reduction in energy consumption and carbon emissions from energy production. The main limiting conditions can include the electric vehicle range (on a single charge). For vehicles with a total weight of over 18 t, manufacturers state a range of about 200 km (Daimler Truck, 2018). In general, the network of charging stations for trucks is insufficient. Therefore, there is scope for systemic analysis of the charging station definition and optimization of the locations of these charging stations. Suppose one considers distribution logistics from a strategic purchasing perspective, i.e., a model that is highly efficient while minimizing costs. In that case, one must also consider maximizing the efficiency concerning possible changes in the system by switching to another form of alternative freight transport powertrains. Gargasas et al. (2018) point to the highly customer-oriented nature of logistic services in distribution logistics, where service providers implement solutions that are demanded by clients and with a view to sustainable development with minimal environmental impact, thus maintaining positive relationships with their suppliers and customers (Lodiené & Kolegija, 2012).

Modern green logistics trends develop and implement several environmental measures to minimize impacts and ensure sustainable production where logistics plays an important role (Karaman et al., 2020). The advantage of green logistics is the possibility of combining distribution logistics with modern urban transport systems, and in this context, green logistics is seen as an option for reducing environmental impacts while respecting the needs of modern distribution (Kurbatova et al., 2020). Many issues must be addressed when implementing green logistics, but ultimately, when resolved, this can bring cost reductions and, therefore, better efficiency of distribution logistics and increase the quality of services provided to end-users and consumers. In addition, green logistics contributes to logistics companies by reducing material purchase costs, energy costs, waste treatment, and disposal fees to eliminate environmental damage (Sidek et al., 2021). The concept of green logistics can be described as a system of measures designed according to human needs and interests; it emphasizes the strategic direction of implementing sustainable development, considering environmental, economic, social, and humanitarian aspects (Gnann et al., 2018). In parallel with the development of green logistics, there is a need to build transport infrastructure supported by intelligent transport systems that will ensure safer, better coordinated, and more efficient use of the transport network for different users (Pečiukėnas et al., 2017). When implementing the objectives of the green logistics concept, the economic, social, and environmental aspects of the overall solution need to be considered. Distribution logistics transitioning to green logistics must adopt the basic principles of lean manufacturing (Lean, Kaizen, etc.) (Schonberger, 1982), i.e., minimizing inefficiency. The transition to green logistics will require building an infrastructure for charging points for trucks, ensuring enough qualified specialists, and, last but not least, implementing advanced information systems with decision-making support. Green logistics is often referred to as sustainable and environmentally friendly logistics, which is why implementing green logistics is a lengthy and complex process that must respect the social, economic, and environmental aspects of modern society. A major impact on the implementation of green logistics will be in road freight transport, which is an important area for securing the region's overall economy and regarding the already built road infrastructure. Strong support from national governments can be expected to reduce the impact of existing logistics and distribution and introduce green logistics principles mainly for the distribution of goods in the range of up to 200 km. Therefore, the introduction of environmental logistics measures in logistics companies is critical to reduce the negative environmental impact of distribution logistics. Therefore, the scientific problem should be formulated as questions concerning the conditions and measures leading to the transition to green logistics. The results of this work should provide a possible solution to the transition to green logistics in short-distance distribution.

The theoretical aspects of final delivery in combination with green logistics have been addressed by many researchers who were comparing the conditions of green logistics in final delivery and reverse logistics, which have similar theoretical aspects (Lingaitis & Bazaras, 2007). When analyzing green logistics, despite the theoretical aspects, many researchers point out the fundamental operational differences between green logistics and reverse logistics, the latter being more focused on the take-back system at final delivery and waste management or end-of-life products. Green logistics operations focus on organizing the entire logistics supply chain to achieve environmentally friendly solutions, using appropriate resources such as packaging, alternative fuel, or other energy sources, and organizing activities to avoid or reduce empty kilometers. It can even be assumed that this concept is important in modern business development and emphasizes social and environmental issues instead of commercial profit (Bajdor et al., 2021). These sources emphasize that green logistics, as a sustainable development concept, is important in addressing the region's environmental, economic, and social problems. The economic aspect of the green logistics concept will be the correct pricing and ensuring the quality and competitiveness of a given company. The environmental aspect will focus on using renewable energy sources, saving fossil fuels, and minimizing emissions associated with distribution logistics. Ultimately, the social aspect will be to increase the social prestige of logistics companies for their lasting contribution to reducing their negative impact on the environment. Therefore, it is necessary not only to implement the solu-

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tions mentioned above but also to simultaneously increase the social responsibility and competence of the employees of the companies concerned (Vienažindienė et al., 2021).

With the increasing influence of legal regulations and the problems of constraints on the flow of traffic, new innovative technological measures need to be applied for strategic management decisions that will lead to increased efficiency of distribution logistics and increased public reputation of companies in the environmental area (Macharis & Kin, 2017). Distribution logistics is a significant contributor to emissions and greenhouse gases. Based on this, the European Environment Agency (2018), together with the European Commission (2019), reported that transport in the European Union (EU) accounts for almost 30% of all carbon dioxide (CO2) emissions, with road transport accounting for 22% of these emissions with 72% of total transport. Heavy goods transport with 26% and light goods transport with 12% of road transport therefore account for around 25% of total transport emissions, which means that they are responsible for around 8% of total CO2 emissions within the EU.

Road transport is responsible for about a quarter of European greenhouse gas emissions. Heavy goods vehicles and buses account for 27% of GHG emissions from road transport (Eurostat, 2020). European Union's (EU) legislation requires CO2 emissions from newly registered heavy goods vehicles to be reduced by 30% by 2030 compared to current levels (EU). Analyses show this is only possible with zero-emission vehicles, i.e., electric or hydrogen-powered trucks (Breed et al., 2021). Current research shows that the lack of charging infrastructure is necessary to expand battery electric trucks (Nykvist & Olsson, 2021).

This paper focuses on finding solutions for optimizing the location of charging stations for electric vehicles in freight transport using the example of the Czech Republic. In order to do so, it employs the mathematical models aimed to enhance resource utilization, mitigate environmental and economic impacts associated with the construction of the new charging stations, as well as explore viable placements within logistics and manufacturing parks.

2. METHODOLOGY

The placement models aim to find suitable relative geographical locations of charging stations. Placement models have been formulated to support the decision and are the focus of interest. The great variety of models that can be found in the literature leads to the need for them to be classified (Gros, 2016):

- One distinguishes models for placing one or more facilities depending on the number of facilities to be placed.
- Depending on the set of available locations, one distinguishes cases with an unlimited set (the facility can be placed anywhere in the area) or a discrete set where a selection must be made from a predefined group of locations.
- One further distinguishes models according to whether the number of facilities to be placed needs to be determined or is predetermined.
- One also distinguishes models according to their location on a plane or in space.

In the placement of logistics facilities (production plants, warehouses, transshipment facilities, etc.), one of the criteria is the cost aspect, i.e., the cost incurred for the connection between the facilities. However, in the case of the placement of charging stations, the main criterion is the requirement for transport service for an individual location, i.e., ensuring the placement of charging stations so that each point is supplied.

$$z = \sum_{j=1}^{n} \left(\left| x - x_j \right| + \left| y - y_j \right| \right) \rightarrow \text{MIN}, \quad (1)$$

where (x_j, y_j) are the points between which the most suitable service center should be located and w_j is the importance of each object.

Finding the coordinates of the new object $N = (x, y)$ is easy if one realizes that the nature of the formulated problem implies that the objective function can be divided into two parts

$$z = \sum_{j=1}^{n} w_j \left| x - x_j \right| + \\ + \min \sum_{j=1}^{n} w_j \left| y - y_j \right| \rightarrow \text{MIN}. \quad (2)$$

If the new object cannot be placed in the found point, one needs to find suitable, different locations, and at the same time, one will have to allow the growth of the purpose function:

$$z = \sum_{i=1}^{m} \sum_{j=1}^{n} w_{ij} \left((x_i - x_j)^2 + (y_i - x_j) \right)^2 + \sum_{i=1}^{n} \sum_{j=1}^{n} w_{ij} \left((x_i - x_k)^2 + (y_i - x_k)^2 \right) \rightarrow \text{MIN}. \quad (3)$$

The study derives the distance function and sets the partial derivatives equal to zero. It obtains a system of linear equations, the solution of which gives the coordinates of the points *N_i* = (*x_i*, *y_i*) for *i* = 1, 2, 3 , ..., *m*.

Mayer's method can be described as an approximate method of constructing round trips with capacity constraints. This solution method suits roundabout problems with a complete path network and a central location. The solution is done in two steps:

- In the first step, the locations are divided into individual circuitous routes. First, the location with the highest route rate is assigned to the central location. To the already selected locations, another location is assigned so that the capacity of the circuit is not exceeded and that this location is the closest to the already assigned locations, i.e., the route rate to an already selected location must be the smallest possible. Additional places are added in the same way until the capacity of the circuit is exceeded;

- The second step ranks the places in each route. In order to find the most suitable circuits, methods for solving the one-circuit problem can be used.

3. RESULTS

Generally, it becomes obvious that the network of truck charging stations is insufficient. Therefore, there is scope for systemic analysis of the charging station definition and for optimization of the locations of these charging stations. The quantity of charging station criteria highlights the complexity of the issue ensuing from the possible charging station sites for which multi-criteria decision-making methods can be used when choosing a compromise solution. The multi-criteria decision-making issue of a charging station definition may, for example, be based on the analysis using the Analytic Network Process (ANP) method.

In terms of definition, the study could include charging stations for electric trucks in the category of logistics facilities, with the possibility to use a facility placement algorithm on a plane with constraint conditions for charging stations. The location issue depends on the multi-level logistic network's complexity (indirect relationship: suppliers – intermediate points – receivers). The analysis represents the multi-criteria decision-making issue of a charging station definition using the selected ANP method (Table 1).

Legislative restrictions and governmental limitations on vehicles with conventional powertrains open the way for the possible use of vehicles with alternative powertrains, particularly the support of electric trucks. Partly, knowledge of the expanding electric mobility in passenger cars can be used, but this is impossible in charging stations. While urban infrastructure, shopping malls, entertainment centers, etc., can be used for passenger cars, it is not possible to use them for trucks, given the throughput limitations in city centers. Therefore, charging stations need to be placed regarding truck accessibility. The study, therefore, considers an area burdened with a certain degree of uncertainty, especially regarding the location of charging stations and the overall vehicle utilization. Given some uncertainty, it is possible to use system analysis methods to address the given issue: the ideal locations for charging stations and how they should be equipped.

The model parameters are set as follows. To find the appropriate locations for charging stations, it is necessary to define model parameters that should reflect the criteria included in the ANP model. If one considers the first four criteria by their weight:

- Charging capability – i.e., the ability to charge using multiple charging adapters (plugs).

- Distance from the substation – to minimize losses due to the distribution network.

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Table 1. Overview of the evaluation attributes and criteria for the charging station definition

Evaluation Attributes	Criteria	Description	Measurable
Economic factors	Construction costs	Costs associated with the purchase of land, project documentation, construction of the charging station	EUR
	Operating costs	Costs, including all operating charges related to daily operation. Operating costs are important in terms of financial gain	EUR
	Return on investment (ROI)	Relevant in terms of cost and operating income assessment. The most crucial economic criterion in the commercial sphere	EUR
Technical factors	Distance from the distribution station	Location near the distribution station affects loss of power transmission	Km
	Impact on the energy network	Relevant for the safe operation of the energy network	MWh
Service availability	Rechargeable Capability	Maximum number of charging stations in a single moment. This sub-criterion is related to the number of vehicles that can be charged	Number of charging stations
	Availability (Convenience of transportation)	Criterion important from the point of view of the available road network by a lorry	Number of accessible roads
Social factors	Capacity expansion	Necessary requirement in terms of further increases of freight electric vehicles	Volume of newly built charging stations
	Local position	Relevant requirement of impact on the potential health problems of the population (electromagnetic fields, traffic growth)	Number of issues released for construction
	Support from local government	This attribute may include possible grant titles for construction (National Action Plan for Clean Mobility)	Number of issues released for construction
	Increasing employment	Relevant for new labor market opportunities and job creation	Number of newly created jobs
Environmental impacts	Environmental impact	Necessary environmental impact assessment (EIA process)	Carbon footprint CO_2
	Energy saving (stability)	Possibility of creating an autonomous station independent of the energy network or creating a hybrid model that could respond to excess energy in the network and thus compensate for fluctuations	MWh
	Impact on the energy network	Immediate demand for performance (charging) can destabilize the energy Network	MWh
Location (geographic location)	Logistic parks	Relevant from the point of view of logistics chain engagement accepting places with a high concentration of vehicles used for products (goods) transportation	Number of available logistic parks
	Logistic objects	Places with a concentration of production plants	Number of production plants and parking areas with logistic services
	Parking places	Transport terminals (ports, railway stations) places with a high concentration of freight traffic	Number of parking places

- Expansion of capacity – possibility to add additional charging stations to the site in the future.
- Logistics parks – i.e., placement in existing or newly emerging logistics parks.

It would, therefore, be appropriate to place charging stations in logistics parks that are able to minimize the impacts of construction, as they meet all three of the further criteria. At the same time, individual transport companies need to have charging capacity on their premises. Since the main charging cycle should take place during night hours as a possibility to balance energy surpluses, and considering the driver's working hours, this is the best way of charging. The proposed network of charging stations should serve as a supplement to the necessary fuel cell recharging along the route.

The initial calculation will, therefore, consider the placement of charging stations in existing locations. To determine whether these locations can be used to supply individual sites in the Czech Republic, it is first necessary to determine the distance of the sites and to identify those with limited vehicle availability with respect to the range distance. At the same time, it is necessary to meet the condition that the vehicle always returns to the starting node, so one has to consider only half the distance of the total vehicle range. Three possible scenarios were considered to simulate the conditions that may occur on the route. The manufacturer gives a vehicle range of 200 km. The capacity margin was set at 10%:

1) Maximum range of 180 km – ideal weather and traffic conditions.

2) Average range of 156 km – deteriorated conditions on the road.

3) Minimum range of 132 km – deteriorated climatic and traffic conditions.

The proposed model is to work with the worst-case scenario, i.e., a maximum range of 132 km. Thus, the individual model parameters and constraining conditions are:

1) Charging stations within a maximum range of 66 km from each municipality (city).

2) Maximum use of existing logistics parks and facilities.

3) Placement of new charging station locations is as follows:

- Placement according to the proximity of the construction plan of the Road and Motorway Directorate (RMD);
- placement within the existing capacity parking areas for freight transport;
- placement in industrial facilities;
- placement in the existing petrol stations;
- placement in municipalities (towns).

3.1. Minimization of greenfield locations

The model input data can be presented in the following way:

- municipalities in the Czech Republic (6254 municipalities, towns, and boroughs);
- districts in the Czech Republic (76 districts and 15 districts of Prague);
- logistic and storage parks (294);
- construction plan of the RMD for the Czech Republic.

The following formulas are used to calculate the coordinates:

Latitude
$$x = \frac{\sum_{j=1}^{n}(x_{ij})}{x_{ij}}, \tag{4}$$

Longitude
$$y = \frac{\sum_{j=1}^{n}(y_{ij})}{y_{ij}}. \tag{5}$$

In the first step, it was necessary to identify the municipalities with limited accessibility based on distances. The range distance to the nearest logistics park location was determined to be more than 66 km. 165 municipalities with limited accessibility to a potential charging station were identified. The mileage used is attached and may be affected based on the actual route passability (the distance was queried using a web service query, and if there was a detour on the route due to reconstruction, the total distance may be affected by this restriction). Subsequently, the ideal location was found based on the requirements as follows:

- Suppose the distance between municipalities in each district was greater than 66 km, and the condition of more than 10 municipalities was also met. In that case, only these municipalities will be included in the calculation of the new location.
- Suppose the distance between municipalities in each district was greater than 66 km and, simultaneously, the condition of more than 10 municipalities was not met. In that case, all municipalities will be included in the calculation of the new location.
- If the distance between the municipalities is less than 66 km, all municipalities will be included in the calculation.
- Suppose the number of municipalities is less than 10 in a single district. In that case, that district will be assigned to an adjacent district

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in the same region or an adjacent district in an adjacent region if the other municipalities are in an adjacent one.

- If the resulting location is more than 66 km from the individual municipalities, that district will be divided into two sub-districts.

The placement of charging stations prior to the subsequent optimization according to the model parameters consisted, in the first step, in the placement of a charging station in the center of the municipalities and so that the placement met the parameters thus minimizing greenfield construction. This way, 15 new locations were identified for municipalities with insufficient distance to the charging station.

As seen from the overview map (Figure A1 in Appendix A), it is evident that some districts could still be merged, thus minimizing the number of charging stations. For further sub-minimization, the following districts were identified:

1) Distr. Klatovy + distr. Prachatice;

2) Distr. Náchod + distr. Trutnov;

3) Distr. Jeseník + distr. Šumperk + distr. Ústí nad Orlicí;

4) Distr. Jindřichův Hradec + distr. Třebíč + distr. Znojmo.

For these merged districts, the same calculation was applied, i.e., the determination of individual distances between the municipalities and the calculated location was examined in terms of the parameters of the model and relocated. Subsequently, the distances were recalculated to determine whether the new location was within 66 km of the individual municipality.

The study merges the distr. Klatovy + distr. Prachatice (Figure A2 in Appendix A). In the original design, two charging sites were created for each district before minimization, but by merging and recalculating distances, only one site was proposed.

After the minimization number of charging points and merging of districts, only eight new charging points were subsequently created that met all model parameters (see Table 2).

If one includes all logistics parks and newly located charging stations for municipalities with limited accessibility in the construction plan, this will create 304 charging locations for electric trucks. In terms of control, the study needs to recalculate the distances of the municipalities to ensure that the newly created locations are within the required distance of 66 km from each municipality. The visualization of charging station locations for communities with limited accessibility after minimization can be found in Figure A2 in Appendix A.

3.2. Minimization model for finding charging points

The model assumes that all existing logistics park locations will be used for the placement of charging stations. This may lead to a degree of uncer-

Table 2. Geographical placement of charging stations after minimizing the districts of the Czech Republic

District	Region	Latitude	Longitude
Bruntál	Moravskoslezský kraj	50.15900728	17.57425855
Frýdek-Místek	Moravskoslezský kraj	49.66998865	18.43487619
Jeseník	Olomoucký kraj	50.52522383	15.81181065
Jindřichův Hradec	Jihočeský kraj	48.99649707	15.34908357
Prachatice	Jihočeský kraj	49.05447693	13.79816438
Příbram	Středočeský kraj	49.66692198	14.42349719
Trutnov	Královéhradecký kraj	50.52522383	15.81181065
Žďár nad Sázavou	Vysočina	49.50952098	16.09027715

tainty as to whether the site owners will accept the construction. Furthermore, there are conditions to minimize the location of charging stations. Suppose the individual depots from where vehicles will depart to their distribution routes are equipped with charging stations. In that case, it is possible to build only minimal charging stations that will only be used by the vehicle to charge the batteries needed to reach the original depot. To minimize the charging stations, the application area of the country was divided into districts, and the individual locations were assessed in terms of the same model parameters plus one new condition – the creation of a station in each district.

The calculation is now based not on distances between municipalities in a given district but on finding an ideal center, which will then be reviewed in terms of parameters. Each municipality will be checked according to its distance to the charging station to ensure the maximum distance for each municipality of 66 km to the charging station.

Figure A3 in Appendix A shows the location of the charging stations:

- Nine times at the locations where the RMD carries out its construction (blue points);
- 50 times at locations of the existing logistics parks (green points);
- Seventeen times at new locations (purple points).

Newly developed locations include industrial parks, existing petrol stations, and TIR (International Truck Transport) car parks. The new locations would have to cover the maximum capacity for charging, and their size and adjacent infrastructure would have to be spatially more significant.

3.3. Evaluation of charging station location models

Both models respect the model parameters and constraining conditions, but model 2 appears more acceptable in minimization (minimization model for finding charging stations). Thus, there is a possibility for creating two charging networks: the primary network, which includes the 76 locations found, and a secondary network consisting of the remaining locations from the first model.

Just as the area of utilization of electric vehicles suffers from a degree of uncertainty, in the area of charging stations, this uncertainty is represented by a certain reluctance to build in the locations found.

To ensure that the newly proposed location of the charging stations meets the specified parameters and is also suitable for trucks, it is necessary to test the solution on real data. To test on real data, only charging station locations in districts were applied, i.e., a solution with 76 charging station locations. The traffic roundabout model method was chosen, using the procedure from Mayer's method and taking the conditions from the Clarke-Wright method. In the first step, the calculation was carried out without the use of charging points, i.e., as for conventionally driven vehicles. In the second step, charging points were added to the model, and the procedure for calculating the steps using the Mayer method was modified so that in the first step, the first delivery is based on weight (the conventional method calculates on distance). In the second step, the standard procedure is already applied, i.e., the next location is found by the shortest distance from the first delivery address. In addition, the next location option has been added so that if the vehicle capacity is exceeded when using the shortest distance from the first address, this address can be skipped, and the next address is now located within 30 km of the last delivery (the distance is based on the 66 km driving distance to the charging station divided by two and taking into account a capacity reserve of 10%). This procedure has been chosen to maximize vehicle use while minimizing the number of kilometers and vehicles used.

When applied to real data, the model demonstrated its applicability to distribution transport and confirmed the accuracy of the charging station location model. However, the overall evaluation showed that the charging station model resulted in a 3% increase in the time spent away from the origin node due to the time spent

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Table 3. Model evaluation

Source: EPA (n.d.).

Model evaluation	Total distance Km	Number of vehicles used	Total time	Km/ default status	Time/ default status	Consumption	CO2 production per total distance (g)
The default distribution solution	478	4	15 hours 49 minutes	not applicable	not applicable	19.,44/100 km	249,591
A weight-based model, complete with a skipping algorithm complete with charging stations	463	4	16 hours 14 minutes	97%	103%	88 kWh/100 km	176,422

Note: The CO_2 ratio was calculated on open source from EPA (the United States Environmental Protection Agency).

charging the vehicle at the charging station in Domažlice. At the same time, however, there was a 3% reduction in the total distance traveled due to the omission of locations that exceeded the vehicle's capacity (see Table 3).

4. DISCUSSION

The study's approach to optimizing the geographical locations of electric truck charging stations is pivotal for enhancing environmental sustainability and reducing carbon emissions. This objective aligns with the broader goals of green logistics. The methodological shift in the current study toward a multi-criteria decision-making process, specifically using the Analytic Network Process (ANP), indicates an evolution from the traditional methods focused mainly on minimizing costs and maximizing efficiency in distribution logistics.

Earlier research often emphasized node-based, path-based, and tour-based models for determining the placement of charging stations (Daşcioğlu et al., 2019; Honma & Kuby, 2019; Metais et al., 2022).

Node-based models are p-median models with charging stations located at nodes such that the requirement of neighboring nodes could be met with a minimum distance traveled (Deb et al., 2018). Thus, this approach can also be used to place charging points for electric vehicles. A charging station covers a certain area or part of the road in node-based models. Therefore, a relatively dense charging network with many charging points is usually modeled. Charging stations can be located at regular distances, and their size can depend on the traffic intensity for neighboring nodes (Speth et al., 2022). Thus, the focus may not be on minimizing charging points but on sizing them. For that model, the traffic volume at each node is always required (Speth et al., 2022).

In contrast, path-based models rely on the traffic flows within the network and address the coverage of the maximum passing traffic with a minimum of stations. The flow-capturing location allocation model is the first subset of path-based models (Hodgson, 1990). In 2013, a charging station model was presented for Barcelona, where only 27 charging stations were placed, which would meet the demand of 92% of the considered flows (Jochem et al., 2019). The general idea of the placement, to supply the maximum of the previously known origin-destination paths with a fixed number of stations, remains the same (Kuby & Lim, 2005). The same model can be used for hydrogen-powered vehicles and thus combine the model with a limitation of charging stations to avoid large unrealistic stations (Rose et al., 2020). The disadvantage of these models is that they are compute-intensive, and therefore, it is necessary to constrain the modeling in some way, for example, by reducing the areas for which people seek suitable locations for charging stations (Jochem et al., 2019). A tour-based model considers individual driving profiles and locates charging stations to match the driving profiles. While the level of detail increases from node-based and path-based to tour-based models, the input data requirements also increase (Speth et al., 2022). For node-based approaches, data from local traffic counts are sufficient. Tour-based models require origin-destination relationships (Speth et al., 2022). GPS data, which are more tour-based, and data from individual trips and distances can be used to accurately model truck infrastructure (Whitehead et al., 2022). The hydrogen refueling station infrastructure for trucks in Germany has been modeled using a tour-based model (Jochem et al., 2019). The analysis was based on 2655 routes. The result was a model of 100 hydrogen refueling stations serving 13000 km of motorways. Since the EU is currently discussing a Europe-wide network of truck refueling stations, it is crucial to understand what such a network could look like in the next few years.

These models generally prioritized logistical efficiency and cost-effectiveness. In contrast, the current study integrates a more holistic approach that considers logistical efficiency and environmental and social factors. The methodology used in the paper is more aligned with the modern principles of green logistics, a comprehensive system designed to address environmental, economic, social, and humanitarian aspects.

The results of this paper demonstrate the inadequacy of the current network of charging stations for electric trucks, highlighting the need for an optimized network that can adequately support electric freight transport and enhance environmental sustainability while simultaneously reducing carbon emissions, which is crucial for reducing environmental risks and optimizing the sustainable economic development. This finding is consistent with previous research (Liu et al., 2023; Alanazi et al., 2023) that pointed to the lack of charging infrastructure as a critical barrier to the expansion of electric trucks. However, the current study advances the discourse by proposing a multi-criteria decision-making framework for placing charging stations, considering the complex logistics network of suppliers, intermediate points, and receivers.

Moreover, it also needs to be emphasized that the optimal location for charging stations is not merely an exercise in logistical efficiency but involves a multi-criteria evaluation, considering factors such as cost, environmental impact, and the existing infrastructure. This approach marks a significant departure from earlier models that predominantly focused on logistical parameters. The results of this paper emphasize that placing charging stations within the existing infrastructure or planned motorway networks in the Czech Republic reflects a pragmatic approach to integrating environmental sustainability within existing economic structures.

CONCLUSION

The study aims to optimize the placement of electric vehicle charging stations to enhance environmental sustainability and reduce carbon emissions in freight transport. It focuses on integrating charging infrastructure into existing logistics networks, facilitating a more efficient and environmentally friendly freight transport system. This optimization task involves a multi-criteria approach, considering logistical efficiency and environmental impact.

The results reveal that the ideal location for charging stations is within existing infrastructure, such as logistics parks or rest areas, or close to logistics and transport companies. In cases where the optimal location falls outside these areas, the study suggests analyzing the costs and efficiency of constructing new charging stations and their capacity to service the anticipated number of vehicles.

The main conclusions drawn from these results emphasize the significance of strategically locating charging stations to support sustainable freight transport development. Placing charging stations within existing infrastructure or near preselected locations minimizes the need for constructing new facilities, offering a financially viable solution. This approach aligns with the goals of sustainable economic development and environmental risk mitigation. Moreover, the study's findings have broader implications, extending beyond the Czech Republic. As the electrification of transport increases, these insights become increasingly valuable for stakeholders in policymaking, infrastructure planning, and environmental protection. The study demonstrates that careful selection and placement of charging stations are crucial for achieving sustainable freight transport and environmental sustainability on a larger scale.

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AUTHOR CONTRIBUTIONS

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REFERENCES

1. Aijaz, I., & Ahmad, A. (2022). Electric vehicles for environmental sustainability. In P. Agarwal, M. Mittal, J. Ahmed, & S. M. Idrees (Eds.), *Smart Technologies for Energy and Environmental Sustainability. Green Energy and Technology* (pp. 131-145). Cham: Springer. https://doi.org/10.1007/978-3-030-80702-3_8
2. Alanazi, F., Alshammari, T. O., & Azam, A. (2023). Optimal Charging Station Placement and Scheduling for Electric Vehicles in Smart Cities. *Sustainability, 15*(22), 1-23. https://doi.org/10.3390/su152216030
3. Ali, I., & Naushad, M. (2022). Insights on electric vehicle adoption: Does attitude play a mediating role? *Innovative Marketing, 18*(1), 104-116. https://doi.org/10.21511/im.18(1).2022.09
4. Bajdor, P., Pawełoszek, I., & Fidlerova, H. (2021). Analysis and assessment of sustainable entrepreneurship practices in Polish small and medium enterprises. *Sustainability, 13*(7), 3595. https://doi.org/10.3390/su13073595
5. Barman, P., Dutta, L., Bordoloi, S., Kalita, A., Buragohain, P., Bharali, S., & Azzopardi, B. (2023). Renewable energy integration with electric vehicle technology: A review of the existing smart charging approaches. *Renewable and Sustainable Energy Reviews, 183,* 113518. https://doi.org/10.1016/j.rser.2023.113518
6. Behnke, M., & Kirschstein, T. (2017). The impact of path selection on GHG emissions in city logistics. *Transportation Research Part E: Logistics and Transportation Review, 106,* 320-336. https://doi.org/10.1016/j.tre.2017.08.011
7. Breed, A. K., Speth, D., & Plötz, P. (2021). CO2 fleet regulation and the future market diffusion of zero-emission trucks in Europe. *Energy Policy, 159,* 112640. https://doi.org/10.1016/j.enpol.2021.112640
8. Cattaruzza, D., Absi, N., Feillet, D., & González-Feliu, J. (2017). Vehicle routing problems for city logistics. *EURO Journal on Transportation and Logistics, 6*(1), 51-79. https://doi.org/10.1007/s13676-014-0074-0
9. Daimler Truck. (2018). *All-electric Mercedes-Benz truck for heavy-duty distribution : Start of practical customer trials: The Mercedes-Benz eActros is entering operation with Hermes.* Retrieved from https://www.daimlertruck.com/en/newsroom/pressrelease/all-electric-mercedes-benz-truck-for-heavy-duty-distribution-start-of-practical-customer-trials-the-mercedes-benz-eactros-is-entering-operation-with-hermes-41261846
10. Daşçioğlu, B. G., Tuzkaya, G., & Kiliç, H. C. (2019). A model for determining the locations of electric vehicles' charging stations in Istanbul. *Pamukkale Üniversitesi Mühendislik Bilimleri Dergisi, 25*(9), 1056-1061. https://doi.org/10.5505/pajes.2019.28475
11. Deb, S., Tammi, K., Kalita, K., & Mahanta, P. (2018). Impact of electric vehicle charging station load on distribution network. *Energies, 11*(2), 178. https://doi.org/10.3390/en11010178
12. European Commission (EC). (2019). Regulation (EU) 2019/1242 of the European Parliament and of the Council of 20 June 2019 Setting CO2 Emission Performance Standards for New Heavy-Duty Vehicles and Amending Regulations (EC) No 595/2009 and (EU) 2018/956 of the European Parliament and of the Council and Council Directive 96/53/EC. *Official Journal of the European Union, 50,* 202-240. Retrieved from http://data.europa.eu/eli/reg/2019/1242/oj
13. European Environment Agency. (2018). *Environmental indicator report 2018. In support to the monitoring of the Seventh Environment Action Programme.* Retrieved from https://www.eea.europa.eu/publications/environmental-indicator-report-2018
14. Eurostat. (2020). *Database.* Retrieved from https://ec.europa.eu/eurostat/web/transport/data/database
15. Fan, L., Liu, C., Dai, B., Li, J., Wu, Z., & Guo, Y. (2023). Electric vehicle routing problem considering energy differences of charging

stations. *Journal of Cleaner Production, 418,* 138184. https://doi.org/10.1016/j.jclepro.2023.138184

16. Gargasas, A., Samuolaitis, M., & Mūgienė, I. (2019). Quality management systems in logistics. *Management Theory and Studies for Rural Business and Infrastructure Development, 41*(2), 290-304. https://doi.org/10.15544/MTS.2019.24
17. Gnann, T., Funke, S., Jakobsson, N., Ploetz, P., Sprei, F., & Bennehag, A. (2018). Fast charging infrastructure for electric vehicles: Today's situation and future needs. *Transportation Research Part D: Transport and Environment, 62,* 314-329. https://doi.org/10.1016/j.trd.2018.03.004
18. Gros, I. (2016). *Velká kniha logistiky [The big book of logistics].* Praha: Vysoká škola chemicko-technologická v Praze. (In Czech).
19. Hodgson, M. J. (1990). A Flow-Capturing Location-Allocation Model. *Geographical Analysis, 22*(3), 270-279. https://doi.org/10.1111/J.1538-4632.1990.TB00210.X
20. Honma, Y., & Kuby, M. (2019). Node-based vs. path-based location models for urban hydrogen refueling stations: Comparing convenience and coverage abilities. *International Journal of Hydrogen Energy, 44*(29), 15246-15261. https://doi.org/10.1016/j.ijhydene.2019.03.262
21. Huang, K., Kanaroglou, P., & Zhang, X. (2016). The design of electric vehicle charging network. *Transportation Research Part D: Transport and Environment, 49,* 1-17. https://doi.org/10.1016/j.trd.2016.08.028
22. Husinec, M., Šubrt, T., & Fejfar, J. (2020). EOQ as a tool for increased transport efficiency. *38th International Conference on Mathematical Methods in Economics* (pp. 205-210). Brno: Mendel University in Brno Faculty of Business and Economics. Retrieved from https://mme2020.mendelu.cz/wcd/w-rek-mme/mme2020_conference_proceedings_final_final.pdf
23. Jochem, P., Szimba, E., & Reuter-Oppermann, M. (2019). How many fast-charging stations do we need along European highways? *Transportation Research Part D: Transport and Environment, 73,* 120-129. https://doi.org/10.1016/j.trd.2019.06.005
24. Karaman, A. S., Kilic, M., & Uyar, A. (2020). Green logistics performance and sustainability reporting practices of the logistics sector: The moderating effect of corporate governance. *Journal of Cleaner Production, 258,* 120718. https://doi.org/10.1016/j.jclepro.2020.120718
25. Kinsella, L., Stefaniec, A., Foley, A., & Caulfield, B. (2023). Pathways to decarbonising the transport sector: The impacts of electrifying taxi fleets. *Renewable and Sustainable Energy Reviews, 174,* 113160. https://doi.org/10.1016/j.rser.2023.113160
26. Kozlovskyi, S., Bolhov, V., Yousuf, A., Batechko, A., Hlushchenko, L., & Vitka, N. (2019). Marketing analysis of the electromobile market as a factor in the innovation of the national economy. *Innovative Marketing, 15*(1), 42-53. https://doi.org/10.21511/im.15(1).2019.04
27. Kuby, M., & Lim, S. (2005). The flow-refueling location problem for alternative-fuel vehicles. *Socio-Economic Planning Sciences, 39*(2), 125-145. https://doi.org/10.1016/j.seps.2004.03.001
28. Kurbatova, S. M., Aisner, L. Y., & Mazurov, V. Yu. (2020). Green logistics as an element of sustainable development. *IOP Conference Series: Earth and Environmental Science, 548,* 052067. http://doi.org/10.1088/1755-1315/548/5/052067
29. Li, X., & Zhou, K. (2021). Multi-objective cold chain logistic distribution center location based on carbon emission. *Environmental Science and Pollution Research, 28,* 32396-32404. https://doi.org/10.1007/s11356-021-12992-w
30. Lingaitis, L. P., & Bazaras, D. (2007). An analysis of reverse and green logistics: Theoretical aspects. *Transport: Prace Naukowe, 60,* 5-12. Retrieved from http://www.wydawnictwopw.pl/strony/z6010.pdf
31. Liu, J., Sun, J., & Qi, X. (2023). Optimal Placement of Charging Stations in Road Networks: A Reinforcement Learning Approach with Attention Mechanism. *Applied Sciences, 13*(14), 8473. https://doi.org/10.3390/app13148473
32. Lodienė, D., & Kolegija, K. (2012). Globalios tiekimo grandinės įtaka verslo organizacijai [Influence of global supply chain for business]. *Management Theory and Studies for Rural Business and Infrastructure Development, 3*(32), 98-105. Retrieved from https://www.mokslobaze.lt/globalios-tiekimo-grandines-itaka-verslo-organizacijai-projektas.html
33. Macharis, C., & Kin, B. (2017). The 4 A's of sustainable city distribution: Innovative solutions and challenges ahead. *International Journal of Sustainable Transportation, 11*(2), 59-71. https://doi.org/10.1080/15568318.2016.1196404
34. Mancini, S. (2017). A combined multistart random constructive heuristic and set partitioning based formulation for the vehicle routing problem with time dependent travel times. *Computers and Operations Research, 88,* 290-296. https://doi.org/10.1016/j.cor.2017.06.021
35. Metais, M. O., Jouini, O., Perez, Y., Berrada, J., & Suomalainen, E. (2022). Too much or not enough? Planning electric vehicle charging infrastructure: A review of modeling options. *Renewable and Sustainable Energy Reviews, 153,* 111719. https://doi.org/10.1016/j.rser.2021.111719
36. Minet, L., Chowdhury, T., Wang, A., Gai, Y., Posen, I. D., Roorda, M., & Hatzopoulou, M. (2020). Quantifying the air quality and health benefits of greening freight movements. *Environmental Research, 183,* 109193. https://doi.org/10.1016/j.envres.2020.109193
37. Montoya, A., Guéret, C., Mendoza, J. E., & Villegas, J. G. (2017). The electric vehicle routing problem with nonlinear charging function. *Transportation Research Part B: Methodological, 103,* 87-110. https://doi.org/10.1016/j.trb.2017.02.004

http://dx.doi.org/10.21511/ee.15(1).2024.02

38. Nykvist, B., & Olsson, O. (2021) The feasibility of heavy battery electric trucks. *Joule, 5*(4), 901-913. https://doi.org/10.1016/J.JOULE.2021.03.007

39. Pan, S., Zhou, W., Piramuthu, S., Giannikas, V., & Chen, C. (2021). Smart city for sustainable urban freight logistics. *International Journal of Production Research, 59*(7), 2079-2089. https://doi.org/10.1080/00207543.2021.1893970

40. Pečiukėnas, A., Pečeliūnas, R., & Nagurnas, S. (2017). Intelektinių transporto sistemų įtaka kelių transporto priemonių srautų reguliavimui [The impact of intelligent transport systems on the regulation of road vehicle flows]. *Inžinerinės ir Edukacinės Technologijos – Engineering and Educational Technologies, 1,* 33-38. (In Lithuanian). Retrieved from https://etalpykla.vilniustech.lt/bitstream/handle/123456789/119390/Intelektini%3F%20transporto%20sistem%3F%20%3Ftaka%20keli%3F%20transporto%20priemoni%3F%20sraut%3F%20reguliavimui.pdf

41. Phadke, A., McCall, M., & Rajagopal, D. (2019). Reforming electricity rates to enable economically competitive electric trucking. *Environmental Research Letters, 14*(12), 124047. https://doi.org/10.1088/1748-9326/ab560d

42. Rajkoomar, M., Marimuthu, F., Naicker, N., & Mvunabandi, J. D. (2022). A meta-analysis of the economic impact of carbon emissions in Africa. *Environmental Economics, 13*(1), 89-100. https://doi.org/10.21511/ee.13(1).2022.08

43. Rapson, D. S., & Muehlegger, E. (2023). The economics of electric vehicles. *Review of Environmental Economics and Policy, 17*(2), 274-294. https://doi.org/10.1086/725484

44. Rose, K. P., Nugroho, R., Gnann, T., Plötz, P., Wietschel, M., & Reuter-Oppermann, M. (2020). Optimal development of alternative fuel station networks considering node capacity restrictions. *Transportation Research Part D: Transport and Environment, 78,* 102189. https://doi.org/10.1016/J.TRD.2019.11.018

45. Schonberger, R. (1982). *Japanese manufacturing techniques*. New York: The Free Press.

46. Sidek, S., Khadri, N. A. M., Hasbolah, H., Yaziz, M. F. A., Rosli, M. M., & Husain, N. M. (2021). Society 5.0: Green logistics consciousness in enlightening environmental and social sustainability. *IOP Conference Series: Earth and Environmental Science, 842,* 012053. https://doi.org/10.1088/1755-1315/842/1/012053

47. Simionescu, M., Strielkowski, W., & Gavurova, B. (2022). Could quality of governance influence pollution? Evidence from the revised Environmental Kuznets Curve in Central and Eastern European countries. *Energy Reports, 8,* 809-819. https://doi.org/10.1016/j.egyr.2021.12.031

48. Speth, D., Sauter, V., & Plötz, P. (2022). Where to charge electric trucks in Europe –Modelling a charging infrastructure network. *World Electric Vehicle Journal, 13*(9), 162. https://doi.org/10.3390/wevj13090162

49. Strielkowski, W., Streimikiene, D., Fomina, A., & Semenova, E. (2019). Internet of energy (IoE) and high-renewables electricity system market design. *Energies, 12*(24), 4790. https://doi.org/10.3390/en12244790

50. United States Environmental Protection Agency (EPA). (n.d.). *Greenhouse Gas Equivalencies Calculator – Calculations and References.* Retrieved from https://www.epa.gov/energy/greenhouse-gases-equivalencies-calculator-calculations-and-references

51. Vienažindienė, M., Tamulienė, V., & Zaleckienė, J. (2021). Green logistics practices seeking development of sustainability: Evidence from Lithuanian transportation and logistics companies. *Energies, 14*(22), 7500. https://doi.org/10.3390/en14227500

52. Whitehead, J., Whitehead, Je., Kane, M., & Zheng, Z. (2022). Exploring public charging infrastructure requirements for short-haul electric trucks. *International Journal of Sustainable Transportation, 16*(9), 775-791. https://doi.org/10.1080/15568318.2021.1921888

53. Wu, Y., Yang, M., Zhang, H., Chen, K., & Wang, Y. (2016). Optimal site selection of electric vehicle charging stations based on a cloud model and the PROMETHEE method. *Energies, 9*(3), 157. https://doi.org/10.3390/en9030157

54. Zhu, G., Gao, Y., & Sun, H. (2023). Optimization scheduling of a wind-photovoltaic-gas-electric vehicles community-integrated energy system considering uncertainty and carbon emissions reduction. *Sustainable Energy, Grids and Networks, 33,* 100973. https://doi.org/10.1016/j.segan.2022.100973

APPENDIX A

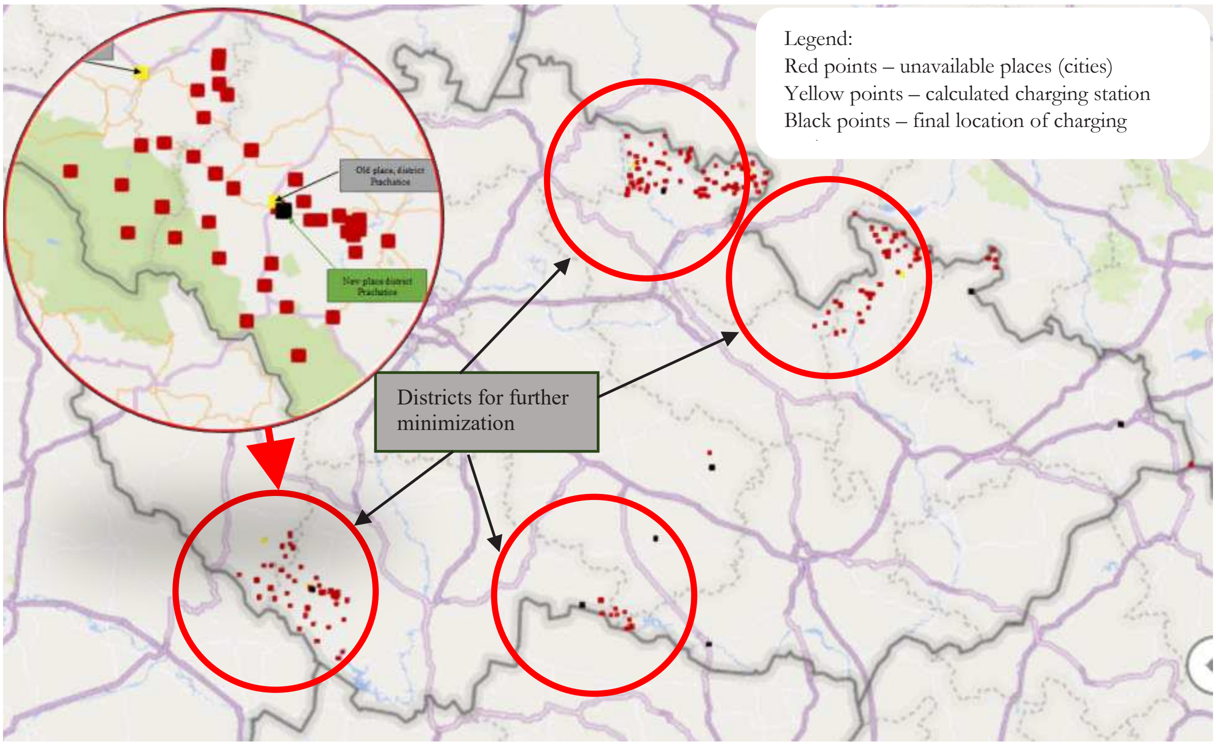

Figure A1. Merging districts before minimizing charging stations

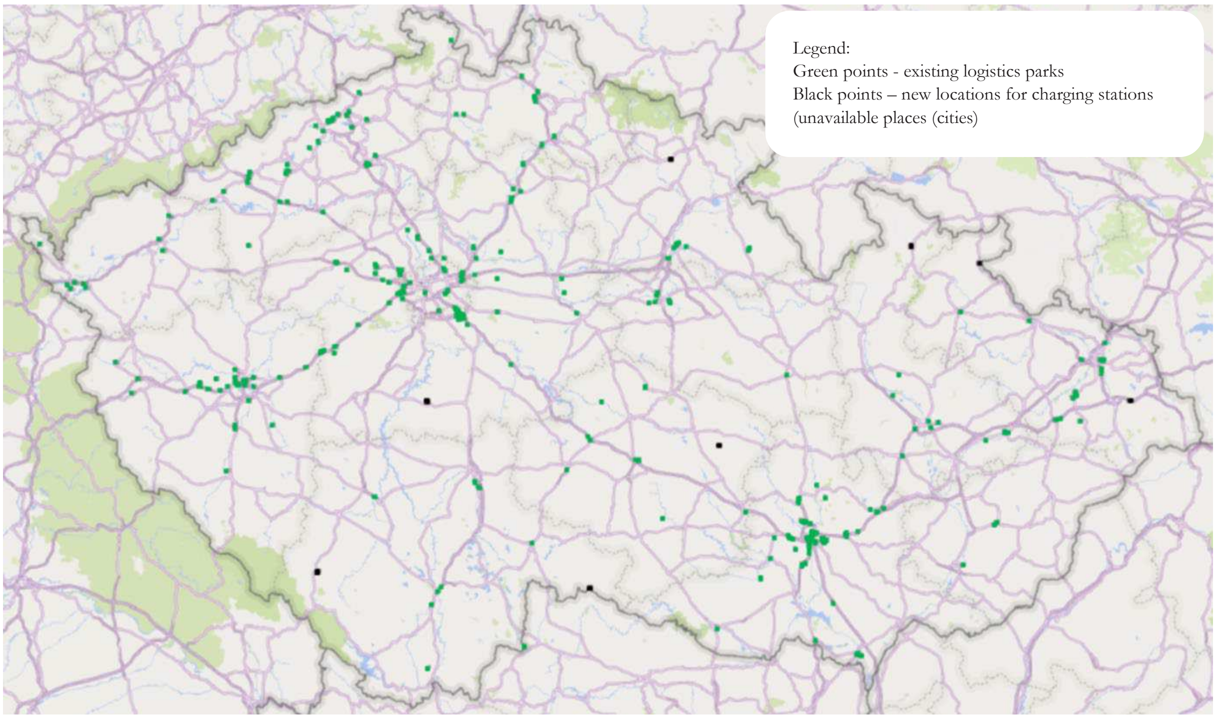

Figure A2. Visualization of charging station

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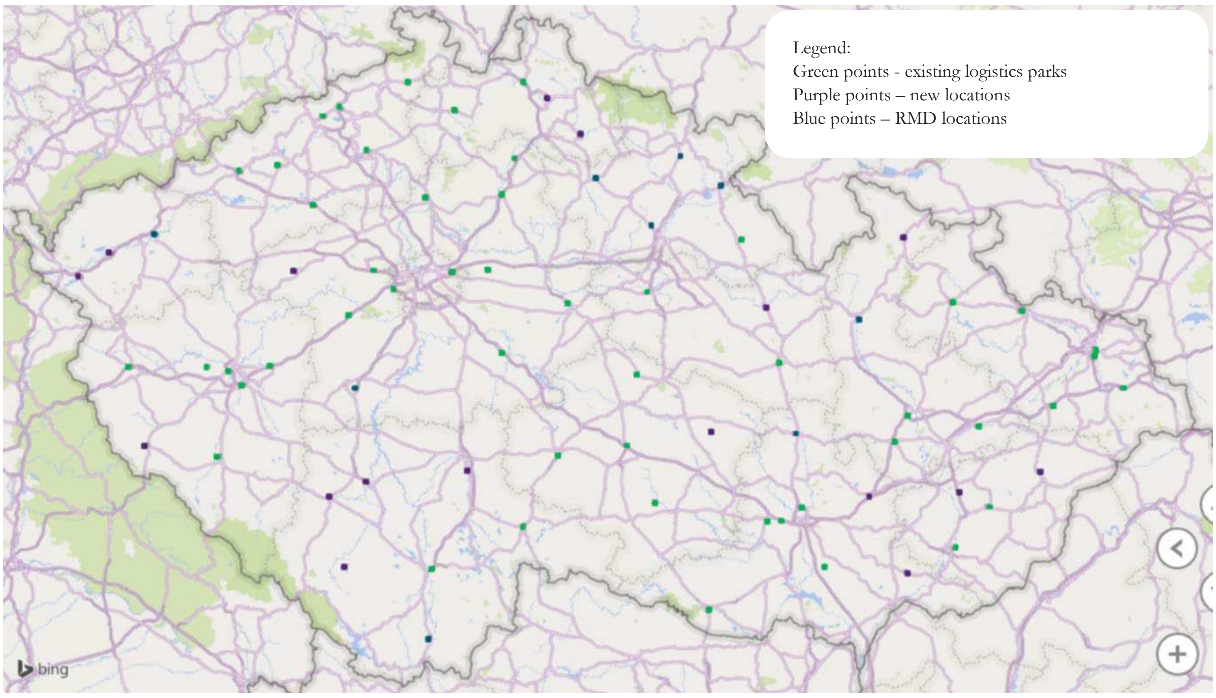

Figure A3. New location of charging stations for Czech districts