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COORDINATION OF OPTIMISATION TARGETS AT DIFFERENT LEVELS OF CHARGING INFRASTRUCTURE DEVELOPMENT MANAGEMENT

The work considers the problem of optimising the urban charging infrastructure as a multi-channel mass service system with a queue. Queues at charging stations are due to the shortage of energy resources in the studied region. An algorithm has been developed and implemented to optimise a charging station for electric vehicles based on the criterion of meeting charging demand has been developed and implemented. At the same time, the main parameters of the system during peak hours were taken into account. The algorithm allows to determine the optimal number of chargers at the station depending on the target value of the demand for charging in the customer radius area. To implement the charging station optimisation model, taking into account the requirements of the entrepreneur, an algorithm has been developed to determine the average queue length based on dynamic data structures. The algorithm is based on an object-oriented modeling paradigm and supports the possibility of using variable statistical values that change during the day. The optimisation algorithm in the charging infrastructure development management system at the business level uses parameters obtained at the customer and society levels. Thus, the connection between the levels of management of the development of the urban charging infrastructure and the possibility of their consistent application has been proven.

Keywords: charging infrastructure, electric vehicle, optimisation problem, queuing model.

1. INTRODUCTION

In order to meet the growing demand for electric vehicles, it is necessary to ensure uninterrupted and efficient charging. The application of programmes to optimise and develop the charging infrastructure will make it possible to easily expand their network as the demand for electric vehicles grows. There are several strategies for the development of

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charging stations: planning their placement (Thingvad at al., 2021; Unterluggauer at al., 2022; Liubyi et al., 2020; Zhenzhao, 2019; Gavranovic et al., 2014; Shengcan Yu, 2019; Hisatomo Hanabusa et al., 2011), development of fast charging infrastructure (Mohammed at al., 2024), integration with intelligent networks (Wadi et al., 2023; Sun et al., 2020), implementation of client incentive programmes (Azin et al., 2023), development of mobile applications and adapted on-line platforms, integration with renewable energy sources (Barman et al., 2023; Allouhi, Rehman, 2023). Most strategic solutions and existing optimisation methods can be adapted to manage the development of any enterprise and its infrastructure. The above strategies are generally defined by global or local social problems and rely on methods and algorithms based on forecasted charging demand. In the process of choosing a strategy, it is necessary to simultaneously take into account the goal of optimising the charging infrastructure from the point of view of various stakeholders. Śmieszek at al. (2023) performed a mathematical formulation of the problem of multi-criteria optimisation of the charging infrastructure for three vectors of development: based on the requirements of customers, entrepreneurs (businesses) and society. But the algorithm for solving the given task was developed only at the level of society's needs. The completed formulation of the problem does not take into account the load limitation that the network infrastructure can support. In addition, there is a difficulty in bringing the proposed objective functions to a common criterion due to the use of incompatible methods of their determination.

The requirements of different interested parties can be taken into account by agreeing on common parameters in separate optimisation criteria. If we consider a charging station as a mass service system, the number of charging points, the intensity of arrival of electric vehicles at the station, the average charging time and others can be determined among the common parameters. At the same time, the moments when customers arrive at a charging station in the model of a multi-channel mass service system are subject to the Markov (Poisson) distribution law (Mohammed at al., 2024). Based on the cost model for queuing systems (Taha, 2007) Śmieszek at al. (2023) proposed a criterion to optimise the charging infrastructure at the business level. The criterion minimises the sum of costs for servicing charging points and losses from delays of electric vehicles in the queue per unit of time. Gulbahar at al. (2023) also uses a queuing decision model to determine the optimal number of charging stations and charging points. Their cost model takes into account the cost of building a new charging station (if necessary), the cost of installing a new charger and penalty costs for not meeting charging needs on the motorway. This model is adequate only under the following assumptions: there is no queue, the electricity supply in the charging system is not limited, there are no electric trucks and motorcycles among the customers. The intensity of the arrival of customers at the station is determined based on the analysis of time series. In the described cost models (Śmieszek at al., 2023; Gulbahar at al., 2023), restrictions are imposed on their parameters.

This paper is a continuation of the authors' research on determining the demand for charging electric vehicles (Tarandushka et al., 2022) and modeling the task of optimising the charging infrastructure (Śmieszek at al., 2023).

The purpose of this article is to develop algorithms for optimising the charging infrastructure at the customer and business level based on queuing models. It is also important to integrate different levels of optimisation through the reconciliation of results obtained by different criteria.

The article consists of an introduction, three main sections and conclusions. The introduction substantiates the relevance of the research topic, defines the purpose of the research. In the first section, the approach to solving the optimisation problem at the level of customers of the charging station is considered. The second chapter describes the charging station optimisation algorithms at the business level. In the third, the relationship between the levels of development of the charging infrastructure is defined; an attempt is made to integrate three optimisation criteria in the generalized algorithm. The conclusions highlight the strengths and weaknesses of this study, as well as directions for future research.

2. IMPLEMENTATION OF THE GOAL AT THE CLIENT LEVEL

In the course of a previous study (Tarandushka et al., 2022), the task of designing a new network of charging stations for electric vehicles was solved based on the number of electric vehicles predicted for 2025 in the city of Cherkasy, Ukraine. The number of electric cars was determined by the profile of a potential owner of an electric car. Due to martial law, there is a lack of financial resources for complete restructuring of charging station networks in small cities in Ukraine. Based on this, it is urgent to reorganise the work of individual stations in the existing network.

We will consider a city charging station for electric cars as a queuing model of the (M/M/*c*) type, where *c* – the number of charging places (Mohammed at al., 2024). Then, within the customer radius, the target function of the station optimisation problem (Śmieszek at al., 2023) at the customer level can be reduced to a ratio that determines the proportion of satisfied demand among the incoming customer flow:

$$TF_1 = \frac{EfDemand}{ForecDemand} \sim \frac{\lambda_{eff}}{\lambda} = \frac{(1-p_N)\times\lambda}{\lambda} = 1 - p_N \rightarrow Threshold \quad (1)$$

where *EfDemand*, *ForecDemand* – effective and predicted charging demands, respectively (Śmieszek at al., 2023), λ, λ_{eff} – the intensity and effective intensity of customers visiting the charging station, p_N – steady-state probability of n clients, *N* – station capacity (number of places for charging (station capacity) and additional places for waiting), *Threshold* – target value, which is determined from given additional conditions.

The EcoFactor Charging Station, Cherkasy, Ukraine, was chosen as the research object. This station contains 7 charging points. Śmieszek at al. (2023) investigated the state of the electric vehicle fleet in Ukraine and showed that the most popular brand in the Cherkasy region is the Nissan Leaf. Therefore, we will take the average indicators of the mass service system for this model. The EcoFactor Charging Station is equipped with three chargers for Nissan Leaf. The station is located in the city centre. Within a radius of 500 m from the station, there is a central market, a shopping centre, office premises, residential buildings, a stadium, the Main Department of the National Police of the region, small shops, city transport stops. The client radius area is very busy. The main roads of the city pass here. Many visitors from other cities in the Cherkasy region enter the customer radius every day. The situation is complicated by the fact that, starting from February 2022, there are many refugees from the occupied territories in this region. Therefore, it is not possible to calculate the intensity of the incoming flow of customers based on the number of registered cars in the customer radius area.

According to Taha (2007), the probability that there will be no free places on the territory of the station is determined as follows:

$$p_N = \frac{\rho^N}{c!c^{N-c}} \times p_0 \quad (2)$$

$$p_0 = \left[\sum_{n=0}^{c-1} \frac{\rho^n}{n!} + \frac{\rho^c\left(1-\left(\frac{\rho}{c}\right)^{N-c+1}\right)}{c!\left(1-\frac{\rho}{c}\right)}\right]^{-1}, \rho \neq c \tag{3}$$

$$p_0 = \left[\sum_{n=0}^{c-1} \frac{\rho^n}{n!} + \frac{\rho^c}{c!}(N-c+1)\right]^{-1}, \rho = c \tag{4}$$

where ρ – the intensity of the outgoing flow of customers of the station, $\rho = \lambda/\mu$.

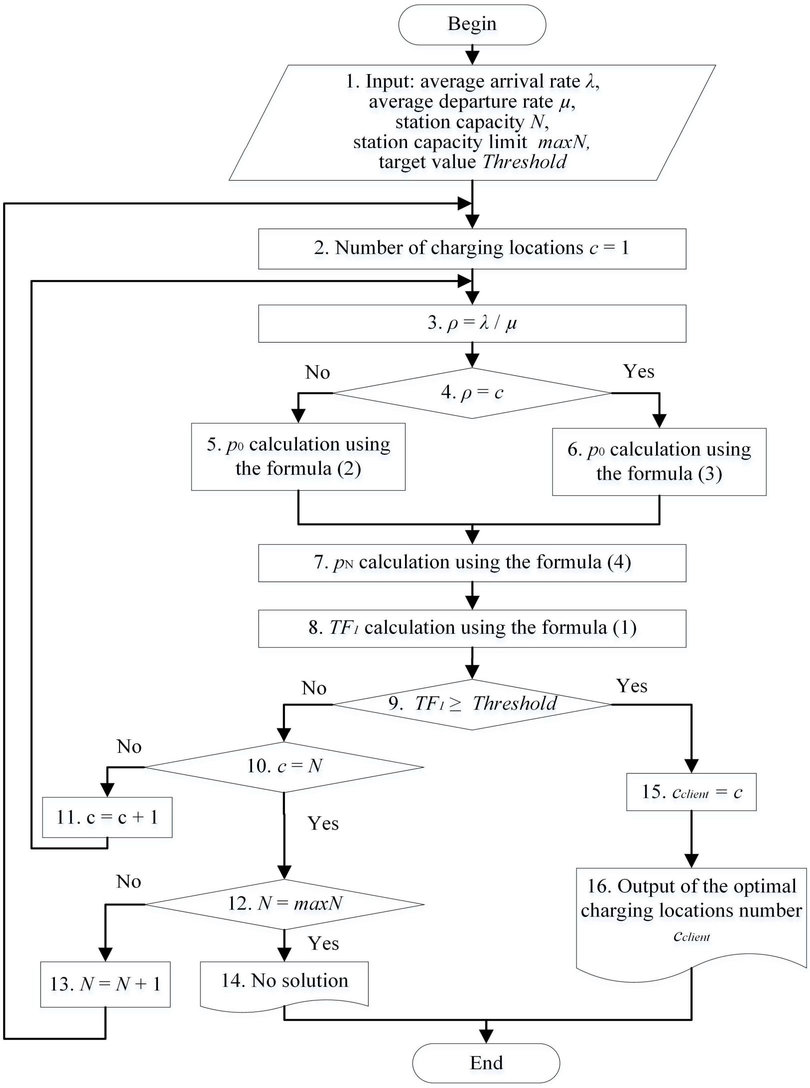

Figure 1. Optimisation algorithm at the client level
Source: own work.

The optimisation parameter is the number of charging places c under the condition of the constant power of the station N. The power of the station can be increased subject to the available land and financial resources, which are determined by the constraints of the optimisation task at a higher level of management (levels of society). If correlations between the power of the station and other system parameters are determined, then it is appropriate to choose the customer radius and the customer loyalty ratio as optimisation parameters (Śmieszek at al., 2023). A consolidated optimization algorithm at the client level is presented in Figure 1.

Based on observations and a questionnaire of Nissan Leaf owners, it was determined that the average daily frequency of visits to the λ station is 7 car/hour, the time for fast battery charging for the Nissan Leaf t_{charge} – 30 min, μ=0.5 car/hour. Nissan Leaf cars can use 3 of the seven charging points, c=3. The station has two additional parking spaces for station customers only. Therefore, the capacity of the station is N=5 cars. The maximum station capacity N_{max} s determined on the basis of social indicators (Śmieszek at al., 2023). Taking into account the lockdowns and peak hours at this station, there was often a queue for charging points. Despite the availability of parking spaces along the adjacent streets, all of these spaces are usually occupied. Electric cars that did not get to the station are forced to look for another charging station. When determining the optimal number of charging points, it is not enough to take into account only the average length of the queue. It is necessary to take into account the maximum possible length of the queue during peak hours. Because we accept the target value of customer satisfaction *Threshold*=0.9. That is, only 10% of electric car owners are expected to be able to get to the station. Intermediate results on individual iterations of the algorithm (Figure 1) are shown in Table 1.

Table 1. Intermediate results of the charging station optimisation algorithm at the client level

N	***c***	p_0	p_N	TF_1
5	1	0.001360718	0.714674491	0.2853
5	2	0.013712204	0.450119178	0.5499
5	3	0.027906526	0.271426495	0.7286
5	4	0.033904665	0.185493395	0.8145
5	5	0.035210945	0.154112070	0.8459
6	1	0.000388625	0.714396750	0.2856
6	2	0.007670268	0.440624707	0.5594
6	3	0.021194869	0.240504932	0.7595
6	4	0.029170153	0.139641901	0.8604
6	5	0.031782318	0.097373903	0.9026
6	6	0.032306621	0.082483543	0.9175

Source: own work.

The values of TF_1 in Table 1 show that increasing the number of charging places at the expense of parking places does not give the target value of customer satisfaction. It is necessary to increase the capacity of the charging station by one place N=6 cars. At the same time, the minimum number of chargers is c=5, and the minimum number of additional waiting places is 1.

3. IMPLEMENTATION OF THE GOAL AT THE BUSINESS LEVEL

At the business level, the charging station optimisation target is set by a cost model (Śmieszek at al., 2023). This model attempts to balance service costs with service delay losses. The last indicator depends linearly on the length of the formed queue. To determine the average length of the queue, an algorithm is proposed, the block diagram of which is presented in Figure 2. The algorithm is based on the use of a dynamic data structure Queue.

The main subroutines for working with the Queue have been applied for the specified structure: checking the fullness of the queue QU.IsEmpty(), determining the current number of electric cars in the queue QU.GetCount(), adding to the queue QU.Add() and removing electric cars from the queue QU.Extract(), obtaining the time intervals between the arrivals of individual electric vehicles at the charging station QU.GetWait(), viewing the current state of the queue QU.Show().

The algorithm simulates the movement of electric vehicles at the charging station during the day (arrival at the station, waiting in line and at charging points, departure). At stages 1-5, initial statistical information is entered. At stage 7 a queue is formed, which is empty at the beginning of the algorithm. At the beginning of a new day, the counter of electric vehicles that have arrived at a charging station is assigned a zero value (stage 8).

The cycle counter (step 9) takes the value of the current time of day from the beginning to the end of the movement in minutes. The traffic at the charging station can last 18 hours (from 5:00 a.m. to 11:00 p.m.). A curfew has been implemented in the region at night due to the introduction of martial law on the territory of the country. At each iteration of the cycle, it is checked which period of the day the current time belongs to (stage 10), as well as the conditions for the arrival of a new electric vehicle at the station (stage 13) and the performance of fast charging (stage 15). If conditions 15 and 19 are fulfilled, then the first electric car in order is removed from the queue (stage 20) and the total waiting time of all customers who used the services of the charging station (cycle 22) is calculated according to formula (5):

$$WaitTime = \sum_{j=1}^{n} \sum_{k=1}^{L} Wait_{jk} \tag{5}$$

where n – the number of electric cars that have reached the charging points and therefore are removed from the queue, L – the current length of the queue, $Wait_{jk}$ – the arrival interval between electric cars in the queue after the j-th customer (may differ depending on traffic intensity).

Thus, the waiting time of each customer is defined as the sum of the time intervals between the arrival of those electric cars that managed to drive to the charging station for the given k-th electric car until the moment it is connected to the charger.

The algorithm provides a review of the current status of the electric vehicle service system at the charging station in 30-minute increments. The average length of the queue can be determined in alternative ways to stage 25 if it is impossible to determine the effective intensity of arrivals at the station.

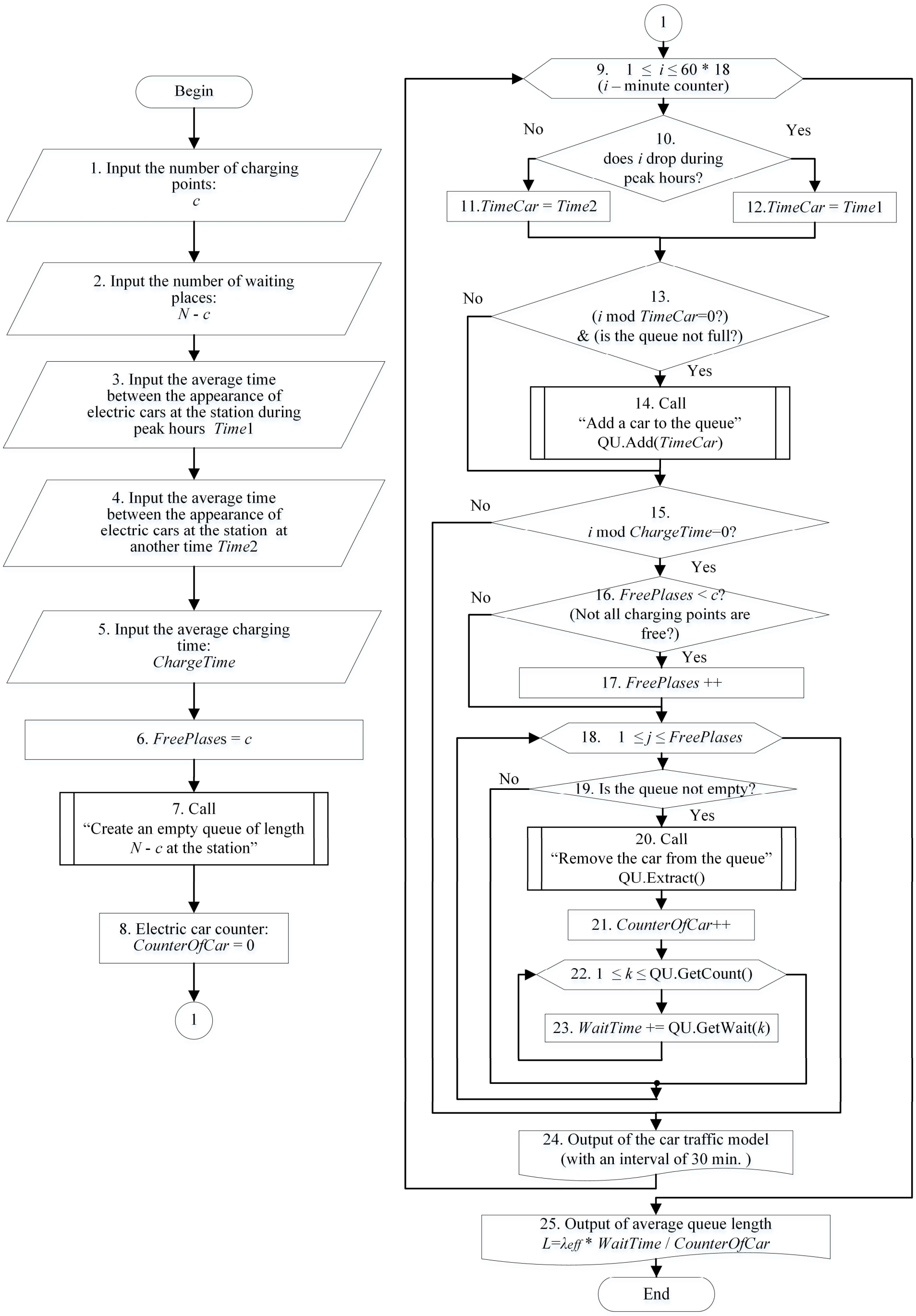

Figure 2. Defining the parameters of the target function at the business level

Source: own work.

The optimal capacity of the charging station (number of chargers) is determined similarly to the model at the client level. The objective function at the business level (TF_2) is correlated with the average queue length (Śmieszek at al., 2023). Therefore, we repeat the algorithm (Figure 2) each time when the number of chargers c increases by 1. In the previous iterations, TF_2 increases when c increases. When TF_2 decreases, the execution of iterations is completed. The optimal value of the chargers is taken to be c, which corresponds to the maximum value of TF_2. In this way, a balance is achieved between service costs and customer losses.

4. CONCLUSIONS

Based on previous research (Śmieszek at al., 2023), it became possible to develop algorithms for multi-criteria optimisation of charging stations in the management system for the development of charging infrastructure at the client and business level. It turned out to be impossible to combine the target functions of different levels of management into an integral function for the given task, since the implementation of the goal at the level of society is not based on analytical dependencies, but on the use of soft technologies. When applying the algorithmic approach, it was possible to combine the procedures for achieving individual optimisation goals into a single logical sequence. The algorithms developed in this article are fully consistent with the optimisation algorithm at the level of society in a multi-level management system (Śmieszek at al., 2023). In the formulated optimisation problem, the charging station is considered as a multi-channel mass service system with a queue. The existence of a queue is justified based on the conditions of operation of the network of charging stations in the studied region. The existing methods for determining the structure and capacity of the charging infrastructure do not ensure the adequacy and implementation of appropriate models and methods in unstable conditions of shortage of energy resources. The proposed method will allow to reduce financial costs in the process of managing the development of the charging infrastructure and takes into account the specifics of the location. At the level of society, the limitations of the parameters of the charging infrastructure are identified, and requirements regarding the energy efficiency, environmental friendliness and safety of the stations are formed. Identified limitations must be taken into account at the client and business level. At the customer level, the effective demand for charging and the minimum number of charging points are determined. This value is specified at the level of the entrepreneur and is within the limits defined at the other two levels of management. In this study, the case where the charger is operated by an electric vehicle of another brand (in the presence of several connectors) was not foreseen. This case reduces the power of the station. Additionally, there are no ways to determine the target threshold at the client level. The problem is solved under the condition of a probable loss of 10% of the forecasted demand for station services. Further research will be aimed at extending the proposed methodology to the urban network of charging stations for electric vehicles.

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