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An Optimisation Method for the Micro-Engineering Upgrade of Urban Electric Vehicle Charging Infrastructure based on Queueing Theory and Graph Theory

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Abstract

Addressing key engineering challenges in existing urban areas-such as the mismatch between supply and demand for electric vehicle charging infrastructure, queuing and congestion, and construction-related disturbances to residents-this paper takes Fengrun District in Tangshan City, Hebei Province, as its study area. It proposes a three-tiered, progressive micro-renewal approach comprising 'macro-queuing theory diagnosis-micro-graph theory optimisation-low-impact construction implementation', thereby establishing a complete technical closed-loop process ranging from bottleneck identification and precise optimisation to construction implementation. Firstly, by comprehensively utilising KNN, Linear SVM and RBF SVM algorithms, the study systematically identifies user charging behaviour patterns, issues early warnings for facility anomalies and assesses battery health, thereby providing data support for subsequent optimisation. Secondly, an asymmetric double-queue queuing theory model is constructed to conduct a macro-level performance diagnosis of charging stations serving local users in the core area of Fengrun District, accurately identifying and locating bottleneck sites requiring optimisation. Thirdly, by selecting these bottleneck sites and establishing an undirected graph model, the Dijkstra shortest path algorithm is applied to optimise the layout of charging piles and vehicle guidance strategies, thereby achieving a balanced improvement in pile utilisation rates; Furthermore, by integrating key factors affecting user charging costs and construction disruption, we conducted scientific measurement and quantitative analysis to design a low-impact construction plan that integrates Gantt charts, network diagrams and BIM technology, ensuring the efficient implementation of the optimisation plan whilst simultaneously enhancing the user charging experience and the operational efficiency of the construction team. SimPy discrete-event simulation results indicate that, following the application of the method proposed in this paper, the average queuing time at bottleneck sites is reduced by 39.9%-45.5%, users' average daily charging costs decrease by 15.0%-16.4%. This significantly reduces disruption to surrounding traffic and residents' daily lives, effectively safeguarding users' needs for convenient and economical charging whilst significantly improving contractors' operational efficiency and reducing construction costs and safety risks. The three-tier progressive micro-upgrade method proposed in this paper achieves a closed-loop process spanning regional bottleneck identification, precise on-site optimisation, and construction implementation. It provides a systematic technical pathway and practical reference for the micro-upgrade of charging infrastructure in existing urban areas, effectively balancing the dual benefits for both users and contractors.

Keywords

Charging Infrastructure; Micro-renovation; Low-impact Construction; Operations Research Models.

1. Introduction

With the rapid growth in the number of new energy vehicles, the imbalance between supply and demand for electric vehicle charging facilities in existing urban areas is becoming increasingly acute[1]. Prominent issues such as excessively long queues for charging[2], haphazard facility layout[3] and significant construction disruption have become engineering bottlenecks hindering the large-scale promotion and adoption of electric vehicles. This situation not only severely undermines the charging experience and willingness to use electric vehicles among users, but also significantly increases the difficulty and cost of renovation for construction companies, hindering the coordinated advancement of the new energy vehicle industry and urban infrastructure development[4].

As a key hub district within Tangshan City, Fengrun District [5] has seen rapid annual growth in the number of new energy vehicles in recent years. The district's main charging stations primarily serve local residents and commuters, with queuing times during peak hours reaching several hours. Key user feedback centres on issues such as congestion caused by queues for charging, uneven utilisation of charging points, insufficient convenience, and poor cost-effectiveness [6]. Core charging needs have not been effectively met, and the imbalance between the supply of charging infrastructure and user demand is particularly pronounced [7], having become a major constraint on the promotion and application of new energy vehicles in the region.

At the same time, the construction of traditional charging points typically involves extensive excavation and the casting of in-situ concrete foundations [8], with construction periods for a single site lasting as long as 7 to 15 days. This not only substantially increases contractors' labour, material and time costs, but also poses safety hazards such as road surface damage and damage to underground utilities; furthermore, the construction process severely disrupts local traffic flow and residents' daily lives [9], running counter to the principles of low-impact, high-quality renovation advocated in micro-renewal projects within existing built-up areas. This not only hinders contractors' ability to improve operational efficiency and control construction costs, but also makes it difficult to establish a positive reputation for their work, thereby further constraining the orderly progress of charging infrastructure retrofitting projects [10]. Furthermore, during the operational phase of existing charging facilities, there is a lack of effective mechanisms for early warning of abnormal conditions and assessment of battery health. Relying solely on a single monitoring method for basic data collection and analysis makes it difficult to proactively avoid issues such as charging point failures and battery damage [11]. This not only affects the user charging experience but also shortens the service life of the facilities; consequently, this issue has become one of the key challenges to be addressed in the current micro-renewal initiative for charging facilities in existing built-up areas.

Currently, research on the optimisation of electric vehicle charging infrastructure, both domestically and internationally, primarily focuses on two key areas: firstly, the macro-level site selection and capacity planning of charging stations [12], where researchers predominantly employ methods such as operations research and topological analysis to achieve the overall optimal allocation of charging resources within a region and enhance the coverage efficiency of regional charging services [13]; secondly, the optimisation of charging point scheduling strategies at the micro level, with research centring on the allocation of charging points within individual stations and the regulation of charging sequences [14], aiming to improve the service efficiency and utilisation rate of charging points at individual stations.

2. Research Area and Analysis

(1)Overview of the Study Area

Tangshan (39°36′–40°26′N, 117°31′–119°19′E) is an industrial hub in the Beijing-Tianjin-Hebei region. The central urban area covers 1,493 km², with a topography characterised by ‘hills in the north and plains in the south’; the northern hills account for 38.9% of the area, whilst the southern plains account for 61.1%. In 2023, the market for new energy private vehicles in Tangshan experienced rapid growth, with the total number of new energy vehicles reaching 84,300 for the year, accounting for 3.2% of the city’s total vehicle fleet. Of these, private vehicles accounted for over 70%, primarily used for family commuting and short-distance urban travel. Popular models such as the BYD Song PLUS New Energy, Qin PLUS and Tesla Model Y dominate the market, with monthly sales in March 2023 reaching 242, 226 and 195 units respectively. In terms of charging infrastructure, the city has installed 13,665 public charging points, forming a “three vertical, three horizontal” energy supply network.

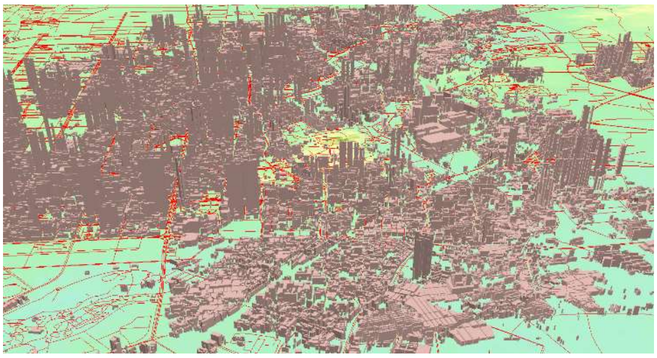


Figure 1. 3D modelling of buildings, roads and elevation in the city centre’s core district

The vector data on administrative divisions is sourced from the National Geographic Information Public Service Platform (Tianditu CGCS2000). The data is in GeoJSON format and uses the GCS_WGS_1984 coordinate system. For the purposes of this paper, the data has been converted to SHP format. Additionally, building outline data for the city’s central urban area has been extracted from Tianditu.

(2)User Research and Analysis in Tangshan

In order to identify and analyse the sentiment expressed in the comments, we conducted sentiment analysis on the transcripts of interviews with users surveyed in Tangshan:

$$N(w)=\sum_{q\in w}O(w)\times I(w) \tag{1}$$

Here, N represents the sentiment score of text w, q represents a sentiment word, O represents the sentiment polarity. Where positive sentiment is denoted by +1 and negative sentiment by -1. And I represents the sentiment intensity weight.

For Chinese comments, the Snow NLP sentiment analysis model is employed. The core of the Snow NLP sentiment analysis model is the Naive Bayes model:

$$P\left(G_i \middle| X_1,X_2,\ldots,X_n\right)=\frac{P\left(G_i \middle| X_1,X_2,\ldots,X_n \middle| G_i\right)}{P\left(X_1,X_2,\ldots,X_n\right)} \tag{2}$$

Here, the random variable G represents the probability of positive or negative sentiment for that category; X represents the probability of a particular feature word appearing in the test sample. When calculating the positive or negative sentiment of each review text, the calculated prior probability P is multiplied by the conditional probability of each of its attribute feature words; finally, the sentiment probability value for each review text is obtained. These values are then compared, and the sentiment assigned to the text is determined by selecting the value with the higher positive or negative sentiment.

Calculations show that approximately 50% of users exhibit a positive sentiment, around 40% exhibit a negative sentiment, and about 10% exhibit a neutral sentiment. Therefore, there remains significant room for improvement in the optimisation of new energy vehicle charging stations, and further analysis of user sentiment is warranted.

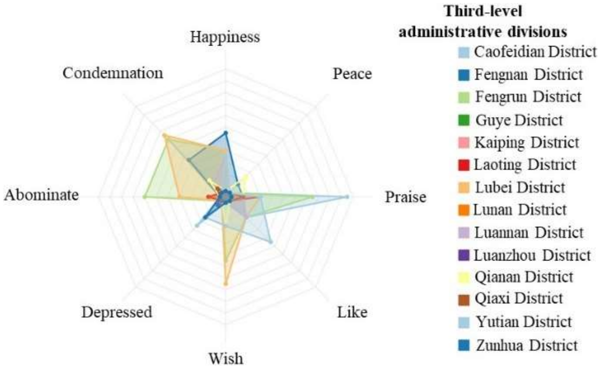


Figure 2. Emotional Radar Chart

Analysis of the multi-dimensional sentiment radar chart reveals that Caofeidian District performs particularly well on the ‘Praise’ dimension; Fengrun District scores highly on the ‘Abhorrence’ and ‘Condemnation’ dimensions, whilst its ‘Praise’ score also remains at a relatively high level. This reflects a marked imbalance in local users’ emotional attitudes, indicating that there is still considerable scope for improving the service experience. The remaining districts each exhibit distinct distribution patterns across different emotional dimensions. In summary, utilising the findings of this multi-dimensional sentiment analysis to implement targeted optimisations and improvements to the operation of regional charging stations holds significant practical and social value.

(3)Overview of Charging Facilities

Fengrun District in Tangshan currently has 127 public charging stations of various types, distributed across key areas such as motorway service areas, transport hubs, commercial buildings and residential estates, forming a charging network that covers the entire district. Among these, stations located in motorway service areas and transport hubs are predominantly equipped with fast-charging points, primarily serving passing vehicles; whereas stations in residential estates and commercial buildings offer both fast and slow charging options, primarily serving local residents and commuters.

Figure 3. Map of charging points in Fengrun District

(4)User-centred classification algorithm

In the context of new energy vehicle charging, the application of user-oriented classification algorithms is primarily evident in three typical scenarios; the core logic lies in enabling precise analysis and decision support through multi-source data accessible to users.

In the context of identifying user charging behaviour patterns, the primary objective is to accurately distinguish between home charging and public fast charging, thereby providing a basis for charging resource planning and time scheduling. The data for this scenario is derived from multi-dimensional information directly accessible to users, including the start time of charging recorded via mobile applications, the type of charging location, the initial battery level displayed on the in-vehicle terminal, and the duration of each charging session recorded by the application. Three types of classification algorithms demonstrate varying levels of effectiveness in this scenario: the K-nearest neighbours algorithm, which relies on matching local features of historically similar samples, is capable of capturing the local specificity of user behaviour-such as charging patterns during fixed time periods-but is prone to classification errors in scenarios involving sporadic behavioural variations, with an accuracy rate of 0.93; Linear Support Vector Machines (SVM) construct hard-boundary classifications based on linear decision rules, using duration thresholds to identify patterns. The model offers high interpretability and low computational complexity, but struggles to handle non-linear scenarios involving multi-feature interactions, with an accuracy of 0.85; Radial Basis Function Support Vector Machines (RBFSVM) achieve non-linear classification by integrating temporal, spatial and state features. They possess adaptive learning capabilities for complex feature interactions and have no significant limitations, with an accuracy rate of 0.96. Overall, the RBFSVM algorithm effectively addresses the complexity and variability of behavioural patterns through multi-dimensional feature integration, demonstrating the best performance in the construction of user behavioural profiles.

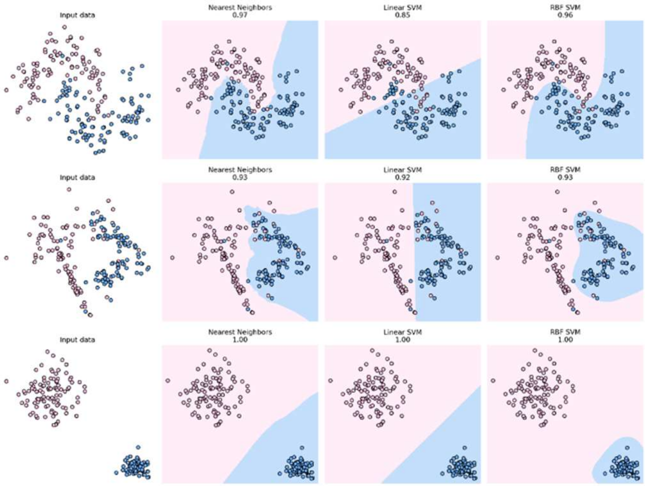


Figure 4. Comparison of classification algorithms for various charging scenarios of electric vehicles

The charging station anomaly alert scenario focuses on the early detection of operational anomalies in charging stations, with the aim of avoiding time losses and the risk of battery damage caused by interrupted charging. Data for this scenario is sourced from two channels: firstly, real-time anomaly alerts pushed via mobile applications or in-vehicle terminals; and secondly, historical characteristics of previous charging anomalies recorded by users. There are significant differences in the operational mechanisms of the three algorithms: the KNN algorithm achieves early warning through feature matching based on historical fault samples; whilst it demonstrates high accuracy in identifying recurring fault patterns, it has blind spots when it comes to new fault patterns, with an accuracy rate of 0.93; LinearSVM relies on a single threshold to establish rigid early warning rules; whilst the model is simple to deploy and responds quickly, it struggles to identify complex anomalies resulting from the coupling of multiple factors, with an accuracy rate of 0.92; RBFSVM employs non-linear correlation analysis of multi-dimensional anomaly features, possessing the capability to uncover hidden fault patterns with no significant limitations, and an accuracy rate of 0.93. Practical experience indicates that RBFSVM is more suitable for anomaly early warning in complex charging environments, whilst LinearSVM can serve as a rapid early warning solution in simpler scenarios, offering practical value in resource-constrained environments.

The battery health assessment scenario aims to classify batteries into healthy or maintenance-required states through the analysis of key parameters, thereby providing users with a basis for battery maintenance decisions and helping to prevent sudden reductions in range and excessive maintenance costs. The core data for this scenario includes the number of charge-discharge cycles displayed on the in-vehicle terminal, the ratio of actual range to rated range, and the proportion of fast-charging sessions recorded by the user. All three algorithms demonstrated ideal performance in this scenario: KNN, which relies on feature similarity matching based on a healthy sample database, achieved high recognition accuracy in scenarios with clear feature distributions, with no significant limitations and an accuracy rate of 1.00; LinearSVM, which performs classification through an iterative-decay linear relationship, is a lightweight model with strong real-time capabilities, with no significant limitations and an accuracy rate of 1.00; RBFSVM integrates multi-dimensional attenuation factors for non-linear modelling, possesses predictive adaptability to long-term performance evolution, has no significant limitations, and achieves an accuracy rate of 1.00. In practical applications, LinearSVM is suitable for rapid real-time diagnosis, RBFSVM is better suited to complex attenuation patterns encountered during long-term use, whilst KNN can achieve high-precision matching when sufficient samples are available.

3. An Asymmetric Two-queue Queuing Model from a Macro Perspective

(1)Model development

Given that charging stations in Fengrun District are generally characterised by the separate arrangement of fast and slow charging points, each charging station is treated as an asymmetric double-queue M/M/m queuing system, with separate models developed for the slow-charging and fast-charging queues.

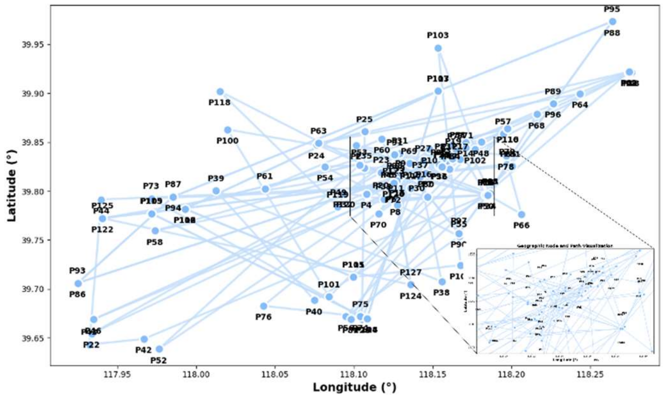


Figure 5. Map of charging station locations in District

Assume that, during the arrival process, the arrivals at both the slow-charging station queue and the fast-charging station queue follow a Poisson distribution, and the arrival rates are independent of one another; During the service process, the service time for a single charging point follows a negative exponential distribution, and there is a difference in service rates between slow-charging and fast-charging points; the queuing rule adopted is first-come, first-served (FCFS), with users queuing only for the corresponding type of charging point and not switching between queues; regarding system stability, it is assumed that the total arrival rate is less than the total equivalent service rate, ensuring that the system can reach a steady state.

Solve for the steady-state average waiting time of the system using an approximate analytical method:

$$W_q = \frac{\lambda_A / \tilde{\mu}_A^2 + \lambda_B / \tilde{\mu}_B^2}{1-(\lambda_A / \tilde{\mu}_A + \lambda_B / \tilde{\mu}_B)} \tag{3}$$

In particular, lambda_A(t) is the instantaneous arrival rate of the slow-charging station queue, which varies with time t and is obtained by fitting historical charging data; lambda_B(t) is the instantaneous arrival rate for the fast-charging station queue, which varies with time t; taking into account the impact of time-of-use pricing policies, it is multiplied by 1.25 during peak periods, by 0.7 during off-peak periods, and remains unchanged during standard periods;mu_A is the service rate per slow-charging station, derived from the average duration of a single charging session; in this paper, the value is set tomu_A = 0.5 vehicles/h, i.e. the average duration of a single charging session is 2 hours;mu_B is the service rate per fast-charging station; similarly, in this paper, we setmu_B = 2.0 vehicles/h, i.e. the average duration of a single charging session is 30 minutes; m_A is the number of slow-charging stations at the site; m_B is the number of fast-charging stations at the site;tilde{mu}_A is the equivalent service rate of the slow-charging station queue,tilde{mu}_A = m_Atimesmu_A;tilde{mu}_B is the equivalent service rate of the fast-charging station queue,tilde{mu}_B = m_Btimesmu_B;rho_A is the service intensity of the slow-charging station queue,rho_A =lambda_A /tilde{mu}_A, reflecting the level of congestion in the slow-charging station queue;rho_B is the service intensity of the fast-charging station queue,rho_B =lambda_B /tilde{mu}_B, reflecting the level of congestion in the fast-charging station queue; W_q is the steady-state average waiting time of the system; it is a key performance indicator reflecting the level of congestion in the station queues.

In the equation, the denominator represents the system stability condition; this term must be greater than zero, i.e. the total arrival rate must be less than the total equivalent service rate, otherwise the system will enter an unstable state characterised by infinite queue growth; When W_q > 15 minutes, this indicates severe congestion at the station, which should be prioritised for inclusion in the scope of minor updates; this model represents a typical multi-class, multi-server queuing system with delay, and its evolution can be viewed as a stochastic process. By solving the system of equilibrium equations to determine steady-state metrics, it is possible to accurately characterise the queuing behaviour at the station.

(2)Model results

A peak period on a weekday (17:00–20:00) was selected as the diagnostic period, as this is the peak charging period for users and best reflects queuing bottlenecks at charging stations. Based on the aforementioned model, the queuing performance of 127 charging stations in Fengrun District was calculated, with 41.73% of stations experiencing congestion. System metrics for four randomly selected core stations are shown in Table 1.

Table 1. System metrics for randomly selected stations

Site	Number of slow-charge /fast-charge points	Fast-charging queue arrival rate	Steady-state average waiting time
1	0/8	9.2	21.3
2	0/8	8.5	18.7
3	0/4	4.6	15.8
4	4/12	7.9	<10

4. A Graph-theoretic Model within a Site from a Micro-level Perspective

(1)Model development

For sites experiencing bottlenecks, the layout of charging point clusters and vehicle guidance strategies are optimised at a micro-level. The core approach involves modelling the charging station as a directed graph G = (V, E), using shortest-path analysis to identify bottleneck nodes in the layout, thereby achieving a dual improvement in both vehicle throughput and charging point utilisation.

In this context, the node set V={v_0, v_1, v_2, ..., v_n} is defined to include the charging station entrance, the charging points, and the exit, with each node representing a key access point; The edge set E={e_{ij} | v_i, v_jin V, ineq j} comprises the connected paths between nodes, where e_{ij} denotes a directed edge from node v_i to node v_j; Edge weight w_{ij} denotes the travel time for a vehicle on edge e_{ij}, determined by factors such as the actual terrain of the site, lane width and turning radius, with values ranging from 5 to 30 seconds; Accessibility A_i is the accessibility of node v_i, defined as the minimum travel time from the entry node v_0 to that node, A_i=min{w_{0i}, w_{0k} + w_{ki}, ...}; the smaller the accessibility value, the better the accessibility of the node.

The primary optimisation objective is to minimise the total time vehicles spend within the station whilst balancing the utilisation rates of each charging point. The mathematical expression is as follows:

$$\min T_{total} = \sum_{i=1}^{k} \left(A_i + W_i \right) \times N_i \tag{4}$$

The constraints are as follows:

$$\max\{U_i\} - \min\{U_i\} \le \Delta U \tag{5}$$

In the equation, T_{total} represents the total time a vehicle spends within the station; A_i represents the accessibility of the i-th charging point; W_i represents the average waiting time at the i-th charging point; N_i represents the average daily number of vehicles served at the i-th charging point; U_i represents the utilisation rate of the i-th charging point; ΔU is the maximum permissible deviation in charging point utilisation; in this paper, a value of 20% is adopted to ensure balanced utilisation.

(2)Model results

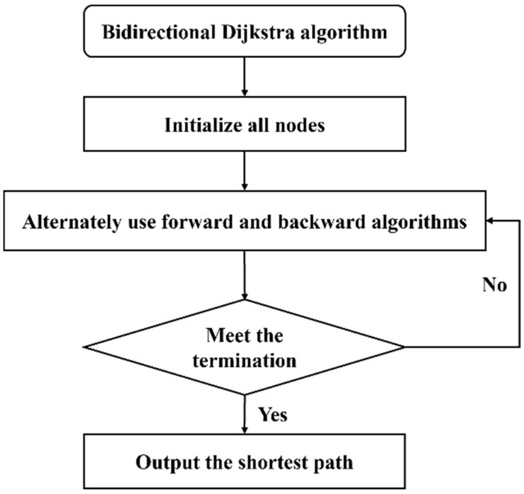


Figure 6. Flowchart of Dijkstra’s algorithm

The Dijkstra algorithm is employed to calculate the shortest paths from the entry node to each pile position node. The core steps of the algorithm are as follows: first, initialisation is performed, setting the shortest path length for the entry node to zero and that for all other nodes to infinity, whilst marking all nodes as unvisited; second, the iteration proceeds by selecting the smallest unvisited node at each step, marking it as visited, traversing all outgoing edges of that node, and updating the shortest path lengths for those nodes; Finally, the termination phase: when all docking station nodes have been visited, the iteration ends; at this point, dist[i] represents the shortest travel time from the entry node to the i-th docking station node. This algorithm identifies docking stations with poor accessibility and low utilisation rates, thereby enabling the formulation of targeted layout optimisation and vehicle guidance schemes to achieve balanced docking station utilisation and improved traffic efficiency.

Based on the results of the macro-level queueing theory model, three bottleneck sites were selected at random for optimisation design:

Site 1 is a standard ground-level charging station, primarily serving the daily charging needs of local residents and commuters. Prior to optimisation, it employed a symmetrical dual-row, dual-side layout, equipped with a total of 12 fast-charging points. The current issue is that the charging points on either side are situated on opposite sides of the carriageway, requiring vehicles to cross lanes to reach the opposite side, resulting in redundant travel routes and poor accessibility to the opposite-side points; there is a significant disparity in utilisation rates between the charging points on either side. Those near the entrance are consistently overloaded with queues, whilst the opposite-side points remain underutilised, creating a marked imbalance in demand. This severely undermines overall charging efficiency and the user experience. Analysis using micrograph theory models reveals that the travel distance from the opposite-side charging points to the entrance is more than double that of the same-side points, with a difference in travel time exceeding 80%. This extreme disparity in accessibility is the core cause of imbalanced charging point utilisation and localised congestion; simultaneously, crossing lanes increases the risk of vehicle collisions. The proposed optimisation scheme therefore utilises the ample longitudinal space available on the site to adjust the dual-row, dual-side layout to a compact configuration comprising a single row in the same direction supplemented by localised dual-row sections. Without reducing the 4-metre width of the traffic lanes, the single row can accommodate 12 charging bays; combined with the localised dual-row areas, the total number of bays increases from 12 to 15, significantly enhancing service capacity; At the same time, by standardising the direction of vehicle traffic and eliminating the need to cross lanes, the difference in access times between all charging points is kept within 15%, ensuring a balanced distribution of charging point utilisation. This scheme achieves the dual objectives of capacity expansion and efficiency optimisation through layout restructuring. The unidirectional layout simplifies the routing of utility lines, reducing construction complexity and costs for contractors, whilst significantly shortening user queuing times, thereby delivering mutual benefits to both users and contractors.

Site 2 is an open-air charging station primarily serving the surrounding commercial district, residential communities and the general public. Prior to optimisation, it featured an irregular, decentralised layout, with charging points scattered across the site and access routes taking a winding, S-shaped path. Current issues: The winding access route results in significant disparities in charging point accessibility. Charging points near the entrance have short access times and an utilisation rate exceeding 80%, whilst those at the far end require multiple turns and detours, with access times more than three times longer than those at the entrance and an utilisation rate of less than 40%. The irregular layout makes it difficult for vehicles to pass each other or turn around, leading to severe congestion within the site during peak hours and extremely low traffic efficiency, which significantly impacts the user charging experience. Analysis using a micro-level graph theory model reveals that, under the dispersed layout, the difference in shortest path lengths between charging points and the entrance exceeds 200%. The winding roads increase unnecessary travel time, which is the root cause of the imbalance in charging point utilisation and site congestion. Furthermore, the irregular road layout increases the operational difficulty and safety risks associated with vehicle movement. Accordingly, the proposed optimisation scheme involves adopting a regularised design comprising a double-row layout with a single-sided auxiliary lane. The main lane is adjusted to a straight east-west route, with a dedicated U-turn area established on the south side to completely eliminate detours; Charging points are neatly arranged on both sides of the main route, with the total number of points remaining unchanged at 15. The variation in access times for all points is kept within 10%, achieving comprehensive balance in charging point utilisation. By reconfiguring the traffic flow, this scheme significantly improves site circulation efficiency. The organised layout simplifies the contractor's pipeline planning and charging point installation processes, reducing construction costs and duration, whilst providing users with a clear and smooth charging route, thereby significantly enhancing the charging experience.

Site 3 is an intersection-type charging station, primarily serving offices, commercial premises and passing vehicles in the vicinity of the junction. Prior to optimisation, it adopted a cross-shaped layout, with charging points distributed along both sides of the four side roads, whilst the main thoroughfare formed a cross-shaped intersection. Current issues: The cross-shaped junction is a natural bottleneck; with vehicles from the four side roads converging frequently, there are frequent instances of vehicles meeting head-on and cutting in, resulting in extremely low traffic efficiency; there are significant disparities in the accessibility of charging points across different side roads; utilisation rates exceed 75% for points on the main road, whilst those at the far ends of the side roads remain below 30%. Furthermore, congestion at the intersection exacerbates this imbalance in utilisation rates, severely impacting both user charging efficiency and traffic safety. Analysis using a graph theory model from a micro-level perspective reveals that the cross-shaped layout results in multiple conflicts in the access routes to charging points. Waiting times at the intersection nodes account for over 40% of the total travel time; the existence of congestion points is the core factor driving down overall traffic efficiency and exacerbating the imbalance in charging point utilisation. Furthermore, the intersection has become a hotspot for safety incidents. Accordingly, the proposed optimisation scheme involves replacing the cross-shaped layout with a double-row parallel layout to completely eliminate congestion at intersections. The total number of charging points is increased, with all points neatly arranged along parallel lanes. Vehicles travel in a single direction with a unified U-turn point, ensuring that the difference in travel time to reach any charging point is kept within 10%, thereby achieving a balanced distribution of charging point utilisation. By eliminating congestion points, this solution addresses site traffic congestion at its root. The parallel layout significantly increases the service capacity of the charging points whilst simplifying the contractor's pipeline installation and road construction processes, thereby reducing construction complexity and safety risks, and providing users with safe, efficient and balanced charging services.

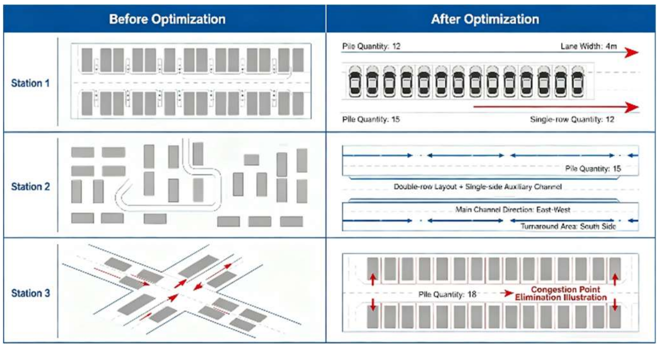


Figure 7. Schematic diagram of bottleneck modifications

5. Low-impact Construction Design

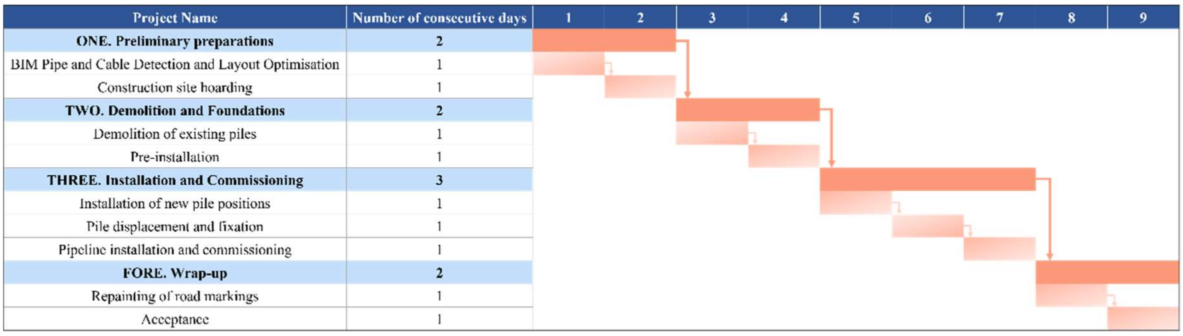
Taking into account the optimisation requirements of bottleneck sites, site conditions and disturbance assessment results, and by integrating Gantt charts, network diagrams and BIM technology, we have designed tailored, low-impact construction plans. These adhere to the principles of minimal disturbance, rapid construction, controllable costs, and safety and efficiency, whilst balancing the contractor's operational feasibility with the users' charging requirements, thereby ensuring the swift implementation of the optimised solutions.

(1)General Principles and Preparatory Work

The overarching principle is to prioritise the use of prefabricated components and modular construction methods to minimise on-site excavation and concrete pouring; to schedule works outside peak hours; to carry out construction in phases and by zone, maintaining normal operations at some charging points to minimise disruption to users; and to strictly adhere to utility avoidance requirements, utilising BIM technology to identify underground utilities in advance and reduce construction safety risks. Preparatory work includes: Using BIM technology to construct a 3D model of the site, precisely locating charging points, underground utilities and surrounding buildings, optimising construction routes and avoiding conflicts with utility lines. Procuring prefabricated pile foundations, modular charging points and other components, completing factory prefabrication in advance to reduce on-site working time. Demarcating construction and access zones, installing warning signs and safety barriers to guide vehicles and pedestrians to pass in an orderly manner. Liaise with the electricity supply department, traffic management authorities, local residents and businesses to inform them of the construction schedule in advance, seek their cooperation and minimise disruption.

(2)Detailed Construction Plan

The optimisation measures for Site 1 involve a single-row, same-direction layout with local double-row sections. This involves the addition of three new fast-charging points, requiring the overall relocation and installation of charging points, with a moderate scope of works. The primary objective is to minimise disruption to residents' daily charging routines, whilst controlling construction noise and traffic disruption. The works involve dismantling the existing 12 fast-charging points and relocating them to a single-row, same-direction layout, utilising the site's longitudinal space to accommodate 12 points in a single row. Additionally, precast foundations will be installed for the three new fast-charging points, with the re-laying of utility lines, repainting of lane markings and commissioning of equipment. Construction should be scheduled to avoid peak charging times for residents (18:00–21:00), with work carried out between 09:00–17:00 and 22:00–06:00 the following day. Low-noise equipment must be used during night-time construction to avoid disturbing residents' rest. The total construction period is 6 days, meeting the construction schedule constraints. Low-impact measures include the use of precast pile foundations and modular charging piles to minimise on-site casting and welding operations; pipeline laying utilises trenchless pipe jacking technology to avoid damaging the existing road; construction is carried out in phases, first completing the relocation of a single row of 12 charging points, whilst retaining some charging points for temporary operation and using mobile charging vehicles as a temporary solution, followed by the installation of the three new charging points; soundproof barriers are erected around the construction area, and directional lighting is used during night-time construction to reduce light pollution; the site is cleared and traffic restored at the end of each day.



Project Name	Number of consecutive days
ONE. Preliminary preparations	2
BIM Pipe and Cable Detection and Layout Optimisation	1
Construction site hoarding	1
TWO. Demolition and Foundations	2
Demolition of existing piles	1
Pre-installation	1
THREE. Installation and Commissioning	3
Installation of new pile positions	1
Pile displacement and fixation	1
Pipeline installation and commissioning	1
FORE. Wrap-up	2
Repainting of road markings	1
Acceptance	1

Figure 8. Gantt chart for construction schedule at Site 1

Optimisation measures for Site 2 involve a dual-row layout with a single-sided service lane. The number of charging points remains unchanged, with a standardised refurbishment involving the reconfiguration of site traffic flow and the reorganisation of charging point locations. No new charging points will be added, but the positions of the existing 15 points will need to be adjusted. The scope of works is moderate, with the primary objectives being to minimise disruption to vehicle charging in the commercial district and local community, and to maintain traffic order on-site during construction. The scope of works comprises the removal of the existing 15 fast-charging points and their relocation according to a standardised double-row layout; the main access route will be converted to an east-west through route, with a dedicated U-turn area established on the south side; road markings will be repainted and directional signage installed; and utility lines will be re-laid. Construction should be scheduled to avoid peak footfall times in the commercial district (10:00–12:00, 14:00–16:00, 18:00–20:00), with work carried out between 12:00–14:00 and 20:00–08:00 the following day. Night-time works will primarily consist of low-noise activities such as road marking and the installation of signage. Measures to minimise disruption include phased construction, maintaining normal operations at some charging points, and renovating areas furthest from the entrance first, followed by those closer to the entrance, to minimise interruptions to charging services; the main access route will be renovated through rapid night-time operations, with steel plates laid during the day to restore traffic flow; pre-formed kerbstones will be used in the U-turn area to reduce on-site wet works; Temporary guidance signage and dedicated traffic marshals will be deployed during construction to ensure the orderly flow of public traffic; dust suppression will be achieved through water spraying, whilst noise-generating equipment will be positioned in corners of the site and fitted with soundproof enclosures.

Figure 9. BIM model of Site 2

The optimisation measures for Site 3 involve a dual-row parallel layout, with the number of bollards increased to 18. This requires the removal of the existing cross-shaped layout and its replacement with parallel lanes, involving road modifications and the addition of new bollard positions. As the scale of the works is substantial, the primary objective is to mitigate traffic risks at the junction and avoid disrupting traffic flow at the junction as well as access to surrounding offices and commercial premises. The scope of works includes the demolition of the existing cross-shaped road layout and bollard positions, and the construction of new dual-row parallel lanes; Installing precast foundations for the 18 new piles; re-laying utility lines; installing one-way traffic signs and designated U-turn areas; and commissioning equipment. Construction should be scheduled to avoid peak traffic hours at the junction (07:30–09:00, 17:00–19:00), with work carried out between 09:00–16:00 and 19:00–06:00 the following day. Road demolition and sub-base works shall be carried out at night, whilst low-noise pile installation and commissioning shall take place during the day. Measures to minimise disruption include the use of fully enclosed hoardings and the installation of diversion signs to guide vehicles at the junction to use surrounding roads; low-vibration breakers shall be used for night-time road demolition, and local residents shall be notified in advance; Utility pipe laying will utilise trench excavation and rapid backfilling techniques, with excavation and backfilling completed on the same day to minimise exposure time; pile installation will employ the hoisting of precast foundations as a single unit to reduce on-site work; dedicated traffic marshals will be stationed at junctions during construction to ensure safety; mist cannons will be used for dust suppression, and high-noise operations will be suspended if noise levels exceed limits.

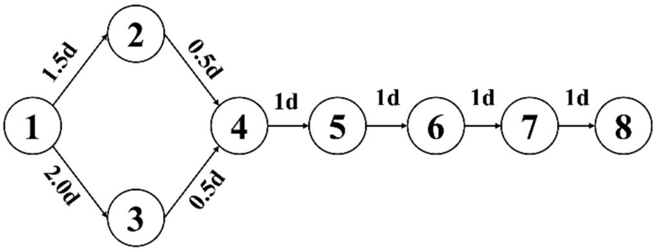


Figure 10. Site 3 Schedule Network Diagram

The construction schedule network diagram is shown in Figure 10. In this diagram, Task 1 is traffic diversion and hoarding; Task 2 is road demolition and removal of existing piles; Task 3 is sub-base construction for the parallel access road; Task 4 is installation of precast foundations; Task 5 is installation of new piles; Task 6 is the laying and commissioning of utility lines; Task 7 is the road surface finishing and road marking; and Task 8 is the installation of signage and final inspection.

(3)Quality and Safety Control

To ensure construction quality and safety, and to minimise safety risks and rework costs for the contractor, the following control measures have been established: In terms of quality control, quality inspections shall be carried out on prefabricated components prior to their arrival on site to ensure compliance with design standards; pile positions shall be determined using BIM technology, with deviations controlled within ±5 cm; pressure tests shall be conducted after the laying of utility lines to ensure there are no leaks; following the completion of equipment commissioning, a trial run of no less than 24 hours shall be conducted to verify that the charging functions are operating normally. In terms of safety control, safety training shall be provided to construction personnel prior to commencement of works, and they shall only be permitted to commence work upon passing an assessment; personal protective equipment must be worn during work at height, and safety nets shall be installed; warning signs and hoardings shall be erected in the construction area, and unauthorised personnel shall be strictly prohibited from entering; prior to underground pipeline works, a combination of BIM technology and manual inspections shall be used to confirm pipeline locations to avoid severing pipelines; first-aid equipment and personnel shall be on standby during construction to respond to any sudden safety incidents.

6. Simulation Verification and Performance Analysis

(1)Simulation modelling

Using the SimPy discrete-event simulation tool, a simulation model of the charging system at the Fengrun District site in Tangshan was constructed to validate the effectiveness of the optimisation scheme and the low-impact construction plan. The simulation model is based on actual charging data and replicates the entire process from user arrival, queuing, charging, to departure. The simulation duration for a single site is 72 hours, equivalent to three working days, covering peak, off-peak and low-demand periods to ensure the representativeness of the simulation results;

The simulation model comprises two scenarios: Scenario 1 represents the pre-optimisation phase, utilising the original site layout and construction plan; Scenario 2 represents the post-optimisation phase, employing the graph theory-based optimisation scheme and low-impact construction plan proposed in this paper. By comparing the evaluation metrics of the two scenarios, the effectiveness of the proposed scheme is verified.

(2)Simulation Results and Analysis

Figure 11 shows the simulation results for three randomly selected bottleneck sites. Based on a combination of disturbance metrics and cost analysis, the optimisation results for each indicator are as follows:

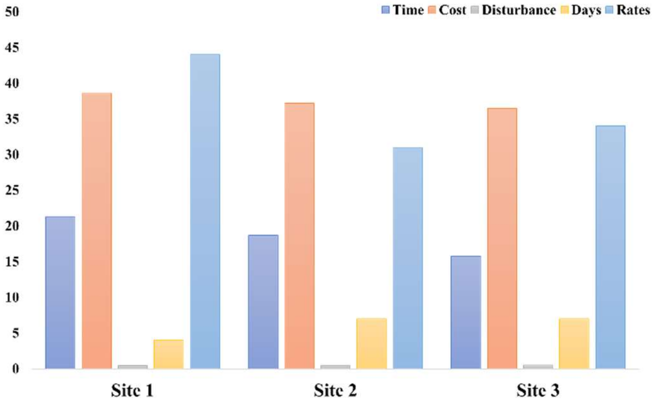


Figure 11(a). Results for Scenario 1

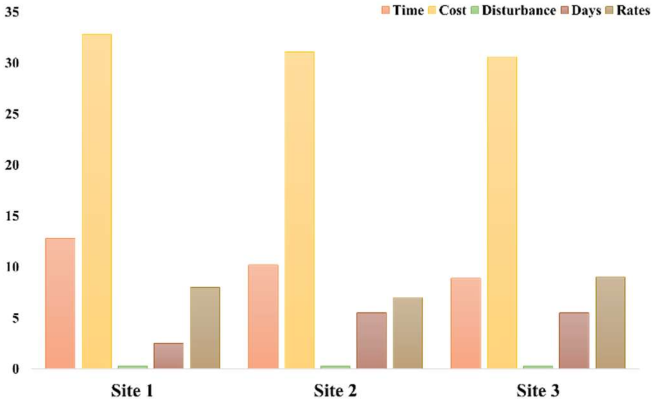


Figure 11(b). Results for Scenario 2

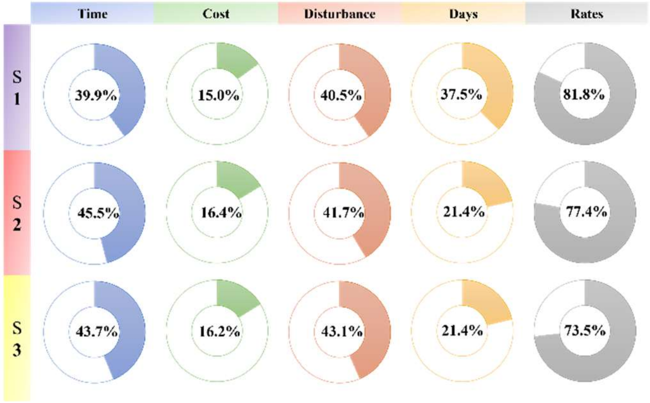


Figure 11(c). Degree of optimisation

The simulation results show that, following the implementation of the optimisation scheme and the low-impact construction approach proposed in this paper, the key indicators at each site have been significantly improved: In terms of benefits for users, the average queuing time at the three stations has been reduced by 39.9% to 45.5%, all falling below the original threshold, thereby effectively resolving queuing and congestion issues; the average daily charging cost for users has fallen by 15.0% to 16.4%, tangibly enhancing the cost-effectiveness and convenience of charging for users and meeting the needs of both core user groups. In terms of benefits for the contractor, the comprehensive construction disturbance index fell below 0.3 across the board, enabling low-impact construction and minimising disruption to surrounding traffic and residents' daily lives; the construction cycle was shortened by 21.4% to 37.5%, reducing construction time and lowering the contractor’s labour and management costs; simultaneously, through quality and safety control measures, construction safety risks and the probability of rework were reduced, thereby improving construction efficiency. In terms of facility operational benefits, the disparity in charging point utilisation rates has decreased from 31% – 44% to 7% – 9%, well below the 20% constraint requirement. This ensures balanced utilisation of charging point resources, avoids resource idling and localised congestion, and enhances the overall operational efficiency of the charging infrastructure.

7. Conclusion

In response to the engineering challenges posed by the mismatch between supply and demand for electric vehicle charging facilities, queuing congestion, and construction-related disturbances in existing urban areas, this study uses Fengrun District in Tangshan as a pilot area. It proposes a three-tiered incremental micro-renewal approach comprising macro-level queue diagnosis, micro-level graph theory optimisation within individual stations, and low-impact construction. Through theoretical modelling, scheme design and simulation verification, the following conclusions were reached:

(1)The asymmetric double-queue model developed can accurately diagnose queuing bottlenecks at regional charging stations, providing precise targeting for micro-upgrade work and resolving the issues of indiscriminate charging point expansion and low efficiency found in traditional optimisation approaches.

(2)The micro-site optimisation method based on graph theory utilises Dijkstra’s shortest path algorithm to optimise charging station cluster layouts and vehicle routing strategies. This significantly reduces queuing times and balances charging point utilisation without the need for large-scale expansion of charging infrastructure, thereby validating the engineering principle that layout optimisation takes precedence over infrastructure expansion, whilst balancing user convenience with cost control for contractors.

(3)A low-impact construction plan was designed, integrating Gantt charts, network diagrams and BIM technology. This achieved a shorter construction cycle, reduced disruption and controllable costs, balancing the contractor’s operational efficiency with the impact on the surrounding environment, whilst ensuring that users’ charging needs were not significantly affected.

(4)SimPy discrete-event simulation results indicate that, following optimisation, average queuing times at bottleneck sites were reduced by 39.9%-45.5%, users’ average daily charging costs fell by 15.0%-16.4%, the construction period was compressed to 1-3 days, and the comprehensive construction disturbance index was kept below 0.3, thereby achieving a threefold improvement in benefits for users, contractors and facility operators.

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