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EVALUATION OF PHYSICAL PROTECTION SYSTEM EFFECTIVENESS: MARKOV CHAIN THEORY APPROACH

1. Introduction

Physical protection systems (PPS) are the combination of systems used to protect valuable facilities or entities from theft, sabotage or any malicious human activities. These valuable facilities may include nuclear power plants, airports, military installations, banks and other related facilities. These would be facilities with high consequential effects on society if malicious activities were carried out successfully. The malicious activities may include sabotage, theft, terrorism, hostage-taking, the release of a harmful substance into the environment, and other illegal activities. Garcia [1] defines PPS more succinctly as "A physical protection system (PPS) integrates people, procedures, and equipment for the protection of assets or facilities against theft, sabotage, or other malevolent human attacks". The primary functions of PPS are detection of a malicious attack, delay of the malicious attack and response to the malicious attack. The PPS requires some elements to carry out these functions: fence, walls, lock and key, sensors, alarm, detectors, response guide or force, lights, cameras, thermocouples, and the rest. These elements have to be appropriately integrated with a laydown procedure to achieve the required objectives of the PPS, and the procedures include the design of the PPS and design evaluation or analysis. The PPS design describes the elements' arrangement, composition, alignment, and interconnectivity, while the design evaluation or analysis measures the effectiveness or efficiency of the design. The latter shall be the focus of this work. Evaluation of PPS measures the level of compliance of the PPS to the preemptive objectives. The evaluation processes are qualitative and quantitative evaluation, respectively; these subdivisions are functions of the size and the level of risk associated with the facility. PPSs designed to protect high-value assets generally require quantitative analysis, while lesser assets may require a qualitative analysis. In a qualitative analysis, the measurement may require a simple test or simulation, then the perceptions of the designer or evaluator on a specific scale such as high, medium or low, which are not physically measurable quantities. The quantitative analysis may include integrating analytical models and procedures to measure the effectiveness of the PPS. Vintr et al. [2] describe PPS effectiveness as: "The PPS ability to withstand a possible attack and prevent an adversary from achieving his objectives is generally characterised as PPS effectiveness". They are several models of analysing the effectiveness of PPS; in this work, we shall make use of the integration of the "estimate of adversary sequence interruption" (EASI) model and Markov chain theory (MCT). The analysis will identify system deficiencies, help evaluate improvements, and enable cost-versus-effectiveness comparisons. A sabotage scenario of a hypothetical nuclear facility (HNF) was used to implement the principle of estimating the effectiveness of the physical protection system.

2. Method and Material

The method employed in this research follows a sequence of events: the HNF designated areas were identified; these include: the off-site areas, limited area, protected areas, controlled building area, controlled building and the targets asset areas. Next, a one-dimension diagram of the HNF designated areas was mapped out using Microsoft office to show vital areas and the targets points, as shown in figure 1. Next, the adversary sequence diagram (ASD, figure 2) was also presented using Microsoft office; figure 2, shows the path progression of the intruder as he navigates the physical protection elements in the facility onto the targets (Lab 1, control room and store). Finally, the probabilities of interruption were computed using the EASI model, and the MCT were analysed using matrix programs.

a. EASI model

EASI model is a computer model that calculates the probability of interruption, PI, the probability of interrupting an adversary sequence, as he approaches the target asset. The model uses the detection probability of the detecting elements, the alarm communication system, the location of delay elements and the response force time.

$$P_I = P_D * P_C * P(R/A) \qquad \text{Eq. 1}$$

Eq. 1 gives the probability of interruption P_I of an adversary sequence for a single detection alarm case, probability of communication P_C of the PPS elements for alarm assessments, and $P(R/A)$ gives the probability of prompt response with respect to alarm.

Eq. 1, depend on the fact that

$$TR - RFT > 0 \qquad \text{Eq. 2}$$

TR is the time left for the adversary to get to the target when detected. RFT is the response for the time remaining for the response function to interrupt the adversary before reaching the target. Eq. 2 can be tailored to follow a random variable distribution that is normally distributed (Eq. 3). Random variable:

$$x = TR - RFT \qquad \text{Eq. 3}$$

with mean and variance:

$$\left\{ \begin{array}{c} \mu_x = E(TR - RFT) = E(TR) - E(RFT) \\ \sigma_X^2 = Var(TR - RFT) = Var(TR) - Var(RFT) \end{array} \right\}$$

The conditional probability $P\left({}^{R}/_{A}\right)$ becomes $P(x > 0)$

$$P\left(\frac{R}{A}\right) = P(x > 0) = \int_0^\infty \frac{1}{\sqrt{2\pi\sigma_x^2}} \exp\left[-\frac{(x-\mu_x)^2}{2\sigma_x^2}\right] dx \qquad \text{Eq. 4}$$

In the case of two or more sensors, the general formula for the probability of sequence interruption Eq. 1 becomes:

$$P(I) = P(D_1) * P(C_1) * P\left({}^{R}/_{A_1}\right) + \sum_{i=2}^{n} P\left({}^{R}/_{A_i}\right) P(C_i) P(D_i) \prod_{i=1}^{i=1}(1 - P(D_i)) \qquad \text{Eq. 5}$$

Eq. 5 gives the probability of adversary interruption in high-security facilities, such as nuclear facilities and military installations, because these facilities rely on multiple layers of PPS elements to give balanced protection.

b. Markov chain theory

The problem of and prediction of the probability of interruption transiting from one target(state) to another within the facility were be solved using the Markov chain theory. The intruder has three separate targets to exploit; having access to the controlled building, he may choose to go in any direction, then transit problem arises, which is the basis for implementing the Markov chain theory. Markov chains are a fundamental part of stochastic processes, widely used in different disciplines. A Markov chain is a stochastic process that satisfies the Markov property, which means that the past and future are independent when the present is known, that is, a sequence of possible events in which the probability of each event depends only on the state attained in the previous event [3][4][5][6][7]. A stochastic process X can be defined as:

$$X = \{X_n, n \in N\} \qquad \text{Eq. 6}$$

$$\left\{\begin{matrix} \text{for all } n \geq 0, & X_n \in S \\ \text{for all } n \geq 1 & \text{and for all } i_0, \ldots, i_{n-2}, i_{n-i}, j \in S \end{matrix}\right\} \quad \text{we have:}$$

$$P\{X_n = j \mid X_{n-1} = i_{n-1}, \ldots, X_0 = i_0\} = P\{X_n = j \mid X_{n-1} = i_{n-1}\} \qquad \text{Eq.7}$$

Markov chains are used to compute the probabilities of events occurring by viewing them as states transitioning into other states or the same state as before. The transition matrix for a Markov chain is a stochastic matrix whose (i, j) entry gives the probability that an element moves from the state S_i to the state S_j during the next process step. Pij denotes the probability, which does not depend upon which states the chain was in before the current state. The probabilities P_{ij} are called transition probabilities, which can be represented as;

$$P_{ij} = \begin{matrix} ij & i & j \\ i & \alpha & 1-\alpha \\ j & 1-\beta & \beta \end{matrix}$$

.

Where α and β are the respective states. S_0 is a (1 x m) probability vector representing the starting distribution. Then the probability that the chain is in state S_i after n steps is the ith entry in the vector: $S_n = S_{n-1}P$. The general formula for computing the probability of process ending up in a certain state is given as:

$$S_n = S_0 P^n \qquad \text{Eq. 9}$$

3. Result and Discussion

The adversary sequence path (figure 2) through the PPS elements were computed into the EASI model to estimate the probability of interrupting the intruder. For easy analysis, the probability of communication, Pc was standardised at 0.95; this gives certainty of the alarm going up as the intruder approaches the detection zones or volume. The delay time was in seconds, and it has a standard deviation of 30%; this should account for any unforeseen delay associated with the elements or any other dynamics at play, such as distance or poor visibility. The probability of interruptions results was displayed in tables 1, 2 and 3, as the intruder approached the target separately. The results show a satisfactory level of interruption, as discussed by Bowen et al., in [8]. It also shows that the PPS elements provide near to perfect protection to the facility; therefore, an upgrade is reasonably not necessary at this very point. However, as time lapses, these elements gradually lose their sensitivities to effects such as climate and weather, maintenance, component failure, durability and other such factors. Finally, the estimated probabilities of interruption along the adversary paths to the targets were modelled into the Markov chain theory (figure 3).

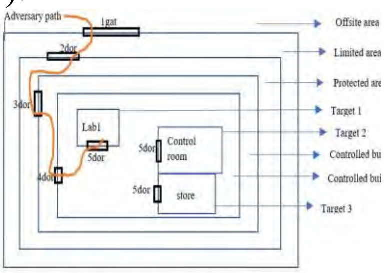

Figure 1: Schematic delineation of PPS elements in the HNF

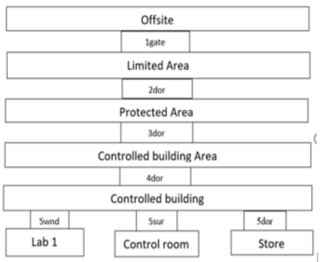

Figure 2: Adversary Sequence Diagram of the Intruder

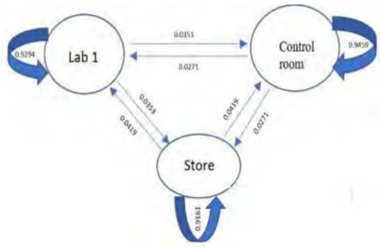

Figure 3: Markov transient states

Estimate of Adversary Sequence Interruption	of Guard Com	Response Force Time (in Seconds) Mean	Standard Deviation
	0.95	300	90

Task	Description	P(Detection)	Location	Delays (in Seconds): Mean	Standard Deviation
1	cut main gate	0.9	B	10	3
2	Run to Limite area	0	B	12	3.6
3	Open Door	0.9	B	90	27
4	Run to Protected Area	0	B	10	3
5	Open Door	0.9	B	90	27
6	Run to cont. build. area	0	B	10	3
7	Open Door	0.9	B	90	27
8	Run to cont. build.	0	B	10	3
9	Open Door	0.9	B	90	27
10	sabotage Lab 1	0.9	B	120	36
11					
12					

Probability of Interruption:	0.929447148

Table 1: Probability of Interruption for Lab 1

Estimate of Adversary Sequence Interruption	of Guard Com	Response Force Time (in Seconds) Mean	Standard Deviation
	0.95	300	90

Task	Description	P(Detection)	Location	Delays (in Seconds): Mean	Standard Deviation
1	cut main gate	0.9	B	10	3
2	Run to Limite area	0	B	12	3.6
3	Open Door	0.9	B	90	27
4	Run to Protected Area	0	B	10	3
5	Open Door	0.9	B	90	27
6	Run to cont. build. area	0	B	10	3
7	Open Door	0.9	B	90	27
8	Run to cont. build.	0	B	10	3
9	Open Door	0.9	B	90	27
10	sabotage Control room	0.9	B	240	72
11					
12					

Probability of Interruption	0.945903828

Table 2: Probability of Interruption for control room

Estimate of Adversary Sequence Interruption	of Guard Com	Response Force Time (in Seconds) Mean	Standard Deviation
	0.95	300	90

Task	Description	P(Detection)	Location	Delays (in Seconds) Mean	Standard Deviation
1	cut main gate	0.9	B	10	3
2	Run to Limite area	0	B	12	3.6
3	Open Door	0.9	B	90	27
4	Run to Protected Area	0	B	10	3
5	Open Door	0.9	B	90	27
6	Run to cont. build. area	0	B	10	3
7	Open Door	0.9	B	90	27
8	Run to cont. build.	0	B	10	3
9	Open Door	0.9	B	90	27
10	sabotage Store	0.9	B	90	27
11					
12					

Probability of Interruption	0.916109055

Table 3: Probability of Interruption for store

Markov chain theory estimates these probabilities as they transit from the present into the future. Due to the necessity, these probabilities of the dynamics of limitations associated with the PPS elements over time. The MC enables the security experts to give estimates and advice on the management effects on the state of the PPS over time. The probabilities were mapped into the Markov matrix as shown in the iterations below. In the study, we considered the initial state of the transition of the intruder's interruption probability to start from Lab 1; hence the probability vector is $S_0 = [1\ \ 0\ \ 0]$. Equation 9, the state of the interruption probability for Lab 1 target can be estimated into the future in terms of months. For a more straightforward analysis, n is estimated on a monthly interval, equation 9 becomes.

From \ To	Lab 1	Control room	Store
Lab 1	0.9294	0.0353	0.0353
Control room	0.0271	0.9459	0.0271
Store	0.0419	0.0419	0.9161

$$P = \begin{bmatrix} 0.9294 & 0.0353 & 0.0353 \\ 0.0271 & 0.9459 & 0.0271 \\ 0.0419 & 0.0419 & 0.9161 \end{bmatrix}$$

Lab 1 state for the initial round, (*n=1*)

$$S_1 = [1 \quad 0 \quad 0] \begin{bmatrix} 0.9294 & 0.0353 & 0.0353 \\ 0.0271 & 0.9459 & 0.0271 \\ 0.0419 & 0.0419 & 0.9161 \end{bmatrix}^1 = \quad [0.9294 \quad 0.0353 \quad 0.0353]$$

For the end of 1st quarter (*n* = 3)

$$S_3 = [1 \quad 0 \quad 0] \begin{bmatrix} 0.9294 & 0.0353 & 0.0353 \\ 0.0271 & 0.9459 & 0.0271 \\ 0.0419 & 0.0419 & 0.9161 \end{bmatrix}^3 = \quad [0.8097 \quad 0.0974 \quad 0.0930]$$

For 2 years (*n* = 24)

$$S_{24} = [1 \quad 0 \quad 0] \begin{bmatrix} 0.9294 & 0.0353 & 0.0353 \\ 0.0271 & 0.9459 & 0.0271 \\ 0.0419 & 0.0419 & 0.9161 \end{bmatrix}^{24} = \quad [0.3703 \quad 0.3680 \quad 0.2618]$$

For 3 years (*n* = 36)

$$S_{36} = [1 \quad 0 \quad 0] \begin{bmatrix} 0.9294 & 0.0353 & 0.0353 \\ 0.0271 & 0.9459 & 0.0271 \\ 0.0419 & 0.0419 & 0.9161 \end{bmatrix}^{36} = \quad [0.3330 \quad 0.3994 \quad 0.2678]$$

The MC result shows the transitional states of the intruder from Lab 1 to the two other targets over eight years (96 months). The sequence was stable over the first four months (1st quarter), then became unstable for the next 24 months, and later became relatively stable as the year progresses, that is, as $n \to \infty$ the sequence converges to a steady-state.

These illustrate that the intruder has a 41% and 27% chance of transiting to the control room and store, respectively, in the foreseeable future if the present PPS elements remain constant. It will be an excellent tool for planning the lifespan of the PPS elements for upgrade or outright replacement.

For 8 years (*n* = 96)

$$S_{96} = [1 \quad 0 \quad 0] \begin{bmatrix} 0.9294 & 0.0353 & 0.0353 \\ 0.0271 & 0.9459 & 0.0271 \\ 0.0419 & 0.0419 & 0.9161 \end{bmatrix}^{96} = \quad [0.3182 \quad 0.4149 \quad 0.2679]$$

4. Conclusion

This study introduces the analytical integration methods of evaluating PPS effectiveness. First, the EASI model was used to analyse the probabilities of interruption of the PPS elements in a sabotage scenario. Then, the Markov chain theory was used to analyse the probability of interruption's transition from the initial state (Lab1) to the two other states (control room and store) over time in the facility. The study also highlighted the importance of integrating PPS evaluation models to give a comprehensive and balanced assessment within tight budget constraints.

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