Problem-based learning in operations research: an integer programming approach to optimal camera placement in campus dormitory areas

Edzel Paul M. Calzeta, Mark Lexter D. de Lara, Destiny S. Lutero
emcalzeta@up.edu.ph, mddelara@up.edu.ph, dslutero@up.edu.ph
Institute of Mathematical Sciences, College of Arts and Sciences,
University of the Philippines Los Baños,
Los Baños, Laguna 4031
Philippines

Abstract

Problem-based learning (PBL) provides an effective framework for engaging learners in mathematical modeling by situating abstract concepts within real-world contexts. This study demonstrates PBL in action through the optimal camera placement (OCP) problem, which addresses the challenge of improving campus security in the dormitory areas of the University of the Philippines Los Baños. Campus safety is a pressing concern, yet the existing Closed-Circuit Television (CCTV) system suffers from inadequate coverage and blind spots. Using a Google Colab notebook, the security issue was reformulated as a mathematical optimization problem. Learners were guided to define objectives, translate the real-world scenario into a two-stage optimization model, and test solutions under different constraints. Four cases were explored. The first three, focusing on main entry and exit points, required 9 to 11 installation sites and 23 cameras, corresponding to the number of streets in the area. The final case, which integrated existing cameras, reduced requirements to only 6 to 7 additional locations. Through this PBL approach, the learners were expected to achieve more than a correct solution. They practiced framing authentic problems, analyzing trade-offs between cost and coverage, and justifying recommendations based on evidence. The activity also fostered teamwork, critical thinking, and communication skills as learners worked collaboratively to interpret results and propose practical strategies. By directly linking mathematics to community needs, the exercise illustrates how PBL can enrich both technical competence and broader problem-solving abilities.

1 Introduction

The use of problem-based learning (PBL) environments has been shown to be highly effective in teaching mathematical modeling [10, 15]. PBL enables the use of real-world contexts, engaging students to actively use mathematical tools in formulating, analyzing, and solving problems, thereby making possible critical thinking, collaboration, and creativity between and among learners. The integration of technology further enhances the learning process as it allows learners to explore math models and refine solutions in ways that traditional methods alone cannot provide [5, 16].

Security is defined as "the state of being away from hazards caused by the deliberate intention of human beings to cause harm" [22]. Ensuring security within a community fosters a sense of safety and well-being among its residents. This is particularly crucial in academic communities where productivity, academic advancement, and institutional growth are dependent on the stability of its environment and the security of its constituents. 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 [9]. Victimized students often suffer academically [19], while the fear of crime can negatively affect attendance even among non-victims [26] since exposure to crime can lead to mental health issues such as trauma, depression, anxiety, substance abuse, and violent behaviors [6]. Overall, crime compromises student well-being and academic success, making campus security a top priority for educational institutions.

Many communities use Closed Circuit Television (CCTV) surveillance systems to address security concerns. CCTV networks consist of cameras often installed on walls or above doors, connected to monitors for real-time or recorded viewing [20]. According to Welsh and Farrington (2009), CCTV is classified as a Situational Crime Prevention (SCP) strategy [28], which reduces crime opportunities by increasing offenders' perceived risk and effort [7]. Studies in the UK and North America have reported crime reductions of 13–21% in areas with CCTV [27, 25, 24]. Similar results have been observed in Polish cities over a nine-year study period [21]. In the Philippines, market analyses from 2025–2030 showed a rising demand for video surveillance, attributed to crime rate increases [1]. Empirical studies also showed that CCTV helps deter crimes against people and property and assists in criminal investigations and apprehensions [8, 2]. Despite its benefits, CCTV effectiveness depends heavily on coverage. Several studies emphasized that the number of cameras alone does not guarantee security; strategic placement is critical [4, 11, 17].

The optimal camera placement (OCP) problem addresses the challenge of minimizing the number of CCTV cameras while maintaining sufficient coverage [29]. 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 [13]. A closely related problem is the Art Gallery Problem (AGP), which aims to find the fewest number of guards to oversee an area [23]. However, AGP results are often too theoretical for real-world applications [12]. Afriyie et al. (2024) combined road network and grid approaches to optimize camera placement in a campus [3]. They assumed camera placement at every road intersection, with each segment covered by at least one camera. While using BIP, they also acknowledged limitations such as static layout assumptions, simplified surveillance zones, and computational overhead. Gaylon et al. (2022) 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 [12]. Despite numerous studies on CCTV effectiveness and placement

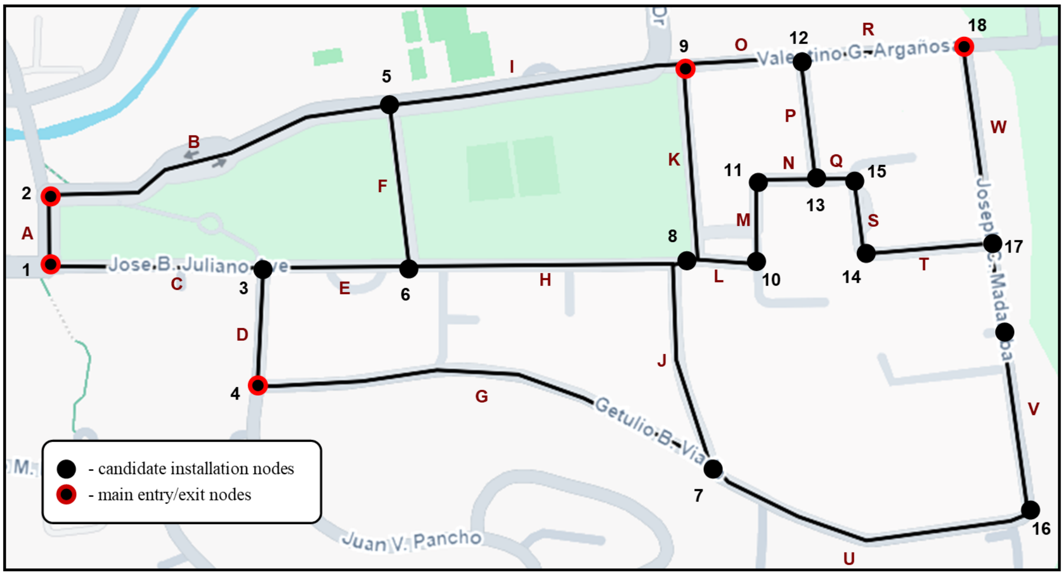


Figure 1: Graph $\mathscr{A}$ over the Google Earth map of the dormitory area of UPLB Lower Campus

optimization[27, 24, 25, 21], few focus specifically on campus settings. This study applied a similar graph-based two-stage approach to optimize CCTV placement in UPLB's dormitory areas, aiming to enhance coverage while minimizing costs. This study adopts a similar approach to [12] and [3], targeting the dormitory area of UPLB.

In addition, with the Google Colab notebook accompanying this paper, readers are provided with an interactive learning material. This notebook may serve as a guided learning exercise in which readers can examine the modelling process, including the formulation of the problem and the implementation of optimization techniques using Python and Gurobi.

2 Methods

The problem of enhancing the security surveillance in the dormitory areas of UPLB through a CCTV surveillance system is modelled as an OCP problem and solved using the approach in [12], herein referred to as two-stage approach.

2.1 Graphical representation of the road network

The environment modeling approach of [12] was adopted for the UPLB dorm areas where the road network is represented as a graph with intersections as nodes and streets as edges. Nodes serve as candidate CCTV installation spots, capable of monitoring their incident streets. Fig. 1 shows graph $\mathscr{A}$ consisting of 18 nodes (labelled 1 to 18), and 23 edges (labelled with Roman alphabets A to W) 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.

2.2 Two-stage Approach

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 towards its direction; and each candidate installation spot has a corresponding installation cost c_i adapted from [12], and the installation at 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 was 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

$$c_i = \begin{cases} 1, & \text{if node } i \text{ is a main entry/exit node} \\ 2, & \text{otherwise} \end{cases}, \text{ where } i = 1, 2, ..., 18.$$

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

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

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

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].

2.2.2 Stage 2

The second stage of the algorithm involves the use of a four-step algorithm based on greedy heuristics. This stage will determine the number of cameras to be installed at each optimal installation spot and the orientation of each camera with the solution obtained from Stage 1 as input. This stage was also implemented using Python code (version 3.11.11) in Google Colab and a Python library called networkx was used to construct graph $\mathscr{A}$ as a graphical network. This was necessary to handle the vertices and edges of the graph in implementing the greedy heuristics algorithm [14].

3 Results and Discussion

The OCP problem in this study considered four cases. The first three cases focused on the placement of CCTVs in the main entry/exit nodes: Case 1, where surveillance at main entry/exit nodes is prioritized but optional; Case 2, where surveillance at DTRI gate (Node 18) is required; and Case 3, where surveillance at all main entry/exit nodes is required. The last case incorporated the current CCTV surveillance system of UPLB. The Google Colab notebook provided with this paper implements the two-stage optimization approach. And as an interactive learning material, it can be used to follow the implementation of the models and generate the results for all cases (link: https://colab.research.google.com/drive/1e-ldu4EiDiDGsQZ2tat-P4IeajjfvFUbu?usp=sharing).

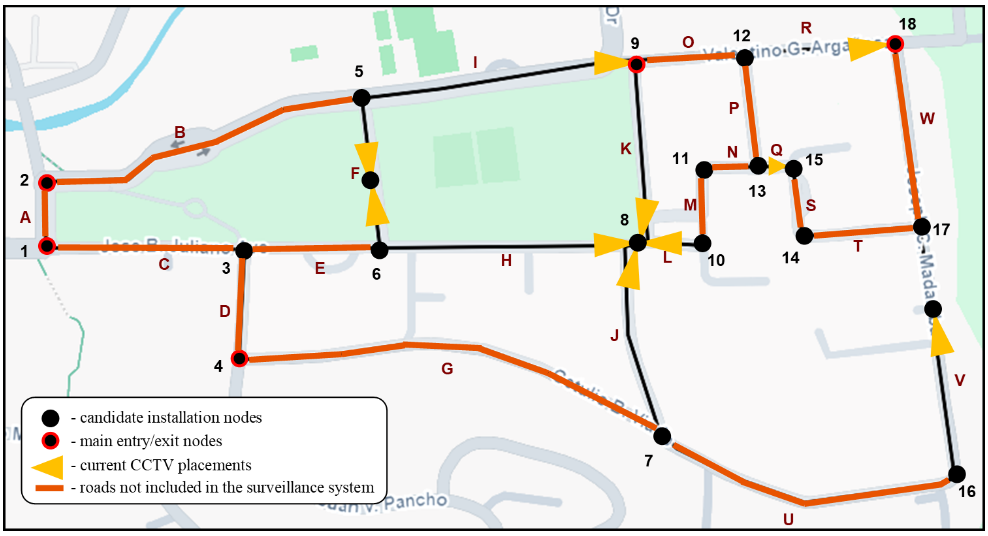


Figure 2: Current CCTV monitoring system in the dormitory area of UPLB Lower Campus

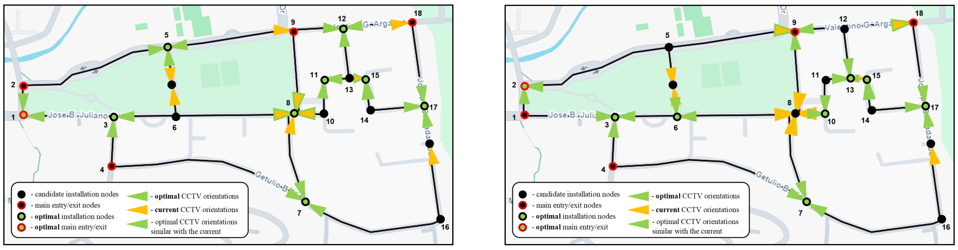
The locations of the cameras with non-redundant coverage, and its covered streets are reflected in Fig. 2. There are six cameras currently installed. Street F and Node 8 each have an omnidirectional unit, while Node 9, Node 15, Node 18, and Street V have fixed-orientation cameras. Node 18 has multiple 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.

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

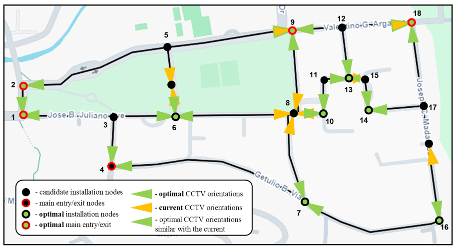
Three different cases that differ according to the assumption on the main entry/exit nodes were analyzed. The results for each case yielded multiple or alternate solutions, which will be discussed. Table 1 shows solutions that had the least number of installation spots among the alternate solutions with ties broken arbitrarily.

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.



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

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



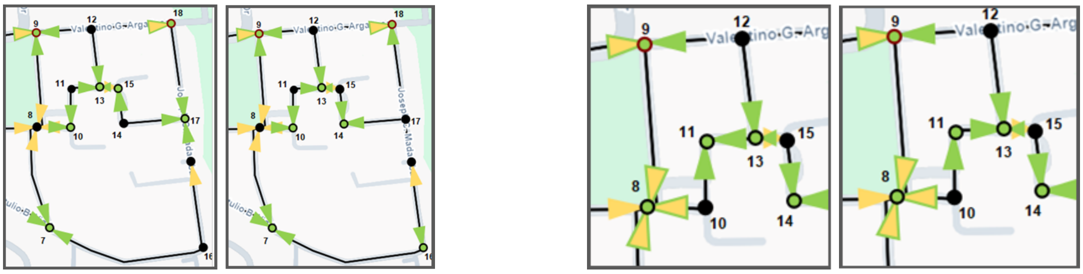
(c) Case 3: Mandatory surveillance at all main entry/exit nodes

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

For all three cases, the two-stage optimization model 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 (Fig. 3a), the solution placed cameras at 9 installation nodes, one of which is a main entry/exit node. This setup still achieved complete coverage while minimizing cost. It can be noted that 4 camera placements in this solution overlapped with the current surveillance system. In Case 2 (Fig. 3b), the solution installed cameras at 10 nodes, including 3 main entry/exit nodes, and ensured full coverage with 23 cameras. This case reflected a targeted increase in surveillance for a vital access point. Also, nodes 9, 15, and 18 have camera placements that coincided with the existing system. In Case 3 (Fig. 3c), this configuration focused on boundary surveillance in the area to enhance perimeter security. Two camera placements in this setup coincided with the existing setup: the camera at Node 9 facing Node 5, and the camera at Node 18 facing Node 12.

The two-stage optimization method yielded multiple optimal solutions in all three cases. In this study, these are largely due to the translocation of cameras, specifically the shifting camera placements while maintaining equivalent coverage. In Case 1, the number of installation spots ranged from 9 to 11, with corresponding changes in the number of main entry/exit nodes (1, 3, or 5). For Case 2, solutions had 10 or 11 installation spots, but the same number of main entry/exit nodes. In Case 3, all alternate solutions had 11 installation spots and 5 main entry/exit points.



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

(b) Translocation from node 11 to node 13 (Case 3: Solutions 3 & 4).

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

Fig. 4 illustrates this with solutions 1 and 4 from Case 2 under the two-stage approach: in 4a, nodes 15 and 17 are selected, while in 4b, cameras are shifted to adjacent nodes 14 and 16, achieving the same coverage. This occurred when adjacent nodes can substitute for each another without compromising the coverage, as also seen in Fig. 4.

Lastly, we considered the current CCTV surveillance system. In all of the previous cases, some optimal camera placements were observed to coincide with the existing surveillance system. This suggested that the setup of the currently installed cameras in the CCTV surveillance system need not be modified to make room for the additional cameras, thus lowering installation costs. For this case, the LP model excluded the constraints corresponding to edges already monitored by the existing CCTV surveillance system. The proposed setup is shown in Fig. 5

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

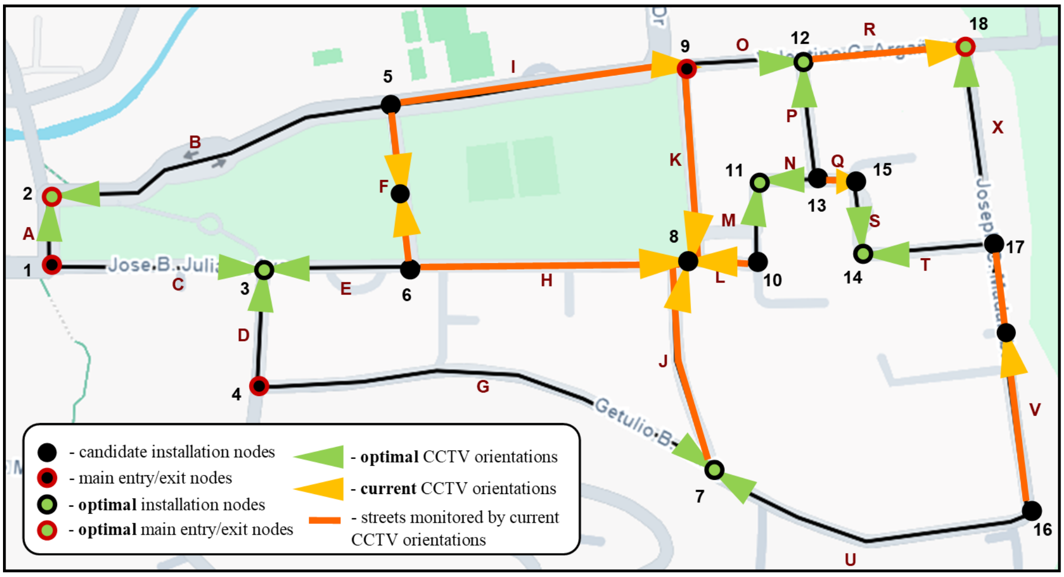


Figure 5: Proposed CCTV surveillance system obtained using two-stage approach on the UPLB context case

CCTV cameras to address blind spots and provide complete coverage.

4 Conclusion and Recommendations

As a PBL paper, this study demonstrated how operations research concepts and mathematical modeling can be applied to a real-world security problem. Using a Google Colab notebook, it provided a project template that guided learners through each stage of the modeling process, from problem identification to solution analysis. The focus was on the dormitory area of the Lower Campus of UPLB, where the local surveillance problem was formulated as an optimal camera placement (OCP) problem and solved using a two-stage optimization approach.

The results showed that the proposed models achieved full coverage of all streets in the dormitory area. In every case, the two-stage approach produced blind spot–free surveillance systems while avoiding redundant camera placements. When the existing surveillance system was incorporated into the model, the required number of new installation sites was further reduced, resulting in a more cost-effective and efficient strategy. These outcomes illustrate how PBL enabled learners not only to apply optimization techniques but also to appreciate trade-offs between efficiency, coverage, and resource constraints.

This study recommends adopting the proposed camera placement solutions: three based on varying priorities for entry and exit nodes, and one that integrates the current system. These can serve as decision-support tools for improving surveillance in the area. Future directions for the PBL framework include incorporating cost data in consultation with the UPLB budget office to strengthen system proposals, and expanding the model to cover the entire campus for comprehensive security planning.

References

[1] 6Wresearch, *Philippines video surveillance market (2025–2031) — outlook, forecast, revenue, companies, growth, analysis, size, trends, share, value & industry*, Tech. report, 6Wresearch, 2023, Product Code: ETC4456770; 85 pages; includes 45 figures and 25 tables.

[2] Aballe, Sean Kenneth B., Bandala, Cherry Mae C., Mercado, Jay R., Rejes Nely H., Teopisto Y. Culanag Jr., and Jose f. Cuevas 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 **05** (2022), 149–160.

[3] Israel Afriyie, Kenneth Ofosu-Kwabe, and Nelson Ativor, *Optimizing cctv camera placement for campus security: A binary integer programming approach for clemson university*, **2** (2024), 263.

[4] Paul Bischoff, *Surveillance camera statistics: which are the most surveilled cities*, 5 2023.

[5] J. M. Borwein and D. H. Bailey, *Mathematics by experiment: Plausible reasoning in the 21st century*, A K Peters/CRC Press, 2013.

[6] Imed Bouchrika, *40 student crime statistics: 2024 data, analysis predictions*, 10 2024.

[7] Ronald V Clarke, *Situational crime prevention*, Crime and Justice **19** (1995), 91–150.

[8] Queen Denise Cuevas, John Carlo Corachea, Ederlina Escabel, and Merwina Lou Bautista, *Effectiveness of cctv cameras installation in crime prevention*, College of Criminology Research Journal **7** (2016).

[9] Uduak Imo Ekpoh, Aniefiok Oswald Edet, and Nse Nkereuwem Ukpong, *Security challenges in universities: Implications for safe school environment*, Journal of Educational and Social Research **10** (2020), 112.

[10] L. D. English and J. Gainsburg, *Problem solving in a 21st-century mathematics curriculum*, Routledge, 2016.

[11] David P. Farrington, Martin Gill, Sam J. Waples, and Javier Argomaniz, *The effects of closed-circuit television on crime: meta-analysis of an english national quasi-experimental multi-site evaluation*, Journal of Experimental Criminology **3** (2007), 21–38.

[12] Rhonil Victor G. Gaylon, Reyn A. Galapia, Romie C. Mabborang, and Alvin G. Bansil, *Proposed optimization algorithm for solving cctv camera placement*, European Journal of Information Technologies and Computer Science **2** (2022), 1–18.

[13] Tal Grossman and Avishai Wool, *Computational experience with approximation algorithms for the set covering problem*, European Journal of Operational Research **101** (1997), 81–92.

[14] Aric Hagberg, Pieter Swart, and Daniel S Chult, *Exploring network structure, dynamics, and function using networkx*, 2008.

[15] D. Hestenes, *Modeling theory for math and science education*, Springer, 2010.

[16] F. Hitt, M. Kinzel, and M. Santos-Trigo, *Mathematical modeling and technology: Teaching and learning*, Springer, 2020.

[17] Hina Uttam Keval, *Effective design, configuration, and use of digital cctv*, 2009.

[18] Gurobi Optimization LLC, *Gurobi optimizer reference manual*, 2024.

[19] Ross Macmillan and John Hagan, *Violence in the transition to adulthood: Adolescent victimization, education, and socioeconomic attainment in later life*, Journal of Research on Adolescence **14** (2004), 127–158.

[20] Roland Martin, *Closed-circuit television*, 11 2024.

[21] Piotr Matczak, Andrzej Wójtowicz, Adam Dabrowski, Michael Leitner, and Natalia Sypion-Dutkowska, *Effectiveness of cctv systems as a crime preventive tool: evidence from eight polish cities*, International Journal of Comparative and Applied Criminal Justice **47** (2023), 37–56.

[22] Selçuk Nas, *The definitions of safety and security*, Journal of ETA Maritime Science **3** (2015), 53–54.

[23] Joseph O'Rourke, *Art gallery theorems and algorithms*, Oxford University Press, 1987.

[24] Eric L. Piza, Brandon C. Welsh, David P. Farrington, and Amanda L. Thomas, *Cctv surveillance for crime prevention*, Criminology Public Policy **18** (2019), 135–159.

[25] Jerry H. Ratcliffe, Travis Taniguchi, and Ralph B. Taylor, *The crime reduction effects of public cctv cameras: A multi-method spatial approach*, Justice Quarterly **26** (2009), 746–770.

[26] Christopher L. Ringwalt, Susan Ennett, Ruby Johnson, Louise Ann Rohrbach, Ashley Simons-Rudolph, Amy Vincus, and Judy Thorne, *Factors associated with fidelity to substance use prevention curriculum guides in the nation's middle schools*, Health Education Behavior **30** (2003), 375–391.

[27] Brandon C Welsh and David P Farrington, *Evidence-based crime prevention: The effectiveness of cctv*, Crime Prevention and Community Safety **6** (2004a), 21–33.

[28] Brandon C. Welsh and David P. Farrington, *Public area cctv and crime prevention: An updated systematic review and meta-analysis*, Justice Quarterly **26** (2009), 716–745.

[29] Jian Zhao, Ruriko Yoshida, Sen ching Samson Cheung, and David Haws, *Approximate techniques in solving optimal camera placement problems*, International Journal of Distributed Sensor Networks **9** (2013), 241913.