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A Two-Stage Optimization Framework for Camera Placement in Campus Dormitory Security Networks

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Abstract

Campus security is vital in providing a safe and conducive environment to students and other residents of a college university. However, the existing CCTV surveillance system in the Lower Campus' dormitory areas of University of the Philippines Los Baños is inadequate in coverage and contains multiple blind spots. This study formulates the surveillance problem as an optimal camera placement (OCP) problem and implements a two-stage optimization framework to find the solution. The study considered a total of four cases. The three primary cases focused on CCTV placements at main entry/exit points. The minimum number of CCTV installation spots was 9, 10, and 11 for Cases 1, 2, and 3, respectively. The minimum number of CCTV cameras for all 3 cases was 23 cameras corresponding to the 23 streets in the area. The last case is an enhanced case where existing cameras in the area were incorporated in the model, where the minimum number of CCTV locations was reduced to only 6 additional locations. All of the CCTV surveillance systems obtained in this study provided improved surveillance by eliminating blind spots while using the minimum number of installation locations and minimum number of cameras, providing cost-effective security enhancement in the UPLB Lower Campus dormitory areas.

1 Introduction

Security is defined as ”the state of being away from hazards caused by deliberate intention of human to cause harm” [28]. Ensuring security within a community is essential for reducing crime and violence, thus fostering a sense of safety and well-being among its residents. Reliable security not only protects the individuals, it also provides an environment conducive to sustained development [21]. However, campus security remains vulnerable to various threats. There are universities with common campus crimes that include cult-related violence, drug offenses, kidnapping, firearm possession, student unrest, election-related conflicts, theft, break-ins, and sexual assault [13]. Victimized students often suffer academically [25], while the fear of crime can negatively affect attendance even among non-victims [32] since exposure to crime can lead to mental health issues such as trauma, depression, anxiety, substance abuse, and violent behaviors [7]. Overall, crime compromises student well-being and academic success, making campus security a top priority for educational institutions.

Closed Circuit Television (CCTV) systems are used for security surveillance. Such networks consist of cameras installed in strategic places, and remotely connected to devices for viewing [26]. Crime rates in UK, North America, and Polish cities were reduced by 13–21% in areas with CCTV [34, 31, 30, 27]. Market analyses for 2025–2030 indicate a growing demand for video surveillance systems in the Philippines, largely driven by increasing crime rates [**?**]. Empirical research has also documented that CCTV systems contribute to crime prevention by discouraging offenses against persons and property, while also supporting criminal investigations and the identification and apprehension of suspects [12, 2]. However, the effectiveness of CCTV systems is not determined solely by the number of installed cameras. Prior studies highlight that surveillance performance is strongly influenced by the spatial coverage of the system, emphasizing that strategic camera placement is essential for maximizing security outcomes [6, 14, 23].

The optimal camera placement (OCP) problem addresses the challenge of minimizing the number of CCTV cameras installed while maintaining sufficient coverage [38]. It is a form of the classical set-covering problem in combinatorial optimization, where cameras serve as sets that cover specific areas such as streets or intersections [17]. [3] combined road network and grid approaches to optimize camera placement in a campus. They assumed camera placement at every road intersection, with each segment covered by at least one camera. While using binary integer programming, they also acknowledged limitations such as static layout assumptions, simplified surveillance zones, and computational overhead. Gaylon et al. [16] addressed this issue by developing an algorithm to optimize camera placement in Intramuros, Manila. Their II-Phase approach (i.e., binary integer programming (BIP) followed by heuristic optimization) ensured coverage of all entry and exit points while minimizing the number of cameras used. Despite numerous studies on CCTV effectiveness and placement optimization [34, 30, 31, 27], few focus specifically on campus settings.

Although binary integer programming has been widely used for camera placement optimization, its application is subject to several limitations, including assumptions of static spatial layouts, simplified representations of surveillance zones, and substantial computational requirements. To address these issues, Gaylon et al. [16] proposed an algorithm for optimizing CCTV deployment in Intramuros, Manila. Their two-phase (II-Phase) framework, which combines binary integer programming (BIP) with a subsequent heuristic optimization stage, was designed to guarantee coverage of all entry and exit points while simultaneously reducing the total number of cameras required. Despite numerous studies on CCTV effectiveness and placement optimization [34, 30, 31, 27], few focus specifically on university campus settings.

Now, the University of the Philippines Los Baños already uses a CCTV monitoring system. To ensure the safety and security of its constituents, the University's Security and Safety Office makes use of this surveillance system on the streets and establishments inside the campus, along with officers that patrol around the campus at night. However, the existing surveillance system exhibits spatial discontinuities, as evidenced by several street segments that fall outside the effective coverage of the CCTV units in the area. This study applied a similar graph-based two-stage optimization framework to optimize CCTV placement in UPLB's dormitory areas, aiming to enhance coverage while minimizing costs. This study adopts a similar approach to [16] and [3], targeting the dormitory area of UPLB.

This research aims to develop a mathematical model that can improve security monitoring around the lower campus dormitories of the University of the Philippines Los Baños (UPLB) through the strategic installation of CCTV cameras. Specifically, it aims to formulate an optimization problem for CCTV placements, solve the problem using the two-stage optimization framework; and propose improved CCTV surveillance systems in the target area.

1.1 CCTV Cameras as Security Measures

The use of Closed Circuit Television (CCTV) Cameras as security measures is categorized as a Situational Crime Prevention (SCP) technique. Clarke [10] states that situational crime prevention techniques function by deterring certain types of crime by manipulating the environment so that the associated risks of committing the said crimes are higher, while possibly lowering the rewards. The focus of this intervention is on the settings where crimes can occur instead of the criminal act itself. It uses discrete changes in management or environment to increase risks and lower rewards of potential crimes [11].

An SCP aims to reduce the opportunity for crimes. Felson & Clarke [15] introduced two theories, the Routine Activity Approach and Rational Choice Theory, that give an idea of how CCTV can help prevent crimes.

The Routine Activity Approach states that a potential crime must consist of three elements; a likely offender, a suitable target; and the absence of a capable guardian against crime [15]. This implies that every crime not only has an offender and a victim but there also exists a guardian that stands between the two. The guardian is any person or inanimate object whose presence deters or discourages the likely offender from committing a crime against the target. This includes guards, police, housewives, doormen, and other people who can be witness to the crimes. Hence, the absence of the guardian element gives the offender an opportunity to commit a crime.

On the other hand, the Rational Choice Theory inspects crime activities from the perspective of the offenders. It states that criminals behave rationally. They can think before they act, capable of evaluating the risks and rewards when committing a crime [15]. As rational humans, their decision-making in planning and committing crimes is based on the objective of minimizing risks and maximizing rewards. In short, the objective of criminals is to gain a net benefit when committing crimes.

CCTV cameras act as guardians whose presence discourages likely offenders from committing a crime. Their presence is similar to those of police, guards, or just a witness that poses a risk to them of being apprehended should they commit a crime. As the Rational Choice Theory suggests, criminals are less likely to consider committing a crime if the perceived risk is high, hence leading to less opportunity for crimes.

1.2 Effectiveness of CCTV Surveillance Systems

As mentioned in the previous section, there have been studies that examined the effectiveness of CCTV in reducing the incidence of crimes. Multiple studies have found that CCTV is capable of a significant or modest reduction in the incidence of crimes [34, 30, 31, 27]. In particular, a study conducted by Welsh & Farrington [34] on the effectiveness of CCTV in the UK and North America, found that CCTV cameras are most effective in preventing crimes in car parks, especially when combined with good street lighting. Similar findings were observed in an updated systematic review and meta-analysis of the effect of CCTV surveillance on crime conducted by Piza et al. [30]. They found that the impact on car parks was the largest and most consistent. Moreover, they also observed that there are significant crime reductions in other settings such as residential areas. They also added that the use of CCTV in reducing crimes is more effective when used along with other interventions. In addition, some also found that CCTV tends to be effective in specific types of crimes. In the study of Welsh & Farrington [35], where they compared the effectiveness of street lighting and CCTV in preventing crime in public spaces, they found that both are equally effective in reducing crime, and both are more effective in reducing property crimes than violent crimes.

However, the effectiveness of CCTV surveillance also extends beyond crime deterrence, they can also be critical in crime investigations as sources of evidence. A study by Ashby [5] examined the value of CCTV cameras as investigative tools in railway environments. They found that CCTV surveillance cameras have been useful in investigations of several kinds of crimes, ranging from assaults, vehicle thefts, sexual offenses, and robberies. They also pointed out that previous studies that criticized the effectiveness of CCTV cameras failed to differentiate the availability of CCTV cameras from its effectiveness, highlighting that data implying the ineffectiveness of CCTV cameras may not have much CCTV. Furthermore, a recent study conducted by Kirui [24], also supports their findings, where it was found that CCTV significantly aided in not just crime investigations, but incident response as well. They said that CCTV was also valuable in incident awareness, traffic management, and crime detection. However, they also pointed out that limited coverage and technical issues can reduce the effectiveness of CCTV surveillance. Such limitations of CCTV cameras tell us that they also need proper strategy and plan when it comes to their implementation so that their effectiveness will be maximized.

1.3 Challenges in using CCTV Cameras

Given the effectiveness of CCTV cameras, it might be intuitive that a higher quantity of cameras leads to an increase in their effectiveness in ensuring security. Except, according to [6], there is little correlation between the number of public CCTV cameras and crime or safety. This is because a large number of cameras does not necessarily guarantee high coverage. A study by Farrington et al. [14] found that a high degree of coverage can positively affect the effectiveness of CCTV cameras in deterring crimes. They said that low coverage may not deter potential criminal offenders because it gives them blind spots where they can commit crimes without being seen.

Similar findings were observed in another study on the impact of poor camera placements. The study of Keval [23] showed that poor camera positioning can lead to blind spots, and criminals tend to be aware of this flaw as observed by the patrols nearby as they saw criminals exploiting the blind spots. That way, the crime is not visible to the cameras and the value of CCTV in maintaining security diminishes.

However, increasing the number of cameras in an area does not immediately guarantee the security of the area. The placement of the cameras matters and must be strategically placed in the area such that the coverage is maximized and there are no blind spots that can be exploited, while also minimizing the cost or number of cameras to be used to make the system cost-effective. This problem can be viewed as an optimization problem, in particular, a set covering problem.

1.4 Mathematical Modeling in CCTV Camera Placement

Implementing a security system in the form of CCTV cameras comes with financial costs. Thus, it is in the best interest to find the minimum number of cameras while still maintaining specific or maximum coverage. This problem is called the optimal camera placement (OCP) problem [38]. It is an example of a set-covering problem in combinatorial optimization, where the goal is to find the minimum number of sets to cover all necessary elements [17]. CCTV represents sets that are capable of covering elements, which are often specific areas, roads, or streets.

The optimal camera placement is very similar to an old optimization problem from combinatorial geometry called the Art Gallery Problem or AGP. The goal of AGP is to find the minimum number of guards needed to guard the interior of an art gallery [29]. However, according to Gaylon et al. [16], results of AGP may not be effective in real life because they are highly theoretical. On the other hand, there have been multiple studies that solve the optimal camera placement problem using different optimization and approximation techniques.

The study of Hörster & Lienhart [20] is one study that tackled the optimization problem In their study, they solved the placement of cameras in a room that gives maximum coverage or specific coverage by treating the area of interest as a 2D grid space. It should be noted that, in their study, they considered the respective field-of-view of each camera in calculating the overall coverage of solutions. They used different approaches in solving for the solutions which can be categorized into two; exact algorithms which give exact solutions but are time/memory costly, and heuristics which do not guarantee the global optima but can give the solution in reasonable time with reasonable complexity. Their findings showed that BIP was suited for optimizing camera placement in small rooms, and heuristic algorithms were much suited in large rooms where it was computationally costly to use BIP.

Similarly, a study by Zhao et al. [38] also used BIP to model the camera placement problem, and presented various approximate methods similar to the study of Hörster & Lienhart [20]. They stated that the problem can fall under two general camera placement problems: minimization of camera resources subject to a performance constraint, and maximization of performance subject to a resource constraint.

Another study by Ahn et al. [4] presented a somewhat different approach, dividing the algorithm into two phases. First, we should note that their study is similar to the study of Hörster & Lienhart [20] where they modeled the target area as a 2D grid space and also took into account the field-of-vision of the cameras in determining its coverage. However, in modeling the space, they assumed that the surveillance area had no obstacles that could obstruct the view of the cameras. Now, the first phase of their algorithm uses BIP to solve for a solution in a low-resolution 2D space, and in the second phase, they attempt to arrive at a more realistic solution by using the hill-climbing method in a model area with high-resolution grids. They were able to apply this 2-phase algorithm to satellite map images of actual landscapes from Korea.

All of these studies modeled the target environment as a 2D grid space in which they plotted the possible camera placement locations, and some also plotted the important areas that needed to be in the coverage of the surveillance system. All of the studies recognized that the optimal camera placement problem is a type of set covering problem, which led them to formulate the problems as BIP problems. The general finding among them was that using BIP in finding exact solutions can be computationally intensive and is only applicable to small-scale problems. Hence, they leaned more towards the heuristic approach or approximation methods to approximate the exact solution. However, there are other ways to model the environment of a camera placement problem. For example, some studies tried to model the environment using the road network of the area instead of treating it as a 2D grid space.

In the study by Afriyie et al. [3], they used a combination of grid space and road network approach by simply overlaying the grid space over the road network. The objective of the study was to increase campus security by optimizing camera placement within Clemson University. They also used BIP to formulate the problem, and they also took into account the field of view of the cameras. One key assumption they made was that there should be cameras at every road intersection such that each street segment is monitored by at least one camera. They also laid out multiple limitations of the model: the road and campus layout are static, Pan-Tilt-Zoom (PTZ) cameras are used, environmental factors (lighting, weather, or obstruction) are not considered, surveillance zones are simplified, BIP may be computationally expensive to solve for larger campuses.

However, the study by Gaylon et al. [16] focuses completely on using the road network instead of the grid space. Their study was conducted in Intramuros, Manila, Philippines where the placement of CCTV cameras was optimized to increase security in the area as one of the most visited areas of Manila. They converted the road network into a 2D graph before formulating the problem as a BIP problem, similar to the previous studies. This problem is not as complex as the previous studies mentioned above because they did not model the environment space as a 2D grid space. Instead, they took a simpler approach to determine the coverage by focusing on monitoring the entry and exit points rather than calculating the camera's field of vision. They treated the problem much closer to a classical set-covering BIP problem. They modeled the road coverage as constraints in the BIP model, where the focus of the constraint is that all entry and exit points of the road network must be covered by the cameras. To solve the problem, they used a 2-phase approach as well, where Phase I solves for the optimal locations of the cameras by solving the BIP using an Excel solver, while Phase II solves for the orientation using a 4-step algorithm based on greedy heuristics.

This research study is similar to the last two studies mentioned above. It focuses on enhancing campus security within the University of the Philippines Los Baños Campus, particularly around the dormitory areas in the lower campus, which is similar to the motivation of the study of Afriyie et al. [3]. Given that the target area of this study is not as complex or large as the other studies mentioned above, the methodology used by Gaylon et al. [16] is more suited to this study. That said, the road network of the area was converted into a simplified 2D network graph, instead of overlaying it with a 2D grid space. The study also only focused on the entry and exit points of the road network to ensure coverage. The proposed 2-phase algorithm was also adapted to solve the problem. But, for Phase II of the algorithm, other heuristics were implemented other than the greedy heuristics approach.

Despite the growing number of studies on the effectiveness of CCTV in ensuring security and the optimization of camera placement for security, there are still few studies that focus on optimizing CCTV surveillance for campus security. Moreover, only one study has considered a simpler approach to modeling this optimal camera placement problem. This simpler approach refers to the representation of the road network as a simplified 2D graph and then focuses on monitoring the entry and exit points to ensure coverage. This study employs this approach to enhance campus security in dormitory areas of the University of the Philippines Los Baños.The model was implemented in Python using the Gurobipy module within Google Colab, which allows easy reproducibility of the results.

2 Methods

The two-stage framework of [16] was used to solve the OCP problem of improving the security surveillance in dormitory areas of UPLB through a CCTV surveillance system.

2.1 Graphical representation of the road network

The road network within the UPLB lower campus dormitory areas was modeled as a graph with intersections as nodes and streets as edges. The nodes serve as candidate CCTV installation spots. Fig. 1 shows graph $\mathscr{A}$ consisting of 18 nodes (labeled 1 to 18), and 23 edges (labeled with Roman alphabets A to X) which was constructed from a 2D map of the study area using Google Earth. Five nodes (i.e., nodes 1,2,4,9,18) were colored red to indicate the main entry/exit points. Additionally, vertex 8 represents two intersections that are sufficiently close to each other such that the cameras that will be installed can cover the incident roads of each other.

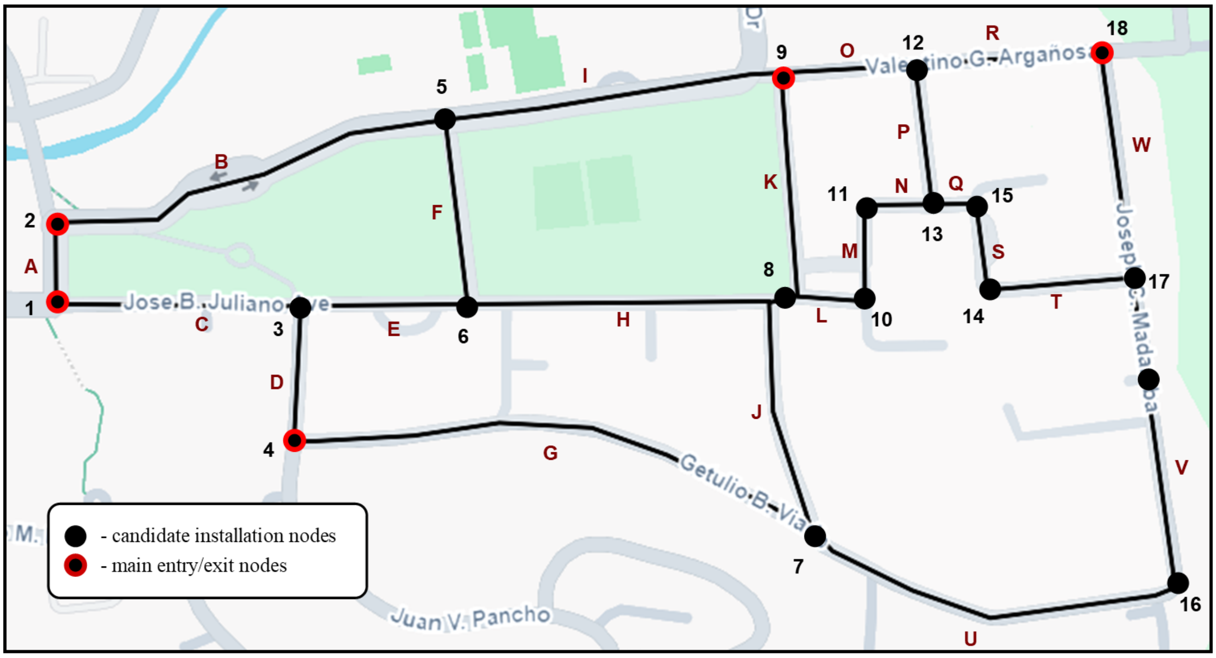


Figure 1: Graph $\mathscr{A}$ over the Google Earth map of the dormitory area of UPLB Lower Campus

2.2 Two-Stage Framework

The model assumes that all streets, represented by edges in graph $\mathscr{A}$ (Fig. 1), must be monitored by the surveillance system; a street (edge) is monitored by the surveillance system if either of its endpoints has at least one CCTV camera facing its direction; and each candidate installation spot has a corresponding installation cost c_i adapted from [16], and the installation at the main entry/exit nodes is prioritized, so the cost at these nodes is reduced.

2.2.1 Stage 1

Linear programming (LP) was used in the first stage of the model. The goal of this stage is to determine the optimal locations for the installation of CCTV cameras. Thus, the objective of the LP model is to find the minimum number of CCTV cameras that will cover all the streets of the area. The decision variable of the model is x_i where

$$x_i = \begin{cases} 1, & \text{if a CCTV camera will be installed at node } i \\ 0, & \text{otherwise} \end{cases}, \text{ where } i = 1, 2, ..., 18.$$

Each installation spot i has a corresponding installation cost c_i defined as

$$c_i = \begin{cases} 1, & \text{if node } i \text{ is a main entry/exit node} \\ 2, & \text{otherwise} \end{cases}.$$

Coverage of all the streets in the area is translated by the constraints below that ensure each edge e (where $e = A, B, ..., W$) of Graph $\mathscr{A}$ has at least one camera at the vertex i incident to j. Thus, the model has the following constraints,

$$\begin{array}{rlrlrl}
x_1 + x_2 \geq 1 & \text{[Street A]} & x_5 + x_9 \geq 1 & \text{[Street I]} & x_{13} + x_{15} \geq 1 & \text{[Street Q]} \\
x_2 + x_5 \geq 1 & \text{[Street B]} & x_7 + x_8 \geq 1 & \text{[Street J]} & x_{12} + x_{18} \geq 1 & \text{[Street R]} \\
x_1 + x_3 \geq 1 & \text{[Street C]} & x_8 + x_9 \geq 1 & \text{[Street K]} & x_{14} + x_{15} \geq 1 & \text{[Street S]} \\
x_3 + x_4 \geq 1 & \text{[Street D]} & x_8 + x_{10} \geq 1 & \text{[Street L]} & x_{14} + x_{17} \geq 1 & \text{[Street T]} \\
x_3 + x_6 \geq 1 & \text{[Street E]} & x_{10} + x_{11} \geq 1 & \text{[Street M]} & x_7 + x_{16} \geq 1 & \text{[Street U]} \\
x_5 + x_6 \geq 1 & \text{[Street F]} & x_{11} + x_{13} \geq 1 & \text{[Street N]} & x_{16} + x_{17} \geq 1 & \text{[Street V]} \\
x_4 + x_7 \geq 1 & \text{[Street G]} & x_9 + x_{12} \geq 1 & \text{[Street O]} & x_{17} + x_{18} \geq 1 & \text{[Street W]} \\
x_6 + x_8 \geq 1 & \text{[Street H]} & x_{12} + x_{13} \geq 1 & \text{[Street P]} & &
\end{array}$$

$$x_i > 0, \quad \text{for } i = 1, 2, \ldots, 18.$$

Lastly, to minimize the installation cost of the cameras, the objective of the model is given by

$$\text{Minimize } Z = \sum_i c_i x_i, \text{ for } i = 1, 2, \ldots, 18$$

The model was implemented using Python, version 3.11.11, and Google Colab, and the gurobipy package (version 12.0.1) was used to solve the LP Model [18].

2.3 Stage 2

The second stage of the algorithm applies a four-step procedure based on greedy heuristics. In this stage, the number of cameras to be placed at each identified optimal location, as well as the orientation of each camera, is determined using the solution obtained from Stage 1 as input. This stage was likewise implemented in Python (version 3.11.11) using Google Colab. In addition, the Python library networkx was employed to construct the graph $\mathscr{A}$ as a graphical network representation. This implementation facilitated the management of the graph's vertices and edges required for executing the greedy heuristics algorithm [19].

The model and its cases can be run and verified using a Google Colab notebook [9].

3 Results and Discussion

The OCP problem examined in this study was formulated under four scenarios. The first three scenarios addressed CCTV placement at the primary entry and exit nodes: Case 1, where surveillance at these nodes is prioritized but not mandatory; Case 2, where surveillance at the DTRI gate (Node 18) is required; and Case 3, where surveillance is mandated at all main entry and exit nodes. The fourth scenario incorporates the existing CCTV surveillance configuration currently implemented at UPLB.

3.1 Current CCTV Surveillance System

The locations of the cameras with non-redundant coverage, and its covered streets are reflected in Fig. 2. There are six cameras currently installed. Street F and Node 8 each have an omnidirectional unit, while Node 9, Node 15, Node 18, and Street V have fixed-orientation cameras. Node 18 has multiple cameras facing the same direction, so they were treated as one single camera for this study. Note that some of these are not located at the designated candidate nodes. Based on placement and orientation, the current system monitors nine out of 23 streets.

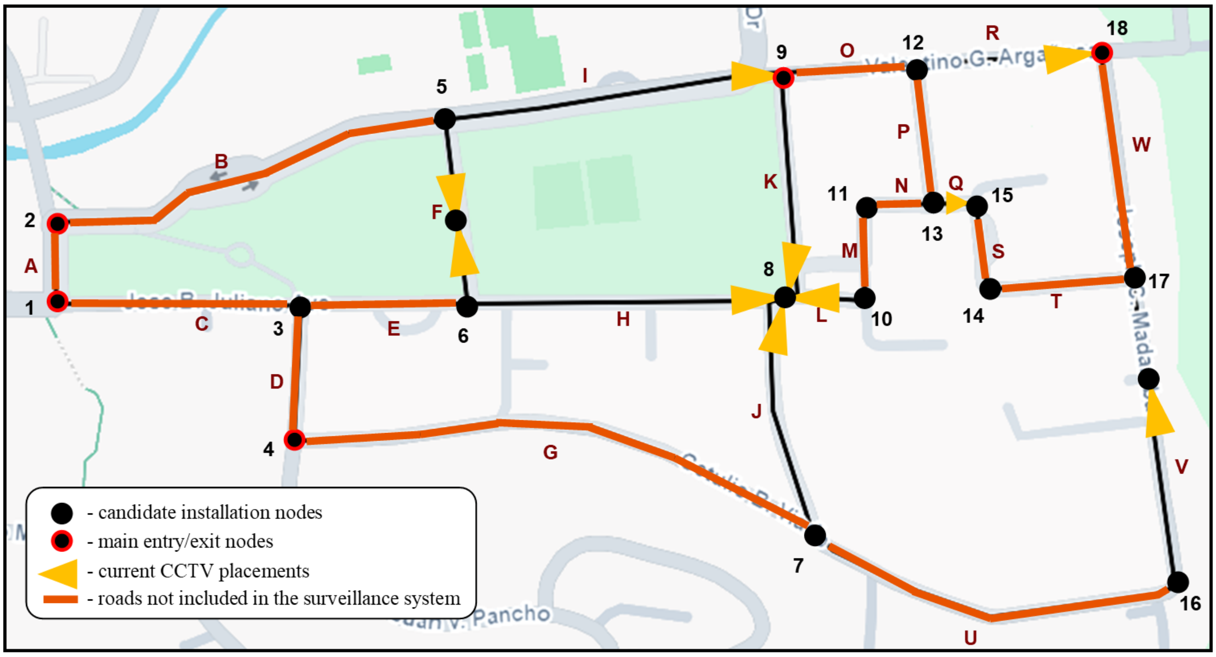


Figure 2: Current CCTV monitoring system in the dormitory area of UPLB Lower Campus

3.2 Two-stage Optimization Framework

This section presents the optimal solutions produced by the two-stage optimization approach for the three (3) cases following implementation in Python using the gurobipy package within Google Colab. The approach generated several possible or alternative solutions, which are discussed in the final subsection. The solutions reported in this subsection were selected based on having the fewest installation locations among the alternative solutions. In this study, the solution with the minimum number of installation nodes for each case was regarded as the optimal solution. These selected solutions are summarized in Table 1.

Three scenarios were examined, each differing in the assumptions regarding the main entry and exit nodes. For every case, the analysis produced several alternative solutions, which are discussed below. Table 1 presents the solutions that resulted in the fewest installation locations among the alternatives, with ties resolved arbitrarily.

Table 1: Number of optimal installation spots and no. of main entry/exit points with installed cameras of the best solutions in each case.

Case	**No. of installation spots**	**No. of main entry/exit spots with installed cameras**
Case 1: Prioritized but optional coverage of main entry/exit nodes	9	1
Case 2: Mandatory surveillance at Node 18 (DTRI gate)	10	3
Case 3: Mandatory surveillance at all main entry/exit nodes	11	5

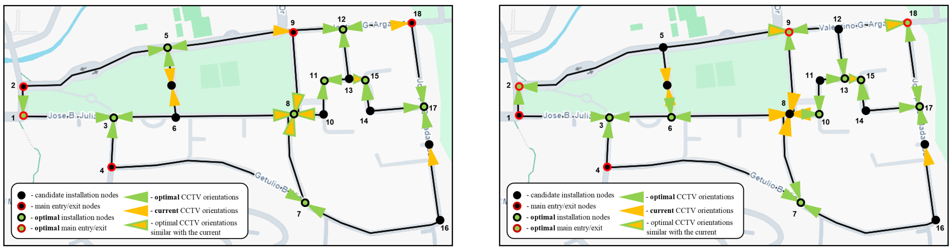
Table 1 shows that the number of installation spots increases as more main entry/exit nodes are assigned to have installed CCTV cameras. The detailed results for each case are presented in Fig. 3.

For all three cases, the results of the two-stage optimization framework proposed the installation of exactly 23 CCTV cameras, corresponding to the 23 streets, ensuring full coverage without redundant surveillance. The key difference between each case lies in the distribution of optimal installation nodes and how the surveillance at main entry/exit nodes will be.

In Case 1, the installation cost of cameras at the main entry/exit nodes was reduced to reflect the assumption that surveillance at these locations is prioritized but not mandatory. As illustrated in Fig. 3a, the resulting solution placed cameras at nine nodes, highlighted in green in the figure. Among these, one node corresponds to a main entry/exit point. Furthermore, the figure indicates that four optimal camera placements in the solution overlapped with the existing surveillance system.

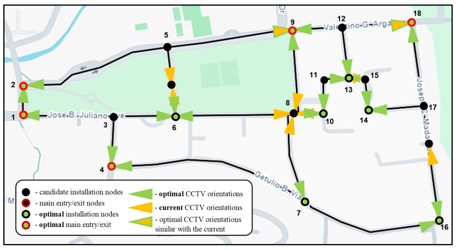
In Case 2, the installation of CCTV cameras directed toward each incident street of Node 18 is required. The DTRI gate, located at Node 18, serves as one of the limited entry/exit points of the campus, linking it to the external environment. Consequently, this case represents a scenario in which the node is considered a critical location requiring dedicated monitoring. The results obtained from the two approaches are presented in Figure 3b. The proposed solution recommends installing cameras at 10 nodes, three of which are main entry/exit nodes. Additionally, two optimal camera placements in the solution coincide with the current surveillance configuration.

In Case 3, the assumption regarding surveillance at main entry/exit nodes is modified so that camera installation at these nodes becomes mandatory. This condition enhances security by ensuring closer monitoring of vehicles and individuals entering or leaving the area. The solution generated by the two-stage optimization framework is shown in Figure 3c. The results suggest installing cameras at 11 candidate locations, which include all five main entry/exit nodes. Moreover, the solution indicates that two camera placements and orientations align with the existing setup: specifically, the camera at Node 9 facing Node 5 and the camera at Node 18 facing Node 12.



(a) Case 1: Prioritized but optional coverage of main entry/exit nodes

(b) Case 2: Mandatory surveillance at Node 18 (DTRI gate)



(c) Case 3: Mandatory surveillance at all main entry/exit nodes

Figure 3: Proposed CCTV surveillance systems obtained using two-stage optimization framework in the three cases

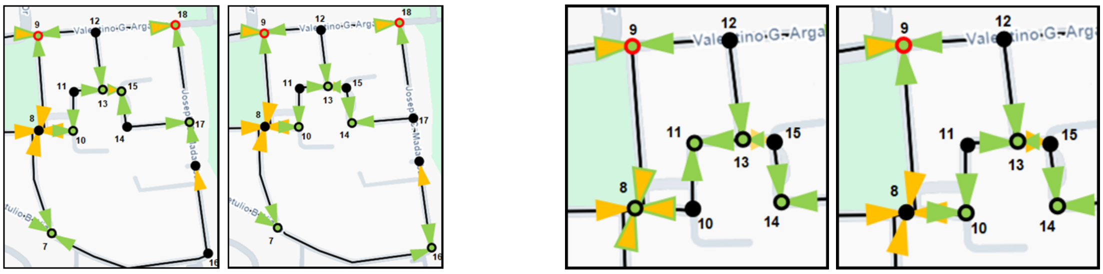
3.3 Alternate solutions

Alternate solutions are presented in this section. The tables outlining the results of each solution can be found in the appendix.

As shown in Table A1, the two-stage optimization framework yielded multiple solutions for each case. In Case 1, the number of optimal installation nodes varied from 9, 10, 11, with 1, 3, and 5 main entry/exit points, respectively. In Case 2, the number of optimal installation nodes was either 10 or 11, with no variation in the number of main entry/exit points across all alternate solutions. Lastly, in Case 3, both the number of optimal installation nodes and main entry/exit points were fixed across all alternate solutions, at 11 and 5, respectively.

The variations observed across alternate solutions for each case are explained by the formulation of the LP model. In the model, the cost of installing CCTV cameras at the main entry/exit nodes is reduced to prioritize installation at these nodes. The LP model found multiple allocations of camera placements that minimize the cost, as demonstrated by the existence of alternate solutions. In this study, these are largely due to the translocation of cameras, specifically the shifting camera placements while maintaining equivalent coverage.

In Table A2, further variations in the solutions are shown. It shows that the allocation of cameras at each node can also vary while still having the same coverage. This is most evident in Case 3 where the number of optimal nodes, and the number of main entry/exit nodes are constant. In Fig. 4 the translocation of cameras in solutions 1 and 4 from case 2 is shown.//



(a) Translocation from nodes 15 & 17 to nodes 14 & 16 (Case 2: Solutions 1 (left) & 4 (right)).

(b) Translocation from Node 11 to Node 13 (Case 3: Solutions 1 (left) & 3 (right)).

Figure 4: Camera translocations observed under the two-stage approach: (a) Case 2, (b) Case 3.

In Fig. 4a, Solution 1 includes Nodes 15 and 17 as installation points, whereas Solution 4 includes Nodes 14 and 16. This indicates that the cameras are effectively shifted from Node 15 to Node 14 and from Node 17 to Node 16, while still preserving coverage of the corresponding adjacent streets. Such behavior arises because neighboring nodes can compensate when the model relocates the optimal installation points, which in this instance are Nodes 15 and 17. A similar phenomenon occurs when two optimal installation nodes are adjacent to one another. An illustration of this situation is provided in Fig. 4b.

The camera translocation in 4b can be observed at Nodes 11 and 13. In Solution 1, a camera is installed at Node 11 facing Node 13. In contrast, Solution 3 places the camera at Node 13, oriented toward Node 11. Although the placement and orientation of the camera differ between the two solutions, the resulting surveillance coverage remains consistent and effective.

3.4 The UPLB Context

This section reexamines the study area within the context of dormitory areas of the lower campus of UPLB. Figure 3 shows that some optimal camera placements in the solutions coincide with the current CCTV system. These placements can potentially reduce the overall cost because the number of installations is reduced to achieve proper coverage. Table A3 summarizes the number of cameras already included in the solution for every alternate solution. This number ranged from 2 to 3 nodes in all three cases. When these preexisting installations are taken into account, the remaining optimal nodes requiring CCTV installation range from seven to nine. It can also be observed that the solutions with the fewest installation nodes are not necessarily those with the smallest number of remaining installation nodes once preexisting placements are excluded.

To further refine the optimal solutions generated by the two-stage framework, an additional case was examined. In this scenario, the constraints of the LP models were modified to exclude streets or edges already covered by the existing CCTV system. Under this modified formulation, the model produced a single solution. The resulting CCTV placement plan for this case is presented in Fig. 5.

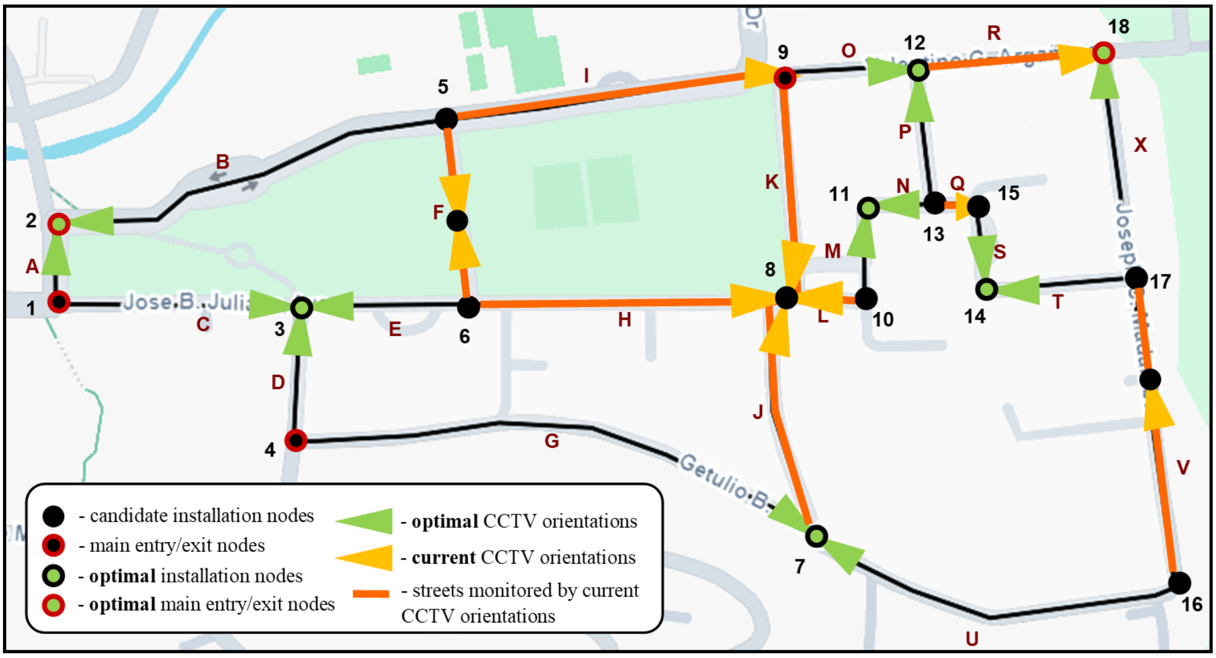


Figure 5: Proposed CCTV surveillance system obtained using two-stage optimization framework on the UPLB context case

As seen in Fig. 5, this case resulted in a single optimal solution with 7 installation nodes, one of which is already in place. Compared to the results of the previous cases, the UPLB context case yielded better results because it proposes the installation of only 6 additional CCTV cameras to address blind spots and provide complete coverage.

4 Conclusion and Recommendations

This study formulated the surveillance problem in the dormitory area of the Lower Campus of UPLB as an OCP problem. By applying the two-stage optimization framework, the OCP problem was successfully addressed. This section concludes the study by summarizing the principal findings and presenting recommendations for further improvement of the work.

The findings of this study demonstrate improved surveillance coverage for all streets within the dormitory area. Across all cases analyzed using the two-stage optimization framework, the resulting solutions produced enhanced surveillance configurations without blind spots, ensuring that every street segment within the study area was included in the monitoring coverage. The results also indicate that camera placements were allocated efficiently, avoiding redundant coverage across the monitored streets. Moreover, when the existing surveillance system was incorporated into the model, the number of additional optimal CCTV installation sites was further reduced. This integration leads to a surveillance configuration that enhances both effectiveness and security.

Based on these findings, the study recommends adopting the proposed camera placement configurations: three solutions corresponding to different priority assumptions for entry and exit nodes, and one solution that integrates the current surveillance system. These configurations may serve as decision-support tools for improving surveillance in the area and can also provide a baseline for subsequent research. Future work may enhance the model by incorporating actual cost data in coordination with the UPLB budget office, allowing for more realistic cost estimates and strengthening proposals for system implementation.

While this paper focuses on improving the security in the lower campus dormitory of the University of the Philippines Los Baños only, the model can be expanded to include a wider community. This extension can be performed as a class exercise similar to the Google Colab notebook in [8], provided that there is ample data. Not only does this allow learners to perform problem-solving involving actual data, it also allows them to use technology and create mathematical models based on existing ones. This allows learners to enrich their mathematical and modelling skills but at the same time, also deliver actionable solutions to a broader community.

A Solution Tables

The implementation of the model and all results presented in this section can be accessed and generated, respectively, using the Google Colab notebook that accompanies this paper. [9].

Table A1: 2-Stage optimization alternate solution results: optimal node locations and main entry/exit points by case

Sol. No.	**No. of inst. spots**	**Optimal nodes**	**No. of main entry/exit spots**	**Optimal main entry/exit nodes**
CASE 1				
1	10	[2, 3, 6, 7, 9, 10, 13, 15, 17, 18]	3	[2, 9, 18]
2	9	[1, 3, 5, 7, 8, 11, 12, 15, 17]	1	[1]
3	11	[1, 2, 4, 6, 7, 9, 10, 13, 14, 16, 18]	5	[1, 2, 4, 9, 18]
4	11	[1, 2, 4, 6, 7, 9, 10, 13, 15, 17, 18]	5	[1, 2, 4, 9, 18]
5	10	[2, 3, 6, 7, 9, 10, 13, 14, 17, 18]	3	[2, 9, 18]
6	11	[1, 2, 4, 6, 8, 9, 11, 13, 14, 16, 18]	5	[1, 2, 4, 9, 18]
7	10	[2, 3, 6, 7, 9, 10, 13, 14, 16, 18]	3	[2, 9, 18]
8	9	[2, 3, 5, 7, 8, 11, 12, 15, 17]	1	[2]
CASE 2				
1	10	[2, 3, 6, 7, 9, 10, 13, 15, 17, 18]	3	[2, 9, 18]
2	11	[1, 2, 4, 6, 8, 9, 11, 13, 14, 16, 18]	5	[1, 2, 4, 9, 18]
3	11	[1, 2, 4, 6, 7, 9, 10, 13, 14, 16, 18]	5	[1, 2, 4, 9, 18]
4	10	[2, 3, 6, 7, 9, 10, 13, 14, 16, 18]	3	[2, 9, 18]
5	11	[1, 2, 4, 6, 8, 9, 10, 13, 14, 16, 18]	5	[1, 2, 4, 9, 18]
6	10	[2, 3, 6, 7, 9, 10, 13, 14, 17, 18]	3	[2, 9, 18]
7	11	[1, 2, 4, 6, 7, 9, 10, 13, 15, 17, 18]	5	[1, 2, 4, 9, 18]
8	11	[1, 2, 4, 6, 7, 9, 10, 13, 14, 17, 18]	5	[1, 2, 4, 9, 18]
CASE 3				
1	11	[1, 2, 4, 6, 7, 9, 10, 13, 14, 16, 18]	5	[1, 2, 4, 9, 18]
2	11	[1, 2, 4, 6, 8, 9, 10, 13, 14, 16, 18]	5	[1, 2, 4, 9, 18]
3	11	[1, 2, 4, 6, 8, 9, 11, 13, 14, 16, 18]	5	[1, 2, 4, 9, 18]
4	11	[1, 2, 4, 6, 7, 9, 10, 13, 15, 17, 18]	5	[1, 2, 4, 9, 18]
5	11	[1, 2, 4, 6, 7, 9, 10, 13, 14, 17, 18]	5	[1, 2, 4, 9, 18]

Table A2: Number of cameras at each installation node using 2-Stage Optimization algorithm by case

Sol. no.	**Nodes**																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
CASE 1																		
1	-	2	3	-	-	2	3	-	3	2	-	-	2	-	2	-	3	1
2	1	-	3	-	3	-	2	4	-	-	2	3	-	-	2	-	3	-
3	2	1	-	2	-	3	2	-	3	2	-	-	3	2	-	1	-	2
4	1	2	-	2	-	3	2	-	3	2	-	-	3	-	1	-	2	2
5	-	2	3	-	-	2	3	-	3	2	-	-	3	1	-	-	2	2
6	1	2	-	2	-	3	-	2	3	-	1	-	3	2	-	2	-	2
7	-	2	3	-	-	2	2	-	3	2	-	-	3	2	-	2	-	2
8	-	1	3	-	3	-	2	4	-	-	2	3	-	-	2	-	3	-
CASE 2																		
1	-	2	3	-	-	2	3	-	3	2	-	-	2	-	2	-	2	2
2	1	2	-	2	-	3	-	2	3	-	2	-	2	2	-	2	-	2
3	2	1	-	1	-	3	2	-	3	2	-	-	3	2	-	2	-	2
4	-	2	2	-	-	3	3	-	3	2	-	-	3	2	-	1	-	2
5	2	1	-	2	-	3	-	3	2	1	-	-	3	2	-	2	-	2
6	-	2	2	-	-	3	3	-	3	2	-	-	3	1	-	-	2	2
7	2	1	-	1	-	3	3	-	3	2	-	-	2	-	2	-	3	1
8	1	2	-	2	-	3	2	-	3	2	-	-	3	2	-	-	1	2
CASE 3																		
1	-	2	2	-	-	3	3	-	3	2	-	-	3	-	1	-	3	1
2	1	2	-	2	-	2	-	3	3	-	1	-	3	2	-	2	-	2
3	2	1	-	1	-	3	2	-	3	2	-	-	3	2	-	2	-	2
4	-	2	3	-	-	2	3	-	3	2	-	-	3	2	-	1	-	2
5	1	2	-	2	-	3	-	2	3	1	-	-	3	2	-	2	-	2

Table A3: 2-Stage optimization results and existing camera overlap by case

Sol. No	**Installation Spots**	**Existing Nodes in Solution**	**New Installations**	**Existing Nodes (List)**	**Existing CCTV Count**
CASE 1					
1	10	3	7	[9, 15, 18]	3
2	9	2	7	[8, 15]	2
3	11	2	9	[9, 18]	2
4	11	3	8	[9, 15, 18]	3
5	10	2	8	[9, 18]	2
6	11	3	8	[8, 9, 18]	3
7	10	2	8	[9, 18]	2
8	9	2	7	[8, 15]	2
CASE 2					
1	10	3	7	[9, 15, 18]	3
2	11	3	8	[8, 9, 18]	3
3	11	2	9	[9, 18]	2
4	10	2	8	[9, 18]	2
5	11	3	8	[8, 9, 18]	3
6	10	2	8	[9, 18]	2
7	11	3	8	[9, 15, 18]	3
8	11	2	9	[9, 18]	2
CASE 3					
1	11	2	9	[9, 18]	2
2	11	3	8	[8, 9, 18]	3
3	11	3	8	[8, 9, 18]	3
4	11	3	8	[9, 15, 18]	3
5	11	2	9	[9, 18]	2

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References

[1] 6Wresearch, Philippines Video Surveillance Market (2025–2031) — Outlook, Forecast, Revenue, Companies, Growth, Analysis, Size, Trends, Share, Value & Industry, 6Wresearch, https://www.6wresearch.com/industry-report/philippines-video-surveillance-market, 2023.

[2] Aballe, S.K.B., Bandala, C.M.C., Mercado, J.R., Rejes, N.H., Culanag, T.Y., Jr., & Cuevas, J.F., Jr., Security Measures: Effectiveness of the Installation of CCTV Cameras in Relation to Crime Prevention as Perceived by the Community, Middle East Journal of Applied Science & Technology, Volume 5, 2022, pp. 149-160.

[3] Afriyie, I., Ofosu-Kwabe, K., & Ativor, N., Optimizing CCTV Camera Placement for Campus Security: A Binary Integer Programming Approach for Clemson University, International Journal of Modern Science and Research Technology, Volume 2, 2024, pp. 255-263.

[4] Ahn, J.-W., Chang, T.-W., Lee, S.-H., & Seo, Y.W., Two-Phase Algorithm for Optimal Camera Placement, Scientific Programming, Volume 2016, 2016, pp. 1-16.

[5] Ashby, M.P.J., The Value of CCTV Surveillance Cameras as an Investigative Tool: An Empirical Analysis, European Journal on Criminal Policy and Research, Volume 23, 2017, pp. 441-459.

[6] Bischoff, P., Surveillance camera statistics: which are the most surveilled cities, https://www.comparitech.com/vpn-privacy/the-worlds-most-surveilled-cities/, 2023.

[7] Bouchrika, I., 40 Student Crime Statistics: 2024 Data, Analysis & Predictions, https://research.com/education/student-crime-statistics#3, 2024.

[8] Calzeta, E.P.M., De Lara, M.L.D., & Lutero, D.S., Problem-based learning in operations research: an integer programming approach to optimal camera placement in campus dormitory areas, Proceedings of the 22nd Asian Technology Conference in Mathematics, https://atcm.mathandtech.org/EP2025/regular/22309.pdf, 2025.

[9] Calzeta, E.P.M., De Lara, M.L.D., & Lutero, D.S., Supplementary Material: Google Colab Implementation for Two-Stage Optimal Camera Placement, https://colab.research.google.com/drive/1GiBF0YfB1ene4OOi1RkT0lVhBr9SZgw9?usp=sharing, 2025.

[10] Clarke, R.V., Situational Crime Prevention, Crime and Justice, Volume 19, 1995, pp. 91-150.

[11] Clarke, R.V., Situational Crime Prevention: Successful Case Studies, Criminal Justice Press, Monsey, NY, 1997.

[12] Cuevas, Q.D., Corachea, J.C., Escabel, E., & Bautista, M.L., Effectiveness of CCTV Cameras Installation In Crime Prevention, College of Criminology Research Journal, Volume 7, 2016.

[13] Ekpoh, U.I., Edet, A.O., & Ukpong, N.N., Security Challenges in Universities: Implications for Safe School Environment, Journal of Educational and Social Research, Volume 10, 2020, p. 112.

[14] Farrington, D.P., Gill, M., Waples, S.J., & Argomaniz, J., The effects of closed-circuit television on crime: meta-analysis of an English national quasi-experimental multi-site evaluation, Journal of Experimental Criminology, Volume 3, 2007, pp. 21-38.

[15] Felson, M. & Clarke, R.V., Opportunity makes the thief: Practical theory for crime prevention, Home Office Policing and Reducing Crime Unit, London, 1999.

[16] Gaylon, R.V.G., Galapia, R.A., Mabborang, R.C., & Bansil, A.G., Proposed Optimization Algorithm for Solving CCTV Camera Placement, European Journal of Information Technologies and Computer Science, Volume 2, 2022, pp. 1-18.

[17] Grossman, T. & Wool, A., Computational experience with approximation algorithms for the set covering problem, European Journal of Operational Research, Volume 101, 1997, pp. 81-92.

[18] Gurobi Optimization LLC, Gurobi Optimizer Reference Manual, `https://www.gurobi.com`, 2024.

[19] Hagberg, A., Swart, P., & Chult, D.S., Exploring network structure, dynamics, and function using NetworkX, Los Alamos National Lab. (LANL), Los Alamos, NM (United States), 2008.

[20] Hörster, E. & Lienhart, R., On the optimal placement of multiple visual sensors, Proceedings of the 4th ACM international workshop on Video surveillance and sensor networks, ACM, 2006, pp. 111-120.

[21] Integrated Emergency Response (IER), The Importance of Community Safety and Security, `https://www.ier.co.za/the-importance-of-community-safety-and-security/`, 2024.

[22] Jeffery, C.R., Crime Prevention Through Environmental Design, American Behavioral Scientist, Volume 14, 1971, p. 598.

[23] Keval, H.U., Effective design, configuration, and use of digital CCTV, Ph.D. dissertation, University College London, `https://api.semanticscholar.org/CorpusID:30747829`, 2009.

[24] Kirui, G., Enhancing Police Operations: The Impact of CCTV in Monitoring, Incident Response, and Crime Investigation in Nairobi City County, Kenya, Valley International Journal Digital Library, 2024, pp. 1823-1834.

[25] Macmillan, R. & Hagan, J., Violence in the Transition to Adulthood: Adolescent Victimization, Education, and Socioeconomic Attainment in Later Life, Journal of Research on Adolescence, Volume 14, 2004, pp. 127-158.

[26] Martin, R., Closed-Circuit Television, `https://www.britannica.com/technology/closed-circuit-television`, 2024.

[27] Matczak, P., Wójtowicz, A., Dabrowski, A., Leitner, M., & Sypion-Dutkowska, N., Effectiveness of CCTV systems as a crime preventive tool: evidence from eight Polish cities, International Journal of Comparative and Applied Criminal Justice, Volume 47, 2023, pp. 37-56.

[28] Nas, S., The Definitions of Safety and Security, Journal of ETA Maritime Science, Volume 3, 2015, pp. 53-54.

[29] O'Rourke, J., Art Gallery theorems and algorithms, Oxford University Press, New York, 1987.

[30] Piza, E.L., Welsh, B.C., Farrington, D.P., & Thomas, A.L., CCTV surveillance for crime prevention, Criminology & Public Policy, Volume 18, 2019, pp. 135-159.

[31] Ratcliffe, J.H., Taniguchi, T., & Taylor, R.B., The Crime Reduction Effects of Public CCTV Cameras: A Multi-Method Spatial Approach, Justice Quarterly, Volume 26, 2009, pp. 746-770.

[32] Ringwalt, C.L., Ennett, S., Johnson, R., Rohrbach, L.A., Simons-Rudolph, A., Vincus, A., & Thorne, J., Factors Associated with Fidelity to Substance Use Prevention Curriculum Guides in the Nation's Middle Schools, Health Education & Behavior, Volume 30, 2003, pp. 375-391.

[33] Topaloglu, H., Fundamentals of Linear Optimization: A Hopefully Uplifting Treatment, Cornell University, `https://people.orie.cornell.edu/huseyin/lp_book.pdf`, 2019.

[34] Welsh, B.C. & Farrington, D.P., Evidence-based Crime Prevention: The Effectiveness of CCTV, Crime Prevention and Community Safety, Volume 6, 2004, pp. 21-33.

[35] Welsh, B.C. & Farrington, D.P., Surveillance for Crime Prevention in Public Space: Results and Policy Choices in Britain and America, Criminology & Public Policy, Volume 3, 2004, pp. 497-526.

[36] Welsh, B.C. & Farrington, D.P., Public Area CCTV and Crime Prevention: An Updated Systematic Review and Meta-Analysis, Justice Quarterly, Volume 26, 2009, pp. 716-745.

[37] Youdeowei, T. & Iruoma, K., Safety in schools: Matters arising, Vanguard, October 22, 2015. `https://www.vanguardngr.com/2015/10/safety-in-schools-matters-arising/`

[38] Zhao, J., Yoshida, R., Cheung, S.S., & Haws, D., Approximate Techniques in Solving Optimal Camera Placement Problems, International Journal of Distributed Sensor Networks, Volume 9, 2013, 241913.