Optimizing Smart Pole Placement: A Strategic Set Covering Approach in Phra Nakhon Si Ayutthaya

Wichai Witayakiattilerd[*], Pantita Lertkrai, Wachirada Limpanawannakul, and Jirawan Phuphon

Department of Mathematics and Statistics, Faculty of Science and Technology,
Thammasat University, Pathum Thani, Thailand
[*]Corresponding author; e-mail: wichai@mathstat.sci.tu.ac.th

Abstract

This research introduces a method for optimally placing smart poles in urban areas, using a model based on a set covering problem principles and hexagonal space partitioning, solved with QGIS and IBM CPLEX. Applied to the Phra Nakhon Si Ayutthaya District, it identified 668 optimal spots for smart poles. The results emphasize the significance of proper location selection for smart pole functionality and its potential application in other cities. This optimization can increase urban efficiency and citizens quality of life.

1. Introduction

Smart city development has become a critical agenda worldwide, aiming to enhance citizens quality of life, ensure sustainable growth, and strengthen urban competitiveness. Thailand, in line with this global trend, has prioritized smart city initiatives as part of its long-term national development strategy. Key aspects of this development include infrastructure modernization, resource allocation, environmental management, and technological integration to improve urban governance. Within this context, smart streetlights have emerged as a fundamental component of smart city infrastructure, contributing not only to public safety but also to the broader objectives of Industry 4.0 and digital transformation.

Smart streetlights provide multiple integrated functions such as emergency charging for electric vehicles, emergency notifications, Wi-Fi distribution, motion and environmental sensors, sound systems, LED beacon systems, and most importantly, a 360-degree closed-circuit camera system for safety and traffic monitoring. These features position smart streetlights as multifunctional urban assets that extend beyond illumination to support connectivity, security, and sustainable urban management. Proper placement and optimization of these smart streetlights are therefore essential to maximize benefits while minimizing costs.

This research focuses on Phra Nakhon Si Ayutthaya district as a case study, aiming to determine suitable locations for smart streetlights using the fewest units possible to reduce installation and maintenance costs. If implemented effectively, AyutthayaThailands top secondary tourist destination and a UNESCO World Heritage Sitecan serve as a model city that demonstrates how smart technologies can simultaneously enhance safety, improve quality of life, and support urban sustainability.

The projects ultimate goal is to transform Phra Nakhon Si Ayutthaya into a smart city that integrates historical and cultural heritage with advanced digital infrastructure.

Phra Nakhon Si Ayutthaya is strategically significant for several reasons. It is located near Bangkok, acting as a gateway for industrial and tourism flows. The province is home to several industrial estates that play a major role in the national economy, while its cultural and historical assets attract large numbers of international and domestic tourists. This dual roleas both an industrial hub and a heritage tourism citymakes it an ideal testbed for smart city development, especially in balancing modern infrastructure with cultural preservation.

Despite its potential, the adoption of smart streetlights faces several challenges, including high installation costs, ongoing maintenance requirements, and limited public awareness regarding the benefits of smart infrastructure. To address these challenges, this study applies the *set covering problem* (SCP) approach to identify optimal locations for installing smart streetlight poles. The SCP is a well-established mathematical optimization technique that minimizes costs while ensuring maximum service coverage, making it particularly suitable for infrastructure planning in resource-constrained environments. Figure 1 illustrates the conceptual framework of this research, linking smart city objectives, technological functions, and optimization methods.
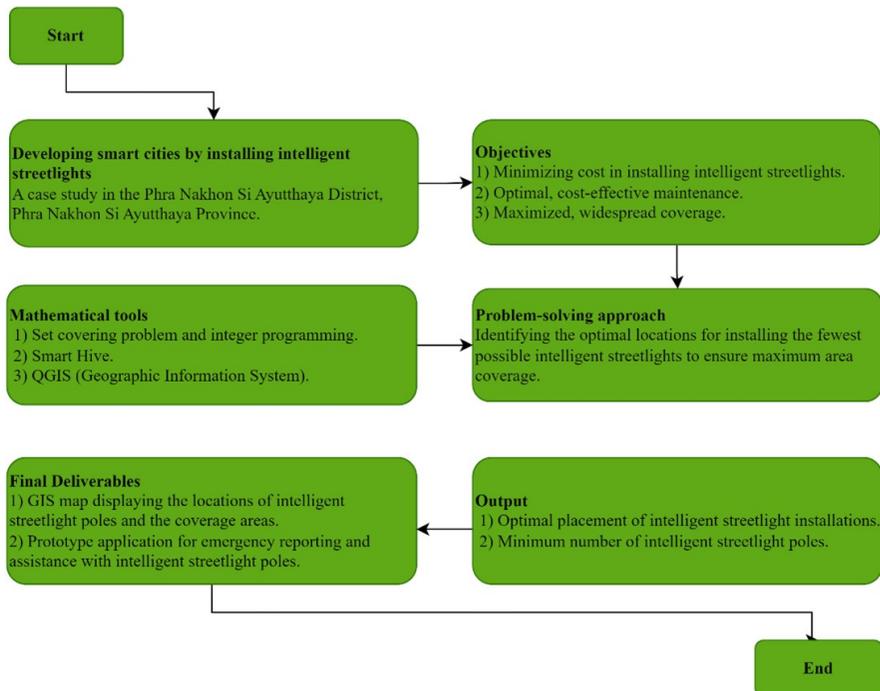
Figure 1 Framework of the key ideas of the research

2. Literature Review

This research investigates the optimal placement of smart poles in Phra Nakhon Si Ayutthaya District using a set covering problem (SCP) approach. The literature review underscores the importance of this topic within the broader frameworks of smart city development, location optimization, traffic management, and infrastructure planning. While a growing body of literature addresses smart technologies and location optimization in urban contexts, there remains a research gap in applying optimization techniques to smart poles in secondary cities with both industrial and heritage significance, such as Ayutthaya.

Alam and Siddiqui (2023) emphasize the transformative potential of artificial intelligence (AI) in urban environments, particularly its ability to enhance quality of life and urban governance. Their findings align with the deployment of smart poles, which integrate multiple technologiesranging from sensors to connectivity systemsto improve living conditions. Similarly, Ligman (2022) highlights the crucial role of smart poles in urban transformation, especially their contributions to energy efficiency, public safety, and urban connectivity.

The strategic placement of smart poles is essential to fully leverage their multifunctional benefits. Velaga and Kumar (2012) demonstrated the positive impact of well-placed smart technologies in both rural and urban settings through their study on smart streetlight systems in India. This insight is further supported by Caprara, Toth, and Fischetti (2000), who provide a theoretical foundation for applying the SCP to optimize infrastructure locations. Together, these studies suggest that effective deployment of smart poles requires both technological integration and rigorous location optimization methods.

Location optimization models have been extensively studied in related fields, offering a strong methodological basis for this research. Campbell (1994) utilized integer programming formulations for discrete hub location problems, highly relevant to infrastructure deployment. Badri, Mortagy, and Alsayed (1998) applied optimization models to fire station locations, while Sarawanangkoor, Chanvarasuth, and Chaysiri (2020) extended SCP models to primary care facilities. More recently, Alizadeh and Nishi (2020) proposed hybrid models combining SCP with dynamic modular covering approaches, demonstrating the adaptability of SCP in handling real-world uncertainties and dynamic urban conditions.

Traffic management and public safety are domains where smart poles play an increasingly critical role. As Velaga and Kumar (2012) noted, smart streetlight systems can reduce energy consumption while simultaneously improving monitoring and safety. These findings reinforce the idea that smart poles are not merely illumination devices but strategic urban assets that strengthen urban resilience.

The integration of advanced technologies into public utilities further supports the relevance of this study. For instance, Kyee and Moin (2018) employed metaheuristic approaches for inventory distribution routing problems, illustrating how advanced algorithms can optimize public service delivery. Likewise, Rakwongwan et al. (2021) demonstrated the use of numerical visualization to model air pollution propagation, highlighting the role of data-driven approaches in urban planning. These studies illustrate the importance of combining technological innovation with infrastructure optimization to address complex urban challenges.

Moreover, Sjahruddin and Dahlan (2024) emphasize the need to incorporate resilience factors such as natural disasters and travel time uncertainty into optimization models for small and medium enterprises. Their findings resonate with the rationale for deploying smart poles, which can strengthen urban resilience by supporting emergency response systems and enhancing infrastructure adaptability.

In conclusion, the literature confirms the relevance of this research at the intersection of smart city development, traffic management, and location optimization. However, few studies have applied the SCP specifically to smart pole placement in secondary heritage cities with industrial significance. By addressing this gap, the present study contributes both theoreticallyby extending SCP applications to multifunctional urban assetsand practicallyby offering insights into cost-efficient deployment strategies that enhance quality of life, public safety, and infrastructure resilience in Thai urban contexts.

3.   Preliminaries

3.1.   Set Covering Problem

The set covering problem is a mathematical modeling technique used to solve decision-making problems. It uses a 0-1 matrix to simulate a situation where the selected representatives cover all target groups. The objective is to ensure that the selected representatives cover all target groups, which may involve selecting more than one representative. For example, setting up a distribution

center to cover at least one customer group. If the distribution center j can serve area i, the value is 1, and 0 otherwise. In the set covering problem, we consider a matrix of 0s and 1s with rows i, where $i \in \{1, 2, 3, \ldots, m\}$, and columns j, where $j \in \{1, 2, 3, \ldots, n\}$. When x_j is a binary decision variable, $x_j = 1$ if column j is selected, and $x_j = 0$ otherwise.

Minimization Problem

The problem of decision-making that requires a minimum value answer can be formulated mathematically by writing the objective function and constraints in the form of equations:

Objective function

$$\min \sum_{j=1}^{n} c_j x_j$$

Constraints

$$\sum_{j=1}^{n} a_{ij} x_j \geq 1, \quad \forall i \in \{1, 2, \ldots, m\},$$

$$x_j \in \{0, 1\}, \quad \forall j \in \{1, 2, \ldots, n\}.$$

Here, A is an incidence matrix of size $m \times n$, where each row corresponds to an element and each column corresponds to a set. The element $a_{ij} = 1$ if element i is in set j, and $a_{ij} = 0$ otherwise. Then, the covering constraint can be written as $Ax \geq 1_m$ where 1_m denotes an m-dimensional column vector of ones.

m denotes the number of rows, representing the items or groups that need to be covered.

n denotes the number of columns, representing the potential covering options (e.g., distribution centers).

Each element a_{ij} in the matrix is either 0 or 1. The value 1 indicates that the covering option j can cover the item or group i, while the value 0 indicates that it cannot.

c_j represents the cost of selecting the covering option j.

x_j: is a binary decision variable, where $x_j = 1$ if covering option j is selected, and $x_j = 0$ otherwise.

The constraints ensure that each item or group i is covered by at least one selected covering option. The objective function minimizes the total cost of the selected covering options. An example of the problem of selecting service locations to cover all user demands with the minimum number of service locations is shown in Figure 2.
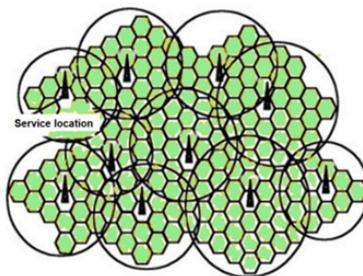
Figure 2 Illustrates the challenge of choosing the least number of service locations that can adequately meet all user demands

3.2. Principles and theories used in the research work
3.2.1 Smart poles

Smart poles are a modern technology and innovation in the era of technology, also known as the Smart City. They incorporate technology, innovation, and creative ideas to create new things

with diverse functions and can support contemporary innovations without limitations and with high efficiency. These reflect the potential of improved urban infrastructure and better quality of life for the people. The main components of smart poles are:

1. Smart pole covers that can accommodate lighting and control devices.
2. Bright lighting systems that provide 360 illumination and high brightness.
3. Wi-Fi internet signal distribution system covering a range of 100 meters.
4. Projector.
5. Warning lights that respond quickly and operate 24 hours a day.
6. 360 camera with features such as image sensors, low light mode with IR, high-resolution video compression, high bitrate video, 3-axis adjustment on-site, motion detection sensors for both day and night and multi-level lighting control. The program can detect motion and cover a wide area.
7. Sound system with speakers and Wi-Fi signal amplifier.
8. Digital signs.
9. Emergency notification buttons that can communicate with responsible officials. Equipped with cameras, speakers, and IP communication systems.
10. EV charging stations.

3.2.2   The honeycomb theory

The honeycomb theory highlights bees' efficient use of hexagons in their hives for optimal honey storage and energy conservation. Hexagons, squares, and equilateral triangles can fill a space without gaps, but hexagons use the shortest perimeter, making them the most efficient. Unlike shapes like circles, hexagons avoid wasted space, reducing bees' workload and maximizing honey storage. Hence, hexagonal partitioning is a highly efficient spatial utilization method with practical design applications.

3.2.3   Choosing the right location for smart streetlights

Selecting suitable smart streetlight locations is key to maximizing coverage, accessibility, and maintenance. Factors to consider include:

1. High-traffic roadside areas for safety and convenience.
2. Business districts with high population and commercial activity, enhancing the business environment.
3. Public parks, where smart streetlights provide safety and comfort for visitors.
4. Market areas with dense populations and heavy traffic are frequently used for community events, where smart streetlights enhance the atmosphere.

The right location maximizes smart streetlights' effectiveness in safety improvement, energy conservation, and enhancing residents' quality of life.

4.   Research Methodology

The methodology for finding the most suitable locations for installing smart streetlights in Phra Nakhon Si Ayutthaya district, Phra Nakhon Si Ayutthaya province, involves the application of set covering problems. The research process consists of six main steps, as follows:

Step 1: **Import the study area's Geographic Information System (GIS) maps.**

For this research, GIS maps of the study area, Phra Nakhon Si Ayutthaya district in Phra Nakhon Si Ayutthaya province, were imported using QGIS software. These maps guide the project in identifying the most suitable locations for installing smart streetlights. The imported geographic map data for the Phra Nakhon Si Ayutthaya District, located in the Phra Nakhon Si Ayutthaya Province, is shown in Figure 3.
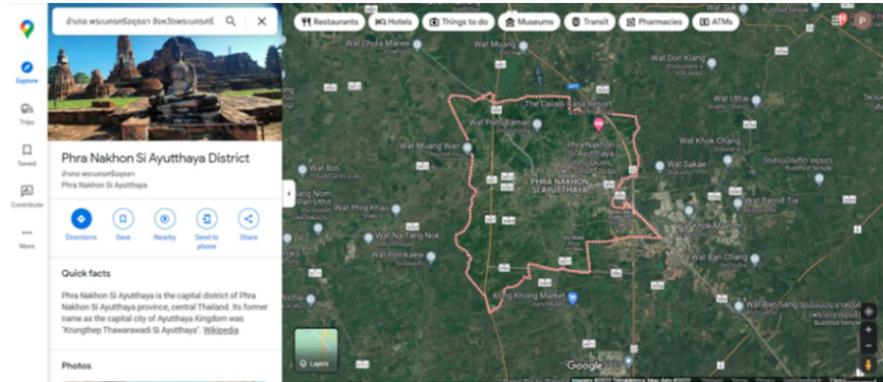
Figure 3 Area survey operations on Google Maps, Phra Nakhon Si Ayutthaya District, in Phra Nakhon Si Ayutthaya Province

Figure 4 Smart streetlights with the components in the research project

Step 2: **Importing Smart Streetlight Data.**

Import smart streetlight data with components according to Section 3.3.1. An example of a Smart streetlight with the components in the research project is shown in Figure 4.

Step 3: **Subdivide the Area into Sub-areas According to the Principles of Beehive.**

The research subdivides the Phra Nakhon Si Ayutthaya district using QGIS software into a hexagonal grid inspired by beekeeping theory. This grid, with a spacing of 90 meters, is based on smart streetlight illumination and camera coverage. As illustrated in Figure 5, smart street-lights placed within this 90-meter hexagon (marked yellow) can serve surrounding hexagons within a 150-meter camera coverage radius.

Step 4: **Collecting Areas with Potential for Smart Streetlight Installation.**

This step can be divided into the following sub-steps:

Step 4.1: **Survey the entire area and identify the study area boundary.**

Google Maps, providing real-time online maps with satellite images, will be used to survey the study area. The researchers will examine 33,415 sites to determine suitable locations for smart streetlight installation, considering roadside areas, business districts, public parks, and marketplaces. The survey operations conducted on Google Maps are shown in Figure 3.
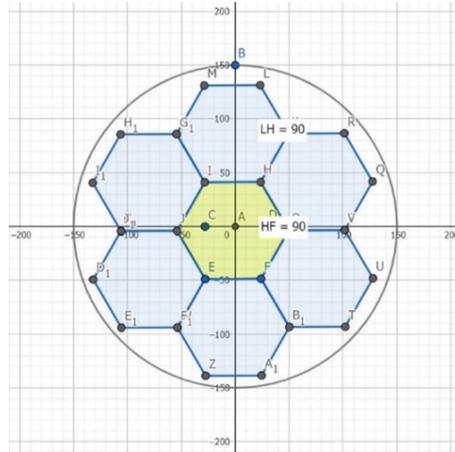
Figure 5 Simulation of the installed hexagonal shape and the surrounding hexagons within the 150-meter radius of the CCTV camera

Step 4.2: **Divide the area into hexagonal shapes according to beekeeping frames and assign area numbers.**
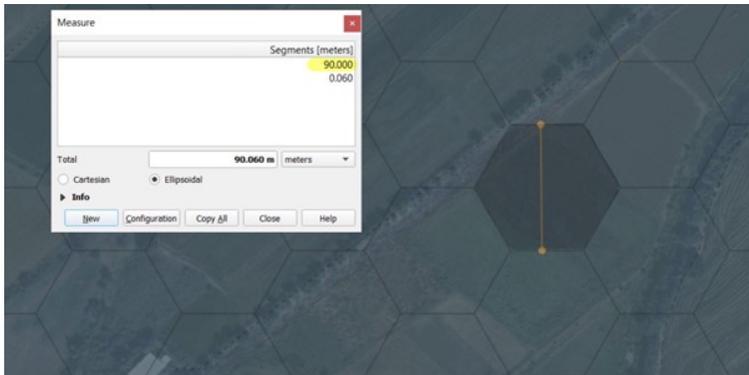
Figure 6 Hexagonal area in QGIS program with a size of 90 meters

After importing the area of Phra Nakhon Si Ayutthaya district, Phra Nakhon Si Ayutthaya Province, the next step will be to divide the area into hexagonal shapes according to the pattern shown in Figure 6. Then, numbers will be assigned to each hexagonal area, and they will be labeled accordingly. This will result in 33,415 hexagonal areas covering Phra Nakhon Si Ayutthaya district, Phra Nakhon Si Ayutthaya Province, as shown in Figure 7.

Step 4.3: **Select and determine areas with potential for smart streetlight installation.**

Microsoft Excel will be used to survey and select areas for potential smart streetlight installation, coded blue, while unsuitable areas will be coded black. This color assignment depends on geographic features, road areas, rivers, canals, buildings, houses, forests, and fields. The total potential smart streetlight installation sites are 1,874 (Figure 8). These sites fall within a 150-meter radius of each smart streetlight's CCTV. Table 1 shows the potential locations for each smart streetlight.

Figure 7 Number labels assigned to each hexagon to represent the coverage area of Phra Nakhon Si Ayutthaya District, Phra Nakhon Si Ayutthaya Province, with 33,415 hexagons covering the entire area

Figure 8 All suitable positions for installing smart streetlights in Phra Nakhon Si Ayutthaya district. The black area represents the entire district area, while the yellow area represents all 668 suitable positions for installing smart streetlights

Table 1 Arrangement of areas covered by the radius of 150 meters of the smart streetlight, with the probability of installing the smart streetlight at each location (partial results)

No.	Suitable area locations	Covered area locations					
1	1321	1320	1483	1484	1322	1158	1157
2	1484	1483	1647	1648	1485	1322	1321
3	1648	1647	1810	1811	1649	1485	1484
4	2139	2138	2302	2303	2140	1977	1976
5	2303	2302	2465	2466	2304	2140	2139
6	2466	2465	2629	2630	2467	2304	2303
7	2467	2466	2630	2631	2468	2305	2304
8	2631	2630	2793	2794	2632	2468	2467
9	2794	2793	2957	2958	2795	2632	2631
10	3766	3765	3929	3930	3767	3604	3603
11	3767	3766	3930	3931	3768	3605	3604
12	4103	4102	4266	4267	4104	3941	3940
13	4267	4266	4429	4430	4268	4104	4103
14	4272	4271	4434	4435	4273	4109	4108
15	4918	4917	5080	5081	4919	4755	4754
16	4923	4922	5085	5086	4924	4760	4759
17	5081	5080	5244	5245	5082	4919	4918
18	5084	5083	5247	5248	5085	4922	4921
...	...	...	...	...	...	...	...
668	28624	28623	28787	28788	28625	28462	28461

Step 5: **Creating a Mathematical Model.**

This research utilizes the Set Covering Problem (SCP) to identify optimal locations for installing smart streetlights, ensuring all requirements are met with the minimum number of installations. The mathematical model is formulated as follows

Decision Variable

$$x_j = \begin{cases} 1, & \text{if the area with the possibility of installing smart streetlight } j \text{ is selected,} \\ 0, & \text{otherwise.} \end{cases}$$

Matrix Representation Let a_{ij} denote an element of a 0-1 matrix A, where

$$a_{ij} = \begin{cases} 1, & \text{if area } j \text{ can cover requirement } i, \\ 0, & \text{otherwise.} \end{cases}$$

Objective Function

The objective is to minimize the total number of areas selected for installing smart streetlights:

$$\text{Minimize } Z = \sum_{j=1}^{1,874} x_j \tag{1}$$

Constraints

Each area i must be covered by at least one smart streetlight, ensuring complete service coverage

$$\sum_{j=1}^{1,874} a_{ij} x_j \geq 1, \quad \forall i \in \{1, 2, \ldots, 1, 874\} \tag{2}$$

The decision variable x_j is restricted to binary values, where $x_j = 1$ indicates that location j is selected for installation, and $x_j = 0$ indicates it is not:

$$x_j \in \{0, 1\}, \quad \forall j \in \{1, 2, \ldots, 1,874\} \tag{3}$$

The objective function aims to minimize the number of selected areas, balancing cost-efficiency and service effectiveness. The first constraint ensures that every requirement is covered by at least one selected location, guaranteeing that all areas fall within the service range of a streetlight. Finally, the binary constraint restricts the solution to a feasible set of decisions, making the model practical for implementation. This formulation ensures all user requirements are met while minimizing the number of installations needed.

Step 6: **Finding the Results.**

In this step, IBM CPLEX software is used to find the optimal positions for installing smart streetlights based on the data collected in Step 4 and the mathematical model developed in Step 5.

5.   Research Findings

Following the research procedures outlined in Section 4 and using IBM CPLEX software to calculate the results of the model developed in Step 6, the suitable areas for installing smart streetlights are presented in Table 2. A value of 1 indicates that the location is suitable for smart streetlight installation, while a value of 0 indicates that the location is not suitable. The research findings indicate that there are 668 suitable locations for smart streetlight installation in the study area, as shown in Table 2. When the results from Table 2 are plotted on a map showing the location of the smart street light installations, the result is shown in Figure 8. The black areas represent the entire area of Phra Nakhon Si Ayutthaya District. In contrast, the yellow areas represent all the suitable locations for the smart street light installations in Phra Nakhon Si Ayutthaya District, totaling 668 locations.

Table 2 Suitable areas for installing smart streetlights in Phra Nakhon Si Ayutthaya district, Phra Nakhon Si Ayutthaya province, totaling 668 locations (partial data).

| Row/Column	1	2	3	4	5	6	...	15	16
1	1484	7524	8441	10527	12140	13421	...	25476	28286
2	2303	7527	8444	10541	12265	13424	...	25497	28287
3	2631	7529	8446	10638	12300	13438	...	25633	28441
4	3766	7532	8461	10656	12309	13460	...	25640	28445
5	4103	7535	8532	10669	12314	13559	...	25644	28453
6	4272	7538	8551	10824	12320	13567	...	25655	28458
7	4756	7540	8589	10837	12433	13589	...	25674	28618
8	5081	7556	8592	10846	12438	13595	...	25680	28623
9	5085	7705	8597	10983	12450	13598	...	25787	
...	...	...	...	...	...	...	...	...	...
43	7414	8436	10500	12100	13302	14690	...	28117	
44	7519	8438	10513	12128	13307	14708	...	28284	

6.   Application of Research Results

In this section, we present ideas for applying the research results in the form of an application that connects to the smart light pole and a preliminary study of the applications use.

6.1. Smart Lighting Research Application Ideas

This section outlines practical applications of smart light poles, including adaptive lighting systems, environmental sensing, integration with smart city infrastructure, energy efficiency, traffic management, and public safety. Aimed at enhancing urban life quality, these applications are graphically represented in Figure 9. The Smart Streetlight application can be used as follows:

1) Download the app from the Play Store or App Store.

2) Create a user account (for first-time users).

3) Login if an account exists.

4) Reset password via email if forgotten.

5) Dial emergency number 1669 through the app.

6) Locate nearby smart streetlights.

7) Display directions to nearby smart streetlights via Google Maps.

8) Access additional options or log out by selecting the three-line icon in the top left corner.
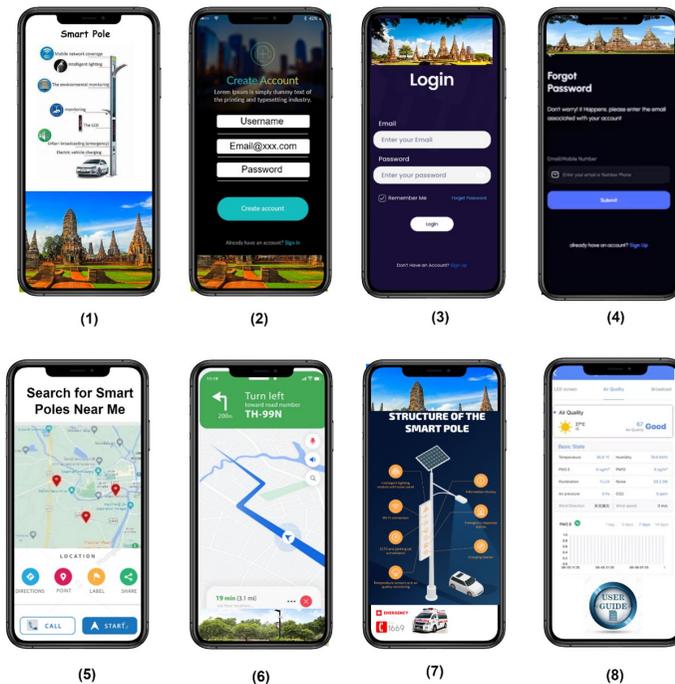
**Figure 9** Infographic showing the applications connected to the Smart Streetlight application

6.2. Possibility of preliminary research work

6.2.1   Business model canvas

The research data has led to the development of a Business Model Canvas (Figure 10), an essential tool to outline a business model visually. Given the significant costs of infrastructure development, government, and private sector support via joint investment or sponsorship is crucial. Revenue from the project may arise from data services, advertising, and surveying equipment installation.

The Canvas, commonly used in strategic management and entrepreneurship, offers a comprehensive framework to understand and design a business model. It considers customer segments, value propositions, revenue streams, key partners, key activities, key resources, channels, customer relationships, and cost structure.

In this project, the Business Model Canvas delineated the feasibility of installing smart streetlights in Phra Nakhon Si Ayutthaya District, outlining potential revenue streams, key partners, and associated costs. The Canvas proved instrumental in evaluating project viability and identifying strategies for success.
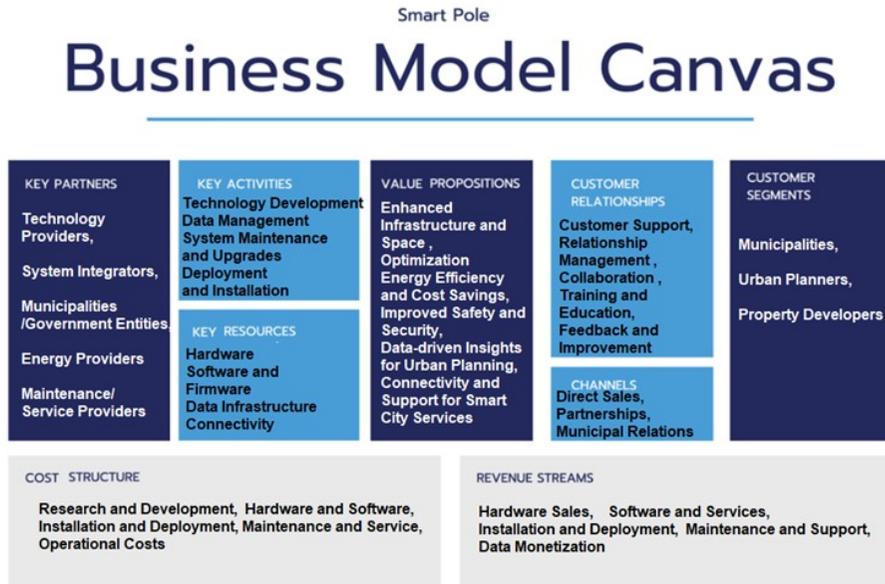
Figure 10 The business model for the development of smart cities using intelligent streetlights

6.2.2 Evaluation and comparison of location, status, and performance of installations

The shift towards smart cities, enabled by smart streetlights, presents promising opportunities and significant challenges. Existing initiatives in Songkhla, Nakhon Si Thammarat, and Phitchit provinces serve as models for safety and smart city evolution, Figure 11. However, achieving full coverage remains elusive due to difficulties in finding suitable installation spots, leading to increased costs and incomplete user needs coverage.

Phra Nakhon Si Ayutthaya District was identified as a potential model for smart streetlight installation to strategically position these lights for user needs fulfillment and cost optimization.

There's a clear contrast between areas lacking smart streetlights and those with installation potential. Installing smart streetlights in promising areas like Phra Nakhon Si Ayutthaya District could yield significant benefits including improved safety, convenience, and additional services. However, careful selection of installation sites is critical to ensure adequate user needs coverage and control costs. These contrasts are visually represented in Table 3.

6.2.3 Analysis of beneficiaries and the level of value that can be utilized

Smart streetlights, aimed for installation in Phra Nakhon Si Ayutthaya District, are designed for residents and commuters. These universally beneficial features cater to all ages and genders. The streetlights, practical in daily life, bring value to the community.

Figure 11 News coverage of the installation of smart streetlights in the provinces of Songkhla, Nakhon Si Thammarat, and Phitchit

Table 3 Comparison of smart streetlight installations in Phra Nakhon Si Ayutthaya District, Phra Nakhon Si Ayutthaya Province

There is no installation of smart streetlights.	Install smart streetlights.	
	Proceed with the research work.	Not carried out according to the research project
No smart streetlights, or devices for safety and convenience, are installed.	Smart streetlights are in use.	Smart poles are available for use.
No smart streetlights, or devices for safety.	There are smart streetlights in use as equipment for creating safety and convenience.	There are smart poles as equipment to provide safety and convenience.
-	Smart poles cover the needs of users.	Smart poles may only meet the needs of some users.
-	Reduce the cost of installing smart poles.	There is an uncertain cost in installing smart poles.

One key benefit is the 360-degree CCTV cameras with a 150-meter radius, providing round-the-clock recording. Emergency buttons alert authorities, while the lights enhance nighttime safety. Additional features include digital information boards, sound systems, and electric vehicle charging stations.

Thus, installing smart streetlights is expected to enrich the community, providing practical utilities that enhance daily living and contribute to residents' and commuters' convenience and safety.

7. Conclusion and Discussion

Envisioning Thailand as a smart city with high living standards, this project seeks to optimize the placement of smart streetlights in Phra Nakhon Si Ayutthaya District. The goal is to enhance safety, energy efficiency, and quality of life while minimizing installation costs, positioning the city as a potential model for future smart city development in Thailand. By integrating cultural heritage with digital infrastructure, Ayutthaya can serve as a blueprint for balancing modernization with historical preservation.

7.1. Theoretical contribution

This study advances the literature on smart city planning by applying the set covering problem (SCP) to optimize the placement of smart streetlights. Theoretically, it demonstrates that urban infrastructure planning can benefit from operations research methods traditionally used in logistics and

facility location. By linking smart city development to mathematical optimization, this research enriches the body of knowledge on how computational models can inform urban resilience, efficiency, and safety. In particular, the integration of SCP into secondary heritage cities fills a gap in existing literature, offering insights into how mathematical optimization can address both cultural sensitivity and modern urban needs.

7.2.   Model selection and results

Using a linear programming approach to the SCP, the study identified 668 optimal locations for smart streetlights from 1,874 potential sites across 33,415 grid cells. This model balances cost minimization with maximum service coverage, ensuring that residents, commuters, and tourists alike benefit from improved safety, connectivity, and convenience. The results validate that SCP is an effective framework for urban infrastructure design, particularly in secondary cities with high cultural and economic significance such as Phra Nakhon Si Ayutthaya. Importantly, the findings show that concentrated coverage is achieved in high-traffic areas, business districts, and heritage zones, thereby aligning the mathematical outcomes with practical urban priorities.

7.3.   Application to practice

In practice, the findings provide policymakers, city planners, and local authorities with an evidence-based framework for strategically deploying smart streetlights. The optimized placement reduces redundant investment, enhances energy efficiency, supports traffic monitoring, and strengthens public safety. More broadly, this framework can serve as a transferable model for other Thai cities aspiring to smart city development, particularly within the Thailand Smart City Master Plan that highlights pilot areas such as Phuket, Chiang Mai, and the Eastern Economic Corridor (EEC). By incorporating this optimization approach, infrastructure investment can be more cost-effective, citizen-centered, and aligned with national development strategies.

7.4.   Critique of results and future work

While the study demonstrates the value of applying SCP to smart city planning, limitations remain. The analysis is constrained by static assumptions and historical data, which may not fully account for future urban growth, population mobility, or technological advances. Moreover, socio-economic challenges such as budget allocation, public acceptance, and long-term maintenance were beyond the scope of this study but are critical for real-world implementation. Future research could integrate dynamic models, real-time data (e.g., IoT sensors, traffic flows), and metaheuristic optimization to capture uncertainties and improve adaptability. Additionally, exploring multi-objective optimizationbalancing cost, environmental impact, cultural heritage preservation, and social equitywould strengthen the applicability of the framework to complex urban environments.

In summary, this research contributes to theory by extending operations research applications to smart city planning, to methodology by demonstrating SCP-based optimization for infrastructure, and to practice by providing a replicable model for policymakers. Together, these contributions reinforce Thailands pathway toward sustainable, equitable, and technologically advanced urban development.

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