ECTI Transactions on Computer and Information Technology
Journal homepage: https://ph01.tci-thaijo.org/index.php/ecticit/
Published by the ECTI Association, Thailand, ISSN: 2286-9131

Optimized Selection of Motorcycle Battery Swapping Stations Under Flexible Demand by Using Distance Function And Gis Technique

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ABSTRACT

Our research proposes an approach to finding a suitable location for a motorcycle Battery Swapping Station (BSS) that considers multiple objectives. We developed a model based on Euclidean distance with K-nearest neighbors (K-NN), the analytical hierarchy process (AHP) function, a desired number of stations, and geographic information system (GIS) based road infrastructure data. This model also considers the maximum coverage area and satisfies the number of stations and geographical features. Additionally, we consider the average driving distance of the battery swapping station location. To facilitate analysis, square grids form cells representing road type, environmental characteristics, places, and population density. Our proposed framework provides decision-makers with a multi-objective and visually optimized motorcycle BSS location, allowing for a more flexible selection of exact BSS locations shown on a map. Our demonstration can be used to resolve the uncertain problem related to finding a place for a motorcycle battery swapping station location.

Article information:

Keywords: Battery Swapping Station, AHP, Spatial Coverage, Smart City

Article history:
Received: August 1, 2023
Revised: August 24, 2023
Accepted: September 14, 2023
Published: September 30, 2023 (Online)

DOI: 10.37936/ecti-cit.2023173.253697

1. INTRODUCTION

Thailand's 4.0 strategy, which spans from 2017 to 2036, includes the development of smart cities [1-2]. The Digital Economy Promotion Agency (DEPA) has chosen Phuket as a pilot program for its "Phuket Smart City" initiative [3]. This initiative aims to boost the country's competitiveness by capitalizing on Phuket's appeal to global tourists and embracing diverse lifestyles, creating an environment conducive to technological advancements. The "Phuket Smart City 2020" serves as a pilot project for a smart province, striving to improve the quality of life and establish a modern, sustainable business model [4]. Achieving this vision requires collaboration among local residents, organizations, and entrepreneurs, where their ideas and designs play a central role. Understanding the city's specific challenges and needs is essential for smart city development, as it enables the implementation of tailored policies and sustainable economic growth for its residents. The "Phuket Smart City" strategy plays a vital role in this initiative, encompassing seven key domains: Smart Economy, Smart Energy, Smart Economy, Smart Governance, Smart Mobility, Smart People, and Smart Living [5]. Within the Phuket City Development Plan, a primary focus lies on establishing alternative energy sources and effectively managing green energy. By embracing these strategies, Phuket aims to become a sustainable and liveable city, setting an example for the nation in enhancing energy security.

In 2022, statistical data from the Department of Land Transport (DLT) reported that Thailand boasts approximately 22 million motorcycles, making it the leading country in motorcycle usage in Southeast Asia. These two-wheeled vehicles serve a variety of purposes, including food and parcel delivery, taxi services, and personal transportation, number of registered electric motorcycles reached a peak at 9,961 units, surpassing previous years [6]. Furthermore, in the first month of 2023, there were 1,577 registered electric motorcycles [7]. However, the existing battery technology for electric motorcycles requires a minimum of 30 minutes for a full charge, which

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falls short of drivers' expectations. To address this issue, the research focuses on identifying optimal locations for battery replacement stations for electric motorcycles. This approach enables riders to swiftly and effortlessly replace depleted batteries with fully charged ones. The case study conducted in Phuket aligns with the 30@30 policy, which aims to have 30% of users employing emission-free vehicles by 2030 [8], contributing to the vision of creating a "Phuket Green City" [9].

The Analytical Hierarchy Process (AHP) is a widely used technique to determine the best location for electric vehicle charging stations. Dogus and Tahsin [10] applied AHP to calculate the weight of decision criteria for charging station locations in Istanbul, Turkey. The criteria included population density, shopping centres, roads, income rates, transportation stations, filling stations, green areas, slopes, and cadastral values. They also used the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method to rank appropriate criteria for station selection. Moralıoğlu et al. [11] created the Super Decisions program for e-scooter sharing in Istanbul, Turkey, using AHP under changing circumstances, considering factors like traffic density, uphill rate, population ratio of young people, and pedestrian traffic density. Anthopoulos and Kolovou [12] employed AHP to determine the conditions for setting up electric charging stations in Greece. These conditions were divided into economic, environmental, policy, technological, social, and other factors.

Moreover, SUN [13] utilized the AHP method in conjunction with GIS to find the optimal location for Electric Vehicle Charging Stations (EVCSs) in Nanshan District, Shenzhen City. They considered social, technological, and environmental factors in their analysis.

The main goal of this paper is to introduce a practical approach for determining the optimal installation of Battery Swapping Stations (BSS) using AHP. The approach considers environmental factors, location suitability, water area availability, and population density as criteria. The obtained results can serve as a valuable guide for decision-makers in planning BSS installations in areas with requirements similar to Phuket.

2. METHODOLOGY

2.1 Analytic Hierarchy Process (AHP)

The AHP is a multi-criteria decision-making method that employs a hierarchical structure to manage intricate problems. Decision-making elements are broken down into multiple dimensions, and the problem is hierarchically decomposed and structured into smaller subproblems, then individually evaluated subproblems, simplifying the decision-making process for complex problems [14]. However, AHP heavily relies on personal experiences, knowledge, and intuition, leading to inconsistency in assessment. Thus, it is crucial that specialists provide authoritative evaluations and that the information they provide is accurately measured.

In this study, the AHP method was employed to calculate the weights of major needs for determining a BSS location in proximity to a specific place. These needs encompass environmental criteria, place, water area, and population density.

The AHP method determines the relative importance of factors within each hierarchy by generating pairwise comparison matrices A (Equation 1). The area above the diagonal matrix is the comparison between the two criteria, and the area under the diagonal is the inverse of the value above the diagonal.

$$A = \begin{bmatrix} 1 & a_{12} & a_{13} & \cdots & a_{1n} \\ 1/a_{12} & 1 & a_{23} & \cdots & a_{2n} \\ 1/a_{13} & 1/a_{23} & 1 & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1/a_{1n} & 1/a_{2n} & 1/a_{3n} & \cdots & 1 \end{bmatrix} \quad (1)$$

These matrices are used to evaluate the results of comparing factors against each other on a scale of 1 to 9, indicating the level of importance of one component over another. To illustrate the significance of absolute numbers in the higher-level hierarchy scale, Table 1 presents the corresponding values [15].

Once the judgment matrices are created for each level, the next step involves obtaining the judgment matrix of each level's largest eigenvalue ($\lambda_{\max}$) and its corresponding eigenvector W (Eq.2). Subsequently, the feature vector is normalized. This normalization involves comparing the evaluation index of each element at the same level with the rank weights of the higher-level index importance.

$$\mathrm{AW} = \lambda_{\max}\mathrm{W} \quad (2)$$

After that, the conformity of the pairwise comparisons was assessed using the consistency ratio (CR), used to measure the consistency of the decision maker's ideas. CR was calculated by comparing the consistency index (CI) of the judgment matrix (Eq.3) with the random consistency index (RI) in Table 2.

$$\mathrm{CI} = (\lambda_{\max} - \mathrm{n})/(\mathrm{n} - 1) \quad (3)$$

A consistency ratio (CR) below 0.1 signifies that the matrix is consistent [16-18]. However, if the CR exceeds 0.1, the pairwise comparisons should be reevaluated to improve consistency.

2.2 The Maximum Coverage

This research paper proposes a methodology for identifying optimal locations for BSS of motorcycles based on the principle of maximum coverage. The approach involves assessing the ability of potential

Table 1: *The definition of the scale of absolute numbers.*

Values	Definition	Explanation
1	Equally important	Both criteria yield equivalent outcomes.
3	Weak importance	Indicates a weak preference of one element over another.
5	Strong importance	Shows a strong preference of one element over another.
7	Demonstrated importance	Demonstrates a very strong preference of one element over another.
9	Absolute importance	Represents an absolute preference of one element over another.
2,4,6,8	Intermediate values	The comparison factor is considered an intermediate of the values mentioned above.

Table 2: *Random consistency index based on matrix size.*

Matrix size	1	2	3	4	5	6	7	8
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41

locations to provide efficient access to charging stations throughout the day, considering factors such as proximity to roads, community areas, and workplaces. The suitability of each location will be evaluated based on the specific needs of the users, such as motorcycle taxi drivers, food delivery services, or postal workers. Furthermore, the study also considers environmental factors that may exclude certain locations, such as rivers or mountains, where it may not be possible to install a battery switching station. By weighting and adjusting these various factors, the research aims to identify the most feasible and effective locations for motorcycle battery switching stations that can provide maximum coverage and accessibility to users.

We applied a concept of Euclidean distance and the k-nearest neighbor algorithm by incorporating the concept of weighting the multi-criteria decision of interest, which is called an "ED + ASS" algorithm from [19]. The proposed framework considers quantitative and qualitative criteria, including population density, environment, and accessibility. To ensure that the framework is comprehensive and representative of the needs and preferences of relevant stakeholders, the analytical hierarchy process (AHP) will be employed. The AHP will gather input from the market and relevant energy representatives, who will provide valuable insights into prioritizing different factors in the decision-making process. By incorporating quantitative and qualitative criteria and soliciting input from key stakeholders, the proposed framework aims to provide a more robust and effective approach to location-based decision-making.

3. BSS MODEL

3.1 Data Preparation

In the data preparation phase of our research, we used Quantum Geographic Information System (QGIS) software to select a target area and divide it into 500×500 meter grids, as depicted in Figure 1. We identified the grid number and latitude and longitude pairs at the centroid of each grid to calculate distances using the Euclidean function. To prepare the data for analysis, we considered several factors: density, population, road type, natural information, waterway information, and community areas. We utilized QGIS to query information from an open street map, an open-source map. For example, we selected natural areas equal to "wood," as shown in Figure 2. These natural areas are referred to as "wooded" and are typically located in or near mountains. We considered each wooded area as a single forest for our analysis.

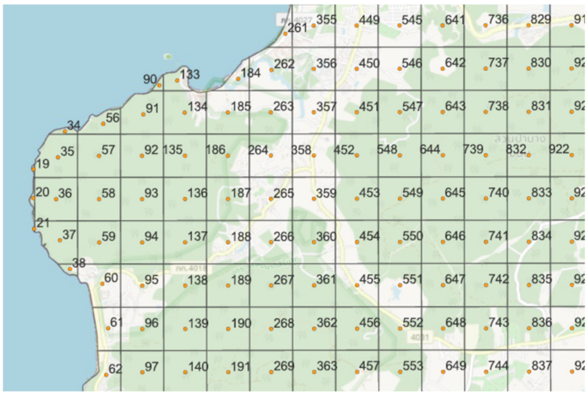


Fig.1: *The ID of each grid that was divided of 500×500 square meters in Phuket province.*

Another crucial factor we considered in our analysis is community areas. We studied the position of restaurants, which is illustrated in Figure 3 along with their distribution and density. We plotted several factors on a map and included them in our analysis, as shown in Figure 4.

After preparing the data, we merged it with the grids of the target area using overlays. This process resulted in each grid containing information such as its grid number, coordinates, road type, amenity data, natural data, and waterway data. Next, we set the distance between stations to 4 km [20] and applied the Euclidean distance and k-nearest neighbour algorithm for our BSS finding approach. By utilizing these methods, we were able to identify optimal locations for BSS that would provide maximum coverage and accessibility to users in the target area.

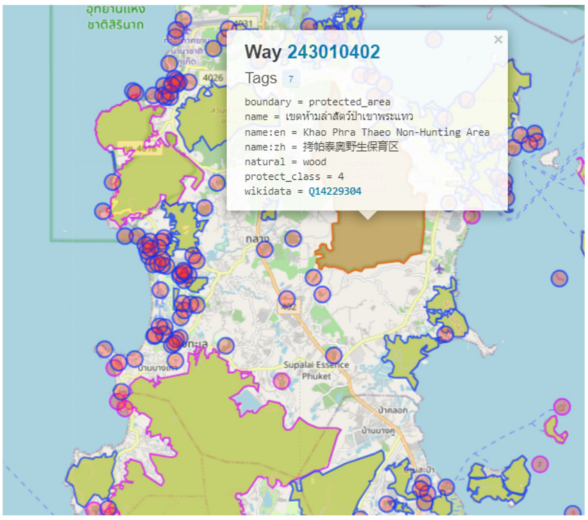


Fig.2: *The area with borderline and circle areas depicts the extensive wooded regions spread throughout Phuket. These valuable insights have been acquired from Open Street Map (www.osm.org), a reliable data provider.*

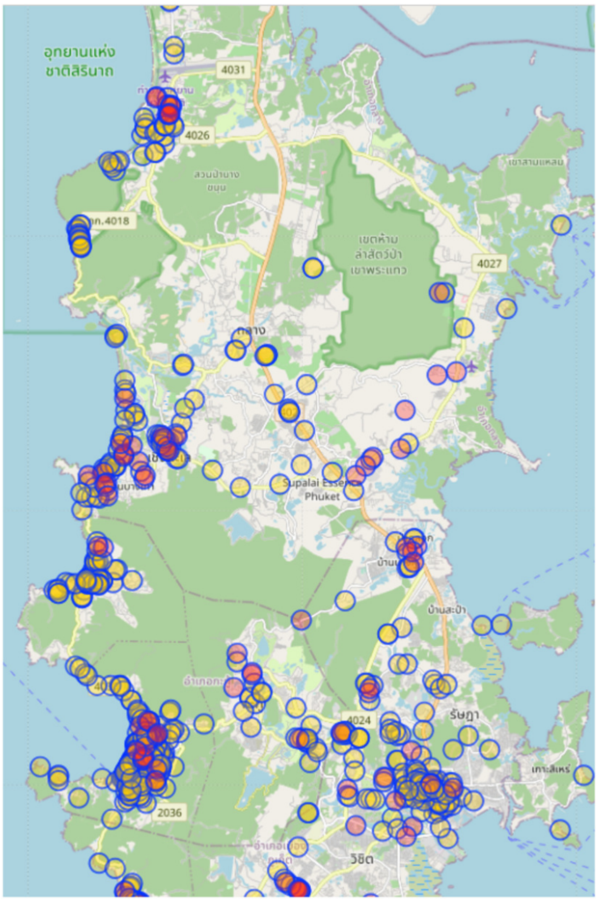


Fig.3: *The location of districts or villages that have high density population (DP).*

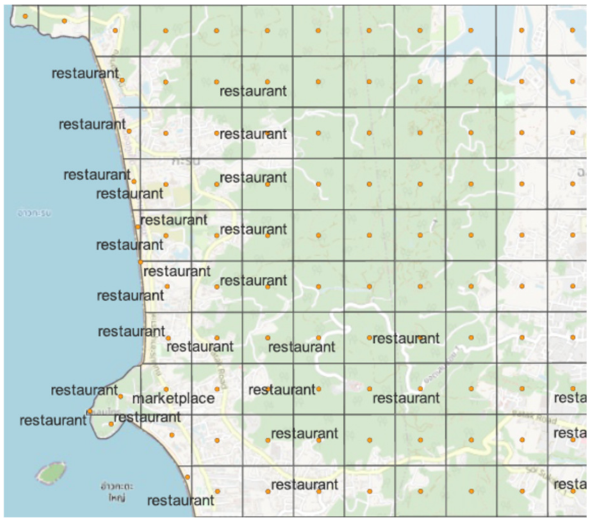


Fig.4: *The location of places that located in each grid.*

3.2 User Profiles

In our BSS finding approach, we aimed to design a methodology following our previous research [21] that is both flexible and suitable for real-world use. This multi-purpose optimization process allows decision-makers to specify the number of locations they require or the maximum amount of coverage they need, enabling the program to process the minimum number of stations necessary. By designing a flexible approach, we have created a decision-making tool that is efficient and effective. Additionally, users can determine factors or needs such as proximity to certain places or escape from specific areas. The primary objective of our method is to acquire maximum coverage area by positioning BSS stations in the most reasonable locations possible. By making our approach flexible and adaptable to various needs and situations, it can be a valuable tool for decision-makers in the real world.

3.3 AHP Analysis

We established five main criteria and 15 sub-criteria to determine a suitable location for the BSS, as shown in Table 3. The AHP method was used to analyze the impact of these criteria on the BSS station. Initially, a judgment matrix was created to evaluate the criteria against the sub-criteria. The hierarchy was then structured, and consistency checks were performed using the judgment matrix. Subsequently, the ranking of the main criteria and the corresponding weights for each layer were calculated, and we computed the influence of the criteria and the weights of the main factors, which are displayed in Table 4. We obtained an overall ranking of criteria based on

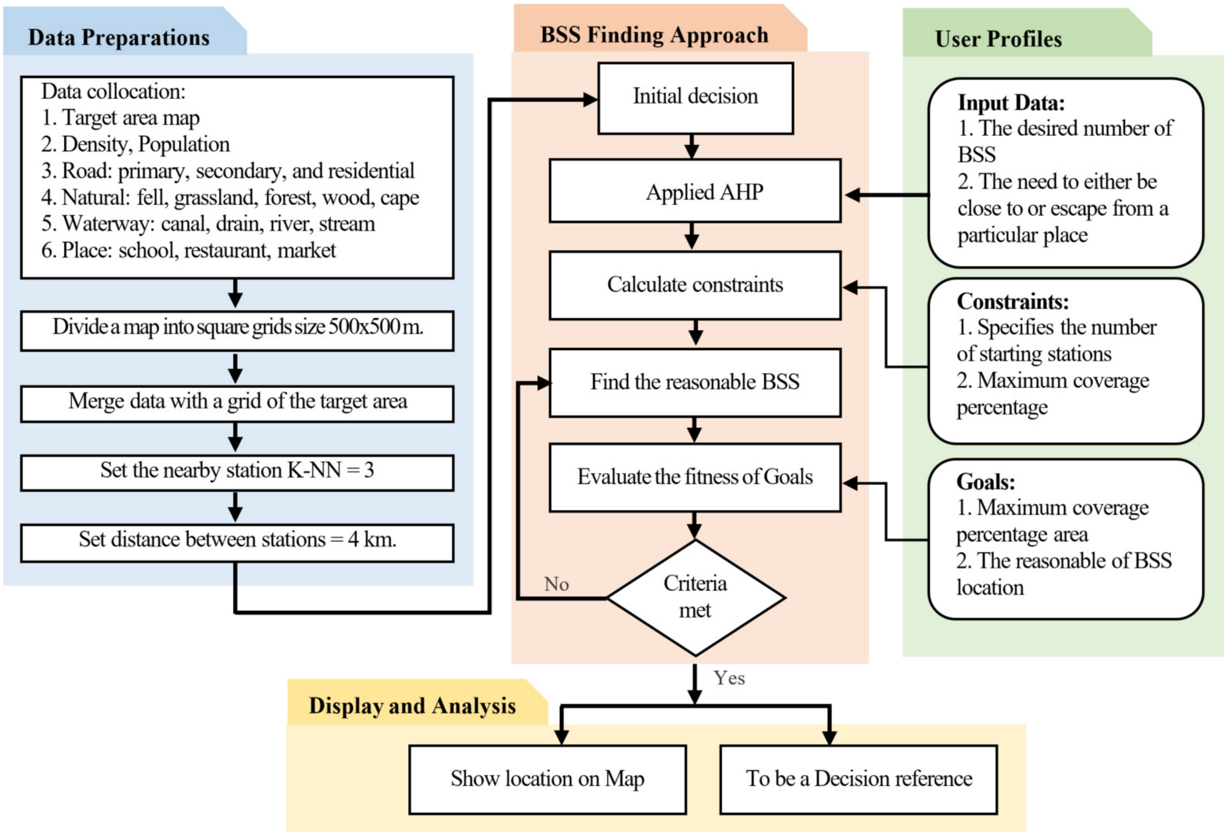


Fig.5: *The framework of our proposed methodological.*

the combined assessment of various criteria. The results show that market, population density, and residential road emerged as the three most significant aspects of BSS planning in this research and attention to these criteria.

Table 3: *The criteria and weights of main considering factors: type of road, Places, type of waterway, type of natural and population density.*

Main Criteria: Sub Criteria	Weight
Road: Secondary	0.0307
Road: Primary	0.1105
Road: Residential	0.1607
Place: Restaurant	0.0447
Place: School	0.1260
Place: Market	0.2369
Waterway: Canal	0.0094
Waterway: Drain	0.0094
Waterway: River	0.0094
Waterway: Stream	0.0094
Natural: Fell	0.0083
Natural: Grassland	0.0083
Natural: Forest	0.0083
Natural: Wood	0.0083
Population density	0.2113

3.4 BSS Finding Approach

The BSS Finding Approach begins with the prepared data, which is used to calculate the distance between BSS stations. The pseudo-code of our proposed algorithm is shown in Algorithm 1. The process starts by selecting the starting station at any grid and simulating the next station in the grid from the first station. This value is then multiplied by the weight, which is calculated from the input of decision-makers and the grid's information, as mentioned above. Each grid is replicated to the next station until the best value of evaluation is obtained for the next station. This method is repeated until the desired number of stations is reached, based on the specified purpose. A brief tutorial demonstrating this process is shown in Figure 5.

Table 4: *Overall weight of criteria and ranking.*

Ranking	Main Criteria	Weight
1	Place	0.4075
2	Road	0.3019
3	Population density	0.2113
4	Natural	0.0417
5	Waterway	0.0376

The Algorithm 1 finding BSS with AHP sudo code can be described as follows:

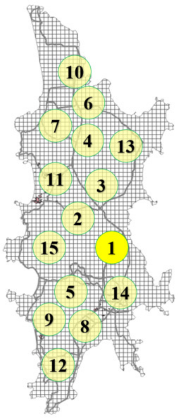
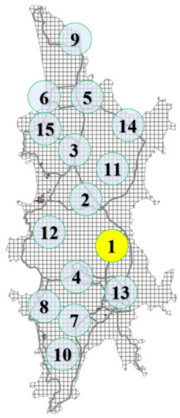
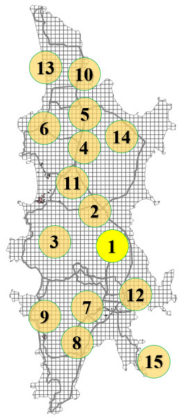
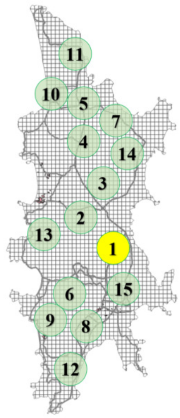
Input: Map; a specified number of stations point, value of criteria, etc.);

Identify the first station and add it to the station list S as $S = \{S1\}$.

Calculate the area (grid) that is not covered by the first station and store it as poor_area.

Set the Total Euclidean Distance (TED) to an initial value.

Table 5: *The results of three cases that depict sequentially results of 15 stations, coverage percentages, mean proximity from roads and places, and the number of stations located inside the urban area or outside the natural area.*

Phuket		Base	Using AHP		
			case1: roads	case2: places	case3: all conditions
		 (A)	 (B)	 (C)	 (D)
coverage percentage		75.55%	72.59%	70.35%	71.68%
Number of stations	proximity of road	12	14	13	11
	proximity of places	1	2	3	1
	inside urban	15	15	15	15
	outside natural area	14	14	15	14
Average of Population Density (Population / Km^2)		1006.95	616.73	1002.80	500.83

4: **For each** candidate station (Li) in the poor_area do
5: Create a temporary_poor_area by excluding the coverage area of station Li.
6: Set $TEDLi$ to an initial value.
7: **While** temporary_poor_area do
8: Calculate the Euclidean Distance (ED) to the three nearest neighbor stations (including both stations in list S and station Li)
9: Multiply the ED by the weight of criteria
10: Sum the value of $TEDLi$ with the weighted ED
11: **End while**
12: If $TEDLi$ is less than the current TED value, set Li as the next station in the station list S.
13: Update poor_area to be the area that is not covered by the current station list S.
14: **End for**
15: Return stations list S

In this study, we incorporated the methodology proposed in a previous research work [21], known as "ED + FSS," to calculate the location of the next station. In order to adapt this method for identifying suitable locations for motorcycle Battery Swapping Stations (BSS), we introduced a modification by introducing source code (line 9) to incorporate the weighting of criteria in the ED calculation. These criteria include type of road, places of interest, type of waterway, type of natural surroundings, and population density, which were collected from expert opinions. Subsequently, we plotted the resulting station locations sequentially onto a map for visual representation and analysis. This approach allows for a comprehensive evaluation and determination of the most appropriate sites for BSS installation, ensuring efficient and effective service coverage in the designated area.

4. RESULTS AND DISCUSSION

In this section, we outline methods and results utilized in the conducted research. For the experimental construction of 15 stations, we employed the "ED + ASS" algorithm obtained from [19]. The result shows that the base of 15 stations collectively covers a maximum area of 75.55% within the study region. To facilitate easy identification, the first station is denoted by circle number 1, and the subsequent stations are sequentially labelled based on their respective lane numbers, as shown in Table 6, Figure (A). Among the fifteen stations, 12 are strategically located along roads, 1 station is positioned in proximity to a specific site of interest, 15 stations serve the community areas, and 14 stations are situated outside natural regions. The collective impact of all 15 stations results in an average coverage of 10,006.95 people per square kilometer, signifying the potential of the network to efficiently serve a substantial population density.

Table 5 and figures (B), (C), and (D) present a comprehensive comparison of station locations obtained through AHP (Analytic Hierarchy Process) calculations, along with the influence of various factors. The initial stations correspond to predetermined base locations, while the subsequent station sequence varies based on the weighting of these influencing factors. In case 1, where the emphasis is on proximity to roads, we observed that 14 stations were located in close proximity to roads, making these locations the best when compared to the other cases. Simultaneously, in Case 2, the consideration of factors such as restaurants, schools, or markets resulted in favorable station positioning outcomes, particularly regarding road proximity and locations outside the natural areas. This led to the establishment of 3 stations near the aforementioned place and 15 stations outside the natural areas, with an average population density of 1002.80 individuals per square kilometer. However, when analyzing the outcomes from Case 3, where all conditions were taken into account, including proximity to roads, communities, city centers, and areas outside natural regions, the experimental results demonstrated that the station's positioning showed no apparent bias. This suggests that the proposed method effectively considers multiple relevant factors, thus necessitating the selection of the optimal position while simultaneously minimizing any unfavorable effects. However, the results show the location of stations for determining the locations of all 15 sites, rendering it a valuable tool and an alternative decision-making resource.

5. CONCLUSION

Our research provides a comprehensive guideline for determining the optimal placement of motorcycle battery switching stations (BSS), considering multiple objectives and the ability to adjust objective settings and station conditions. Firstly, we determine the maximum spatial coverage based on the defined number of locations. Subsequently, we consider the proximity of neighbouring stations. In cases where the BSS station is unable to provide service, nearby locations are identified that are still within reasonable distance to cater to demand. Furthermore, we examine the location with respect to various variables, including distance from the road, proximity to points of interest, natural areas, water sources, and population density. Our proposed method effectively calculates the demand weight to determine the optimal BSS station location. Through our research conducted in three different cases, we observed the following outcomes: In Case 1, assigning weight to prioritize stations near the road resulted in a 5% decrease in spatial coverage compared to the baseline, while the average distance from the road increased by 10%. Twelve stations were situated near roads, while three stations were positioned approximately 500 meters away from roads. In Case 2, emphasizing proximity to points of interest led to a 6% decrease in spatial coverage compared to the baseline, accompanied by a 12% increase in average proximity to roads.

When establishing a motorcycle battery switching station (BSS) network within cities, it is crucial to strike a balance between BSS locations and achieve maximum coverage to effectively serve the population. Various spatial considerations arise, including the necessity to position stations near roads for convenient access, near establishments like restaurants or community areas, and the avoidance of challenging installation areas such as mountains or valleys. Our proposed methods effectively meet these requirements. The findings demonstrate that if city planners consider the economic benefits and investment costs associated with constructing a BSS network, the proposed method can yield outstanding results.

ACKNOWLEDGMENT

The authors acknowledge the financial support by the Faculty of Informatics, Burapha University, Research project: Toward Appropriate Location Selection for the Battery Swap Station with AHP methods using GIS, ID 05/2565 and IRB no. is HS053/2565.

AUTHOR CONTRIBUTIONS

Conceptualization A.O. and N.P.; Data curation A.O. and J.A.; Investigation A.O. and N.P.; Methodology A.O.; Resources J.A.; Supervision N.P.; Validation J.A. and A.O.; Visualization J.A.; Writing-Review & editing A.O., N.P. and J.A.; All authors have read and agreed to the published version of the manuscript.

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