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SYSTEMS ENGINEERING CAPSTONE REPORT

A SYSTEMS ENGINEERING APPROACH TO SCHOOL SYSTEM ENHANCEMENTS FOR COUNTERING ACTIVE SHOOTERS IN U.S. K-12 SCHOOLS

by

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December 2018

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LIST OF ACRONYMS AND ABBREVIATIONS

AI	artificial intelligence
AS	active shooter
ASR	active shooter response
AVG	average
CONOPS	concept of operations
COTS	commercial off-the-shelf
FTA	fault tree analysis
IRB	Institutional Review Board
K-12	kindergarten through 12th grade
MOE	measure of effectiveness
MOP	measure of performance
NPS	Naval Postgraduate School
ROTC	Reserve Officers' Training Corps
ST	success tree
SWAT	Special Weapons and Tactics
TSA	Transportation Security Administration

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I. INTRODUCTION

The last concern students, faculty, and parents should face is the possibility of a school shooting. A school should be a safe place; however, in today's society this is sadly not guaranteed in United States kindergarten through twelfth grade (K-12) institutions. The question is not if a school shooting will occur but rather when the next tragedy will take place. There were 22 school shootings in the first 20 weeks of 2018—an alarming average in excess of one per week (Ahmed and Walker 2018). Gun-related violence in U.S. schools is a widespread concern that has become increasingly prevalent in recent history. Shootings have transpired with an alarming frequency in the United States, claiming many lives, and are becoming a growing concern in today's society.

The earliest documented school shooting in the United States took place in Pennsylvania in 1764. In what became known as the Pontiac's Rebellion School Massacre, four Lenape American Indians killed the schoolmaster and at least nine children (K12 Academics n.d.). From January 1968 to February 2018, 75 school shooting cases occurred in U.S. universities and 246 occurred in K-12 schools (Cato 2018). Since then, through April 2018, four more incidents occurred in United States K-12 schools and three more in U.S. universities (Ahmed and Walker 2018). These tragedies are continuing to unfold one after another with few meaningful accomplishments to prevent subsequent threats.

In the first five months of 2018, deaths from school shootings exceeded all military deaths for deployed personnel (Bump 2018). With much of the recent media attention encompassing active shooter (AS) incidents, a strong indication exists that school safety is of the utmost concern for parents, faculty, staff, and students. Similar concerns occurred after the September 11, 2001, attacks. In response to the September 11thth attacks, the U.S. government created the Transportation Security Administration (TSA), "a coordinated body which identified air travel security concerns and addressed those threats with consistent, effective, evenly applied security solutions and procedures, executed at all airports across the country" (Hevia 2018). The reaction to the terrorist attacks of September 11th transpired quickly, resulting in a comprehensive solution with nationwide applicability. In essence, the TSA emerged as an enterprise system whose framework and standards could be applied across a broad spectrum of facilities. The United States K-12 education system presents a poignant corollary to the air transportation system. Both systems entail a network of interspersed facilities, with each individual location exhibiting various capacities, capabilities, and funding levels. In 2001, a single act of terror sparked rapid action—so why have the same efforts not been carried out for the school system to protect our children?

Gun control and mental health provisions are commonly asserted solutions to the problem at hand. While efforts to minimize the accessibility of weapons to high risk individuals may be a part of the solution, no legislative measures appear on the verge of passing that will be sufficient to combat the threat of active shooters. The American legislative process is arduously slow and continuously hampered by the influence of competing priorities, vociferous debate, and lobbyists. At current rates, dozens of school shootings are likely to occur in the time it would take to legislate new gun control measures. A multifaceted approach to system enhancements for countering active shooters in our K-12 schools is needed.

A. PROBLEM STATEMENT

An all-too-common tendency when faced with complex issues is to rush to an answer without thoroughly analyzing the true nature of the problem. This is the case with school shootings. Prominent figures and common citizens alike vehemently argue their opinions about the best means to fix the issue—whether their solution is federal gun control laws, mental health reform, or other sweeping measures. While the ultimate solution may include components of these recommendations, it is essential to start at the core of the problem in order to effect an unbiased analysis. The problem is simple: active shooters can gain access to K-12 institutions and kill or injure students, faculty, and staff.

B. BACKGROUND

In the United States alone, 250 active shooter incidents occurred between 2000 to 2017, producing 2,217 total student injuries and deaths (Federal Bureau of Investigation n.d.). U.S. government agencies define an active shooter as "an individual actively engaged in killing or attempting to kill people in a confined and populated area" (ALICE Training Institute n.d.). Active shooters generally use firearms and other weapons of destruction, with no common pattern or method for their killings. Active shooter situations are generally unpredictable and can take place with little to no warning.

> More people have died or been injured in school shootings in the U.S. in the past 18 years than in the entire 20th century … During the 20th century, active shooters killed 55 people and injured 260 others at schools especially in America's Western region. Most of the 25 shooters involved were white males who acted alone … Sixty percent of shooters were between 11 and 18 years old. Since the start of the 21st century, there have already been 13 incidents involving lone shooters; they have killed 66 people and injured 81 others. (Springer 2018)

Although these statistics are a significant concern, the disparity between U.S. statistics and those of other countries is even more alarming. As shown in Figure 1, between 2000–2010 the United States had almost as many school killings with multiple deaths as the next 36 other countries combined. In 2010, the U.S. population was approximately 309 million, while the populations of these other countries totaled 3.8 billion. In that period, Germany experienced three shootings; Finland encountered two. Thirteen other countries each saw one incident with at least one person being wounded or killed. During that decade, America had 27 such incidents (Fisher and Keller 2017).

Currently, most of the debate, energy, and effort in America is directed at how to prevent an active shooter incident from occurring. However, additional attention is required to reduce the lethality of an incident that has already commenced. Similar to the defense-in-depth cybersecurity architecture—which provides a layered approach wherein if one protection mechanism fails, another is already in place to thwart an attack—a single solution cannot eliminate, prevent, or counter these threats.

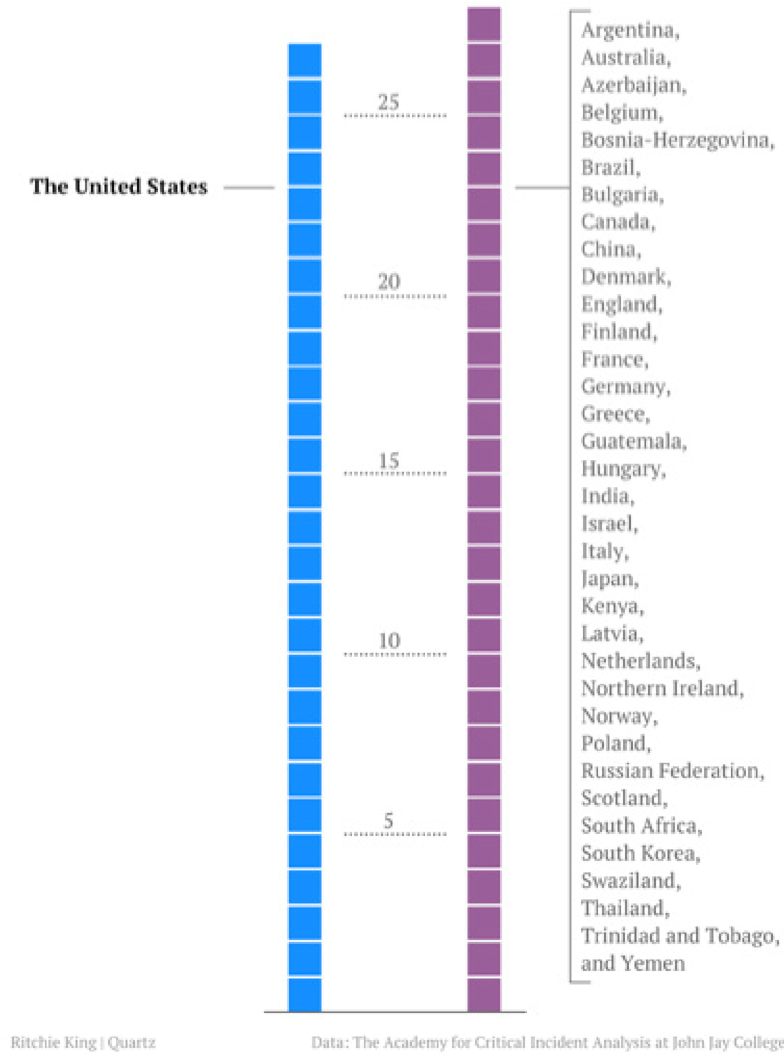

Figure 1. School Killings with Multiple Victims between 2000 and 2010.
Source: Foxman and King (2012).

Many nations have applied the layered approach concept to protect their schools. As an example, Dick (2012) describes the measures that schools in Germany have implemented. Many German schools have replaced traditional handles with special locking systems on classroom doors; during an emergency, it is only possible to open the door from the inside. Another measure includes laying out school facilities according to color codes with the aim of making it easier for police and emergency personnel to orient themselves on school grounds Furthermore, several German schools have installed monitoring systems, enabling employees to identify a possible active shooter threat before he starts an attack. Additionally, they have initiated an emergency notification system that notifies local authorities of a threat, expediting the potential response of an interdicting force. Finally, they created a common set of guidelines for schools to follow when responding to an active shooter, which reduces potential confusion and ensures security protocols are active before a shooter can locate and engage targets (Dick 2012).

Germany is not the only country with active measures to counter school shootings. Csere (2013) describes the various measures that Israel has enacted to protect students from gun violence. Israel requires schools of 100 or more students to have dedicated armed guards. Israel's ministry of education requires schools to hold daily reviews of administrative actions for the day to ensure there are no impacts to the established security plans. They now require schools to use chartered buses instead of public transportation. They frequently review safety and security protocols and procedures. During an emergency, school staff members enact protocols to expeditiously move groups to safety, such as using security forces to escort students to their residences (Csere 2013).

Despite the existence of modern security options that schools can incorporate to counter the active shooter threat, the lethality of these incidents is still on the rise in America. Cato (2018) lists the nearly 250 school shootings that have occurred in the past 50 years. From this list, it is evident that these events have become more frequent in recent years and that individual attacks have become deadlier. Furthermore, Cato's list includes a broad range of school locations and types, suggesting that no single category of school (e.g., inner-city, high school, or low-occupancy) may be more susceptible to this threat than others. A systematic process is necessary to identify where improvements can be made in the American school system's response to active shooter incidents, starting with analyzing individual situations to see what lessons can be learned.

C. CASE STUDIES

This study examined several school shooting cases, selected from available documentation about active shooter incidents at American K-12 institutions from 1968 to 2018. The capstone team considered several factors when choosing cases to analyze, such as the overall lethality of the event and how the nuances of each specific situation provided an opportunity to glean unique improvement recommendations. Each case study discusses the background of the shooter and the activities that led up to the shooting. At the end of this section, the capability gaps are addressed, followed by an analysis of the lessons learned from the events and any improvements that could be made based on the issues noted.

1. Red Lake High School Shooting

On March 21, 2005, violence devastated Red Lake High School at the Red Lake Reservation in Minnesota when Jeff Weise, a 16-year-old local Native American, took the lives of nine people and injured 15 others before killing himself (Enger 2015). As Enger describes, the shooting on the morning of March 21 began when Weise shot Daryl Lussier, his grandfather, and Daryl's companion Michelle Sigana. After this, Wiese stole his grandfather's pistol, shotgun, bulletproof vest, and squad car, and then set off to Red Lake High School. Upon reaching the school, Weise entered through the front doors and started firing. He aimed his first shots towards an unarmed, on-site security guard, killing the guard, then broke through the lock of one of the classrooms before shooting a teacher and five students. Weise continued through the hallways of Red Lake until law enforcement arrived (Enger 2015). It took law enforcement several minutes to corner Weise in an isolated room with no exits, where Weise shot himself (Connolly and Harris 2015). After Weise's death, authorities moved into the classrooms and escorted students and teachers out of the school (Connolly and Harris 2015).

Enger (2015) describes two security measures in place at Red Lake High School before the shooting that helped the school counter the active shooter threat. First, the school district appointed a dedicated, but unarmed security guard to the school. Additionally, the high school utilized a camera surveillance system to monitor visitor entry and departure. The security guard, although not trained to handle an active shooter incident, was still able to delay Weise's entry into classrooms. Enger explains that the guard briefly fought with Weise and used his body to block some of the bullets aimed at the students present in the hallway. The camera system provided the security guard a visual indication of Weise, but not his concealed weapon, as he was entering the school grounds (Enger 2015).

On the other hand, several weaknesses existed in the school's security structure that worked in favor of the shooter. The school did not have a protocol in place to notify emergency services of a potential active shooter (Hughes 2005). Hughes explains that the school's telephone lines happened to be down during the incident, which necessitated the use of a student's cell phone to notify authorities. Later, when a reporter questioned school authorities regarding this incident, authorities commented that they were not aware of any previous failures with their phone system and that the event on the day of the shooting might have been an isolated case (Minnesota Public Radio 2005). The age of the school's classrooms did not make it any easier to reduce the active shooter threat. Weise forced his entry into a classroom, where the teacher and the students used their bodies as a barrier to block the door from opening, since its lock had broken (Enger 2015). Unfortunately, Weise was able to penetrate the classroom and follow through with his attack.

2. Rancho Tehama Elementary School Shooting

A string of shootings between November 13 and 14, 2017 in Rancho Tehama Reserve, California, left five individuals killed and 12 others injured (Tchekmedyian 2017). The shootings encompassed several separate locations, including Rancho Tehama Elementary School. Although the shooter was able to kill several victims unhindered on the morning of the 14th, he failed to kill any students, faculty, or staff during the attack on the school.

Tchekmedyian (2017) describes the events, which began when Kevin Jansen Neal killed his wife the day before attacking the school and hid her body under the floorboards of his home. The next morning, Neal killed his neighbor and two other men, stole a truck, and proceeded in the direction of the school. On the way, he shot at another truck on the road, injuring two people (Tchekmedyian 2017).

During this time, nearly 100 students were playing outside at the nearby Rancho Tehama Elementary School (Kohli 2017). As Kohli describes, staff members heard the gunfire and a secretary quickly initiated lockdown procedures, which were nearly complete by the time Neal rammed a gate on the fence around the property and gained access to the school grounds. Kohli continues, explaining that Neal began shooting at a custodian - the first-person Neal saw in the schoolyard - but appeared to be having difficulty with his weapon. During this time, the school staff completed the lockdown. Neal entered the yard dividing the school's four classrooms, attempted to gain access to the various buildings, and shot at windows and doors. Ultimately, he only hit one student, who was not in Neal's line-of-sight, and whose injuries were not fatal (Kohli 2017). Having failed to kill anyone and unable to find any other potential victims to engage, Neal left the school grounds.

Rancho Tehama Elementary is a small school with few faculty members and less than 100 students. The only physical security measures described at the school included the gate (indicative of a perimeter fence) that the shooter drove through to gain access and the fact that the classrooms and other buildings were lockable. The staff members had practiced drills, to include lockdowns, before the incident (Kohli 2017). This proved critical in minimizing the effectiveness of the attack, since no students were in the shooter's line-of-sight by the time he was in the vicinity of the schoolyard. The presence of the school's custodian provided a de facto defense mechanism. The delay associated with Neal attempting to kill the custodian gave enough time for the students and the rest of the staff to finish securing themselves in the other buildings. No other intervention occurred, and the shooter left the school on his own without law enforcement interdiction. Police eventually responded to the attacks and killed the shooter, but not until Neal was able to leave the school and kill other victims on the road (Tchekmedyian 2017).

3. Sandy Hook Elementary School Shooting

On December 14, 2012, 20-year-old Adam Lanza stormed into Sandy Hook Elementary School in Newton, Connecticut, armed with four weapons—a shotgun, a rifle, and two handguns (Biography 2018). The Biography (2018) article describes the shooting, explaining that Lanza strolled through the elementary school hallways and randomly murdered 20 children and six adults, injuring two others. During this time, Lanza fired 154 rounds throughout the five-minute event in which 700 students were present. According to the article, most of the shooting occurred within two classrooms, with 14 students in one classroom and six in another, and the remaining students spread throughout the wing of the school. At the end of the incident, Lanza took his own life (CNN n.d.).

The incident occurred during school hours and Sandy Hook Elementary School already had some security measures in place. Sandy Hook Elementary required all visitors to check in at the main office and only allowed visitor access to the campus by doorbell service and with proper identification (CNN n.d.). The security protocol required staff to lock the school doors daily by 0930 (CNN n.d.). The gunman essentially shot his way through all these security measures.

An article by the *New Haven Register* (2013) describes the police response to this incident. According to the article, the first emergency call came in at 0935 and police arrived four minutes later. Unfortunately, police were confused as to what was happening inside the school. Conflicting reports suggested the possibility of multiple shooters and the existence of an unidentified male running outside with something in his hand. The article states that police waited another five minutes before entering the school while determining how to proceed. By the time they entered the school, the shooter had taken his life and the shooting was over (*New Haven Register* 2013).

4. Marjory Stoneman Douglas High School Shooting

On February 14, 2018, Nikolas Cruz, an expelled student, entered building 12 of Marjory Stoneman Douglas High School in Parkland, Florida, and killed 17 people with a .223-caliber AR-15 rifle (Chockey, Hobbs, and Zhu 2018). The authors of this article explain that Cruz pulled the fire alarm and walked through the hallways of the first, second, and third floors, shooting into classrooms and down the hallways for six minutes. The authors assert that Cruz did not injure anyone on the second floor because the students covered the doors and windows of their classrooms with paper. Cruz dropped his rifle and backpack on the third floor, left the building, and mixed in with students and staff in the chaos. Approximately one hour later, police found Cruz walking through a nearby neighborhood and arrested him (Chockey, Hobbs, and Zhu 2018).

Ovalle et al. (2018) outline the school's response during the Parkland shooting, including the actions of the resource officer assigned to Marjory Stoneman Douglas High. As the authors describe, the school began lockdown procedures four minutes after the start of the shooting. During this time, the school resource deputy made his way to building 12 but never entered, as he was unsure whether there were shots at the football field or only in building 12. After Cruz left the building, the deputy radioed, “Do not approach the 12 or 1300 building, stay 500 feet away” (Ovalle et al. 2018). Five minutes after the shooting ended and Cruz had left, Broward police officers entered building 12 (Ovalle et al. 2018).

Although Marjory Stoneman Douglas High School had security measures in place, they were inadequate to counter Cruz’s killing spree. The school was not on lockdown for several minutes after the attack started and Peterson, the resource officer, directed officers to avoid entering building 12. The one partially successful action accomplished was that teachers covered windows with paper, so Cruz could not see into the classrooms.

5. Santana High School Shooting

On March 5, 2001, Charles Andrew William wreaked havoc at Santana High School in Santee, California, by killing two classmates and injuring 13 students and school staff members (Dickey 2013). As Dickey describes, William brought a .22 caliber pistol with 40 bullets to school; he started the shooting event in the bathroom of the school and continued outside for several minutes. Dickey recounts that during the event, William reloaded four times and nearly used all his bullets. When the school security guard investigated the initial shot in the bathroom, William shot him three times. Ultimately, William surrendered to the police (Dickey 2013).

Santana High School had two primary security measures in place for active shooter scenarios. First, the school district assigned a security guard to Santana High, who was responsible for crime prevention (Dickey 2013). Second, the school had a good communication and security plan which outlined actions to take in times of crises (Helfland 2001).

6. Case Study Comparison

While the active shooters in these cases used various techniques and gun types, every situation resulted in death or injury. The school shootings involved a lone shooter using public access points. In most of the cases, there were fatalities on the school premises.

The only noted exception is Rancho Tehama Elementary School in which no students or faculty were killed.

Additionally, the case studies highlight further trends. In almost all instances, communications proved ineffectual, which delayed notification of emergency responders. In most cases, school occupants were not aware of the threat until after the shooting had commenced. Furthermore, none of the schools successfully prevented the shooter from accessing the school grounds - even those that had access-control measures in place. Visual barriers (e.g., solid doors and impromptu window blinds) limited the lethality of the incidents, as shooters were unable to locate potential targets.

7. School System Capability Gaps

Several common shortcomings existed with the schools' security. These capability gaps are shown in Table 1. First, communication between law enforcement, school security officers, and school officials was not effective. This lapse in communication delayed response time, thereby affording the active shooters more time to carry out their attacks. By the time law enforcement arrived on scene, several fatalities and injuries had transpired.

Table 1. Capability Gaps Associated with Case Studies

Capability Gaps	Red Lake High School	Rancho Tehama Elementary School	Sandy Hook Elementary School	Marjory Stoneman Douglas High School	Santana High School
No method to detect a weapon	x	x	x	x	x
No protection for windows / doors	x	x	x	x	x
Lack of physical barriers between AS and school occupants	x	x	x	x	x
No surveillance to monitor grounds		x	x	x	x
Poor communication between school and first responders	x		x	x	x
On-site security officer inexperienced in AS events	x			x	x
No on-site security officer		x	x		
Poor lockdown procedures	x			x	

Besides poor communication, schools also lacked a surveillance capability to monitor for potential threats. Also, the schools lacked the technology to detect and track a threat within the school premises to maintain situational awareness in support of response implementation. Another common trend was ineffective physical security measures. Shooters were able to access schools with concealed weapons. Finally, the lack of an on-site security officer enhanced the shooter's ability to maximize casualties.

Capability gaps provide initial insight into what system enhancements are needed to counter the active shooter threat. However, reviewing these gaps is not sufficient by itself to determine how the system should behave; therefore, this review needs to be augmented by further analysis. The next chapter serves to refine the problem space and define the overarching system needs.

D. OVERVIEW OF APPROACH

The school shooting epidemic currently facing the United States is likely to remain a problem for years to come. Nevertheless, the potential exists to limit the lethality of these heinous acts even if it is impossible to prevent them altogether. The inherent complexity of this problem makes the systems engineering approach a valuable method for enhancing school system security.

The remainder of this study will utilize the systems engineering process to develop a set of school system enhancements to counter the active shooter threat. The process will start with the definition of the scope, functional analysis, then lead into the development of a system architecture. The system architecture will be modeled to facilitate an examination of alternatives that can augment school system security.

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II. PROBLEM DEFINITION

A. SCOPE

This project incorporates systems engineering principles to develop a method for evaluation system enhancements that counter the effectiveness of active shooters in schools. To support this process, we consider the school to be an existing system with the ability to implement improvements. Applying the systems engineering process ensures that any potential system enhancements are traceable to the system's effective needs and the capability gaps that make schools susceptible to the AS threat.

1. Objective

While a single solution may not be ideal for all schools, the objective of this systems engineering effort is to develop an architectural model of the school system to analyze the implementation of system enhancements. From this model, we will develop a tailorable tool that will allow decision makers to assess the effectiveness of potential enhancement alternatives in reducing the number of occupants an AS can kill or injure during an attack.

2. System Boundary

The school system boundary, depicted as the dotted circle on the context diagram in Figure 2, includes the school infrastructure and school occupants (e.g., students, faculty, staff, on-site security officers). The context diagram also shows the active shooter whose goal is to penetrate the system boundary during the attack. Additionally, emergency services interact with the system, but are external elements.

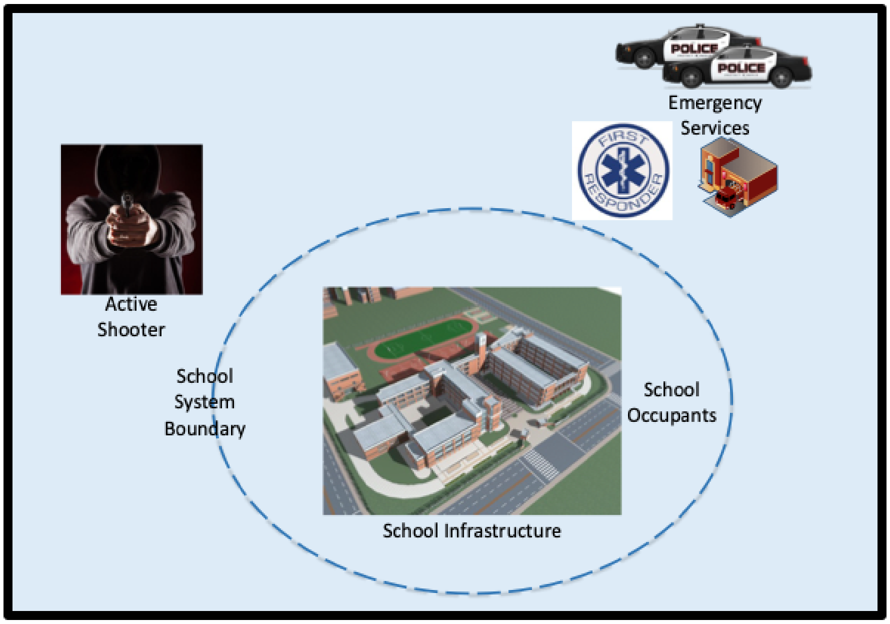

Figure 2. School Security System Context Diagram

Ultimately, the process taken to investigate potential school system enhancements will explore technical solution spaces in an effort to augment existing security measures to counter the active shooter threat. Proposed modifications will not attempt to identify a potential shooter in the days and months leading up to an attack but will instead focus on reducing the school system's vulnerability to an active shooter who is approaching the school's property with the intent of carrying out an attack, or where an attack has already started.

3. Assumptions

The following list outlines assumptions that the capstone team considered in the development of the system model. These assumptions address the support that will be available for schools to implement potential system enhancements, as well as any existing infrastructure and policies that are available to leverage.

- School system enhancements may either augment and integrate with or replace existing security measures, as appropriate.

- The school faculty members and staff will be the primary users of the security enhancements while the students will mainly act as beneficiaries.
- The school includes, at a minimum, a physical structure commensurate with traditional public schools, including alterable exits and windows.
- The system enhancements will be tailored appropriately with respect to the unique requirements of individual schools.

4. Constraints

The design and selection of school system enhancements shall take into consideration the following constraints:

- school resources, such as budget and schedule
- diverse school infrastructures across the nation
- existing school's physical infrastructure (e.g., classroom layout, acreage, adjacent non-owned buildings).

B. NEEDS ANALYSIS

As a precursor to formalizing system requirements, a critical step is to refine the stakeholder's primitive needs into effective needs. To further understand the capability gaps that exist, the capstone team conducted a series of interviews, which led into the shooter success tree (ST) and the fault tree analysis (FTA). We interviewed school administrators and faculty, members of police organizations, and representatives from private security firms. The feedback from these interviews, in conjunction with data presented in case studies, led to the selection of events for the ST and FTA. The ST and FTA both explore the logical connections between resultant events and their causal factors. The ST illustrates the shooter's perspective and considers what the shooter may do to achieve his desired goal, while the FTA captures the events from the school system's perspective and addresses the failures that ultimately lead to an undesired end state.

1. Stakeholder Identification

Many diverse groups are concerned with school safety, but not all of these individuals have pertinent input for the design of security enhancements to counter the active shooter threat. The stakeholders for this system include school staff, law enforcement, private security professionals, parents, and students – all of whom have a direct interest in enhancing school system security. The first three types of stakeholders are potentially able to make decisions about enhancement alternatives. They also are more likely to have professional experience in dealing with the AS problem. We interviewed these three categories of stakeholders, consisting of 32 individuals, as shown in Table 2.

Table 2. Stakeholder Interviews Conducted

Category	**Number of Personnel Interviewed**
School Staff	18
Law Enforcement	10
Security Professional	4
Total	**32**

We developed a standard set of questions for interviewing stakeholders and submitted this questionnaire to the Naval Postgraduate School (NPS) Institutional Review Board (IRB). The approved questionnaire is included for reference in Appendix A. Table 3 summarizes the stakeholders' primitive needs and associated concerns, which we then refined into a set of overall effective needs that the enhanced system must address.

Table 3. Stakeholder Analysis

<table>
<tr><th>Stakeholder</th><th>Primitive Needs</th><th>Concerns</th><th>Overall Effective Needs</th></tr>
<tr><td>School Administration/ Staff (Design Contributor)</td><td>- A safe environment to teach and learn
- Non-intrusive security measures on school premises
- Clear incident response plan and training
- Communications within the school and with first responders</td><td>- Danger to occupants and the inability to provide education
- Adverse effect of a perceived decrease in safety with the addition of overt security measures
- Unfamiliarity with AS protocols leading to mistakes
- Inadequate understanding of situation, delaying its resolution</td><td rowspan="3">- Ability to detect an approaching threat
- Communicate existence of danger to entities capable of suppressing the threat
- Monitor progress of threat so as to maintain situational awareness
- Prevent or at least minimize shooter's ability to reach school’s occupants</td></tr>
<tr><td>Law Enforcement (Design Contributor)</td><td>- Situational awareness of activity within the school
- Secure communications with school personnel
- Chance to work with school administrators/ staff on safety protocols and procedures.
- Accessibility to school</td><td>- Excess delay in discerning situation providing opportunities for shooter
- Inability to provide effective guidance to school occupants
- Lack of school active shooter training leading to unsafe decisions
- Barriers on school premises preventing rapid intervention</td></tr>
<tr><td>Private Security Professional (Design Contributor)</td><td>- Monitor surveillance for potential threats to school
- Maintain organization’s stability by providing effective solutions while complying with local laws</td><td>- Ignorance of school situation precluding ability to intervene
- Ineffective recommendations or school code violations damaging reputation of the firm</td></tr>
</table>

Table 3. (Con't) Stakeholder Analysis

Stakeholder	Primitive Needs	Concerns	Overall Effective Needs
Parents (System beneficiary)	- A safe learning environment for their children - Involvement of local law enforcement - Clear school crisis /emergency management plan	- Fear that their child will be the next to fall victim - Proficiency of those responding to threats - Uncertainty whether or not school will be able to react appropriately	
Students (System beneficiary)	- A safe learning environment - Subtle measures that provide security	- Injury or death due to active shooter incident - Perception of being at-risk for attack	

2. Success Tree Analysis

The ST is an analytical, event-based representation of the combination of events that lead to success (Dillon-Merrill, Parnell, and Buckshaw 2009). We use a success tree to represent a school shooting incident from the perspective of an AS. The ST consists of a series of hierarchical events based on the objective of maximizing the casualties on the school premises during an AS attack. It uses Boolean logic gates to associate the condition for an event to occur. An "AND" gate depicts an event that requires all subordinate events to have occurred, while an "OR" gate implies that the event requires the occurrence of at least one of the subordinate events.

Figure 3 depicts the top two levels of the ST for an AS attack. The shooter's primary goal is to maximize the casualties he can inflict. To do so, he must maximize his number of opportunities to engage targets (thereby providing more chances to kill), or he needs to maximize the lethality of an individual engagement (increasing the likelihood of killing a targeted individual).

Figure 3. Maximize Casualties

Starting with the left branch of the ST, Figure 4 shows how the shooter can maximize engagement opportunities. Three primary mechanisms contribute to the shooter's ability to increase the chances to engage and cause harm to school occupants. These include increasing the relative percentage of time at the school that the shooter spends actually engaging targets, increasing the available engagement area to facilitate access to targets, or protecting himself to continue the attack.

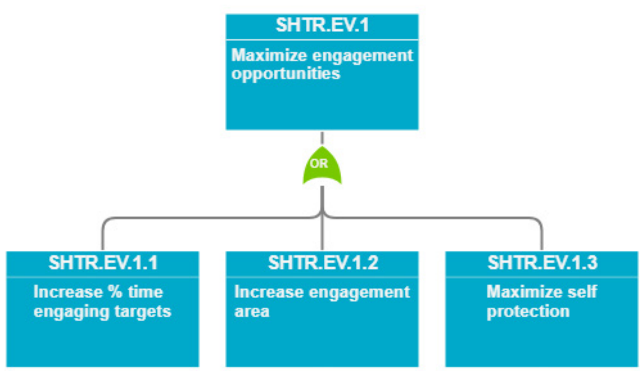

Figure 4. Maximize Engagement Opportunities

As shown in Figure 5, the shooter has several tactics available to increase the percent of time engaging targets. The shooter can delay security response to avoid confrontations, carry a greater volume of ammunition to prolong the attack, or increase mobility within the school to reach new attack positions faster.

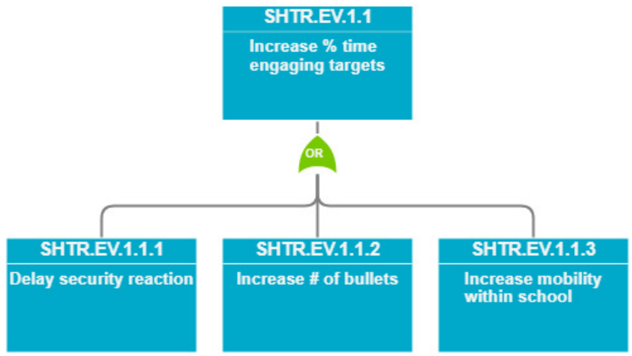

Figure 5. Increase Time Engaging Targets

Figure 6 shows how the shooter can delay the security response. One way is to disable any existing security system, illustrated further in Figure 7, to avoid any impediments in the execution of the attack. The shooter can eliminate any on-site security responders through force or misdirection. Additionally, the shooter can directly disable security measures such as monitoring systems or communication networks, as well as indirectly disable security systems by severing electrical power.

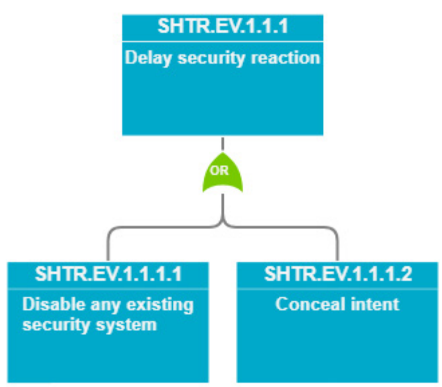

Figure 6. Delay Security Reaction

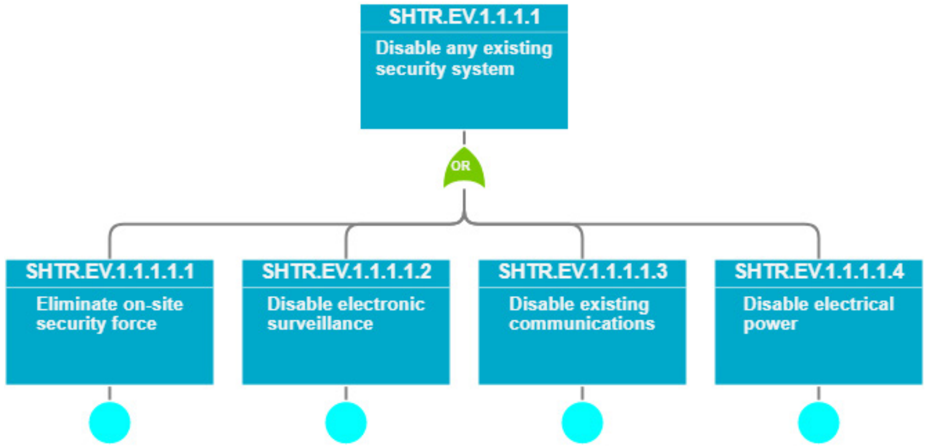

Figure 7. Disable Existing Security System

Figure 8 depicts the other means the shooter can employ to delay security response: concealing the attack. The shooter can conceal his intent to attack by waiting until an optimal time to carry out the incident (e.g., when on-site security force coverage is not present) or the shooter can hide the weapons he will use. The shooter can conceal the weapons by not having them physically visible for detection, either because the gun is small enough to be hidden under normal clothing or because the shooter wears apparel that can hide larger weaponry. The shooter can also pre-stage weapons and ammunition in the school, thereby circumventing any security measures in place while he is approaching the school for an attack.

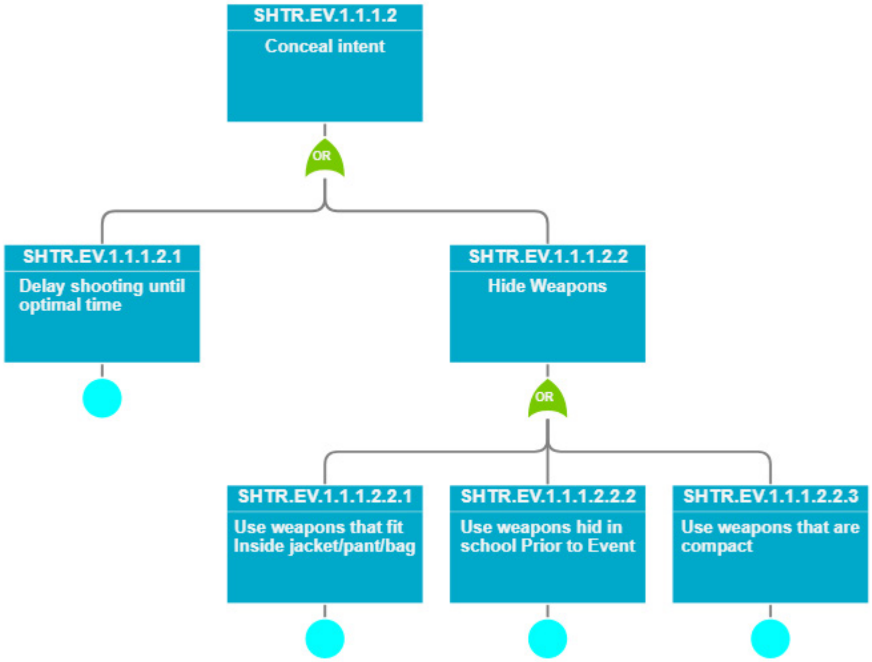

Figure 8. Conceal Intent

Figure 5 shows that the AS can also increase the percent of time engaging targets by increasing the number of bullets, which Figure 9 shows in more detail. To increase bullet quantity, the AS has two options. He can either pack smaller bullets (allowing him to fit more ammunition in a limited storage capacity) or increase his available storage volume by using an object such as a backpack.

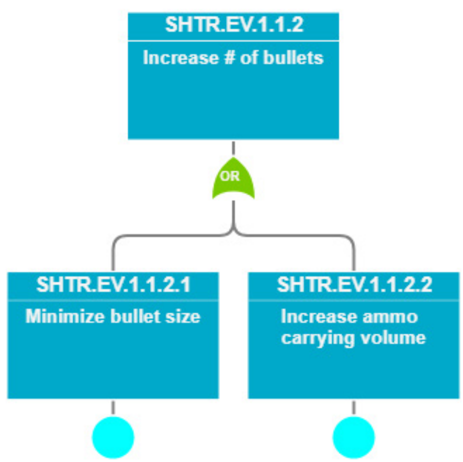

Figure 9. Increase Ammunition

Figure 10 depicts another way to lengthen the percent of time engaging targets. The shooter's mobility within the school supports his ability to reach new targets and continue the attack. The shooter increases his mobility by avoiding obstructions such as locked doors or intervening forces. The shooter can also pre-plan his attack route to ensure that he chooses the most efficient path to get to new areas. He can do this by gaining access to school maps or conducting reconnaissance of the target site prior to the event. The shooter also benefits from having knowledge of the school's emergency response protocols, providing a prime opportunity for engagement since he will know where potential targets are likely to muster and can choose to go to those areas first.

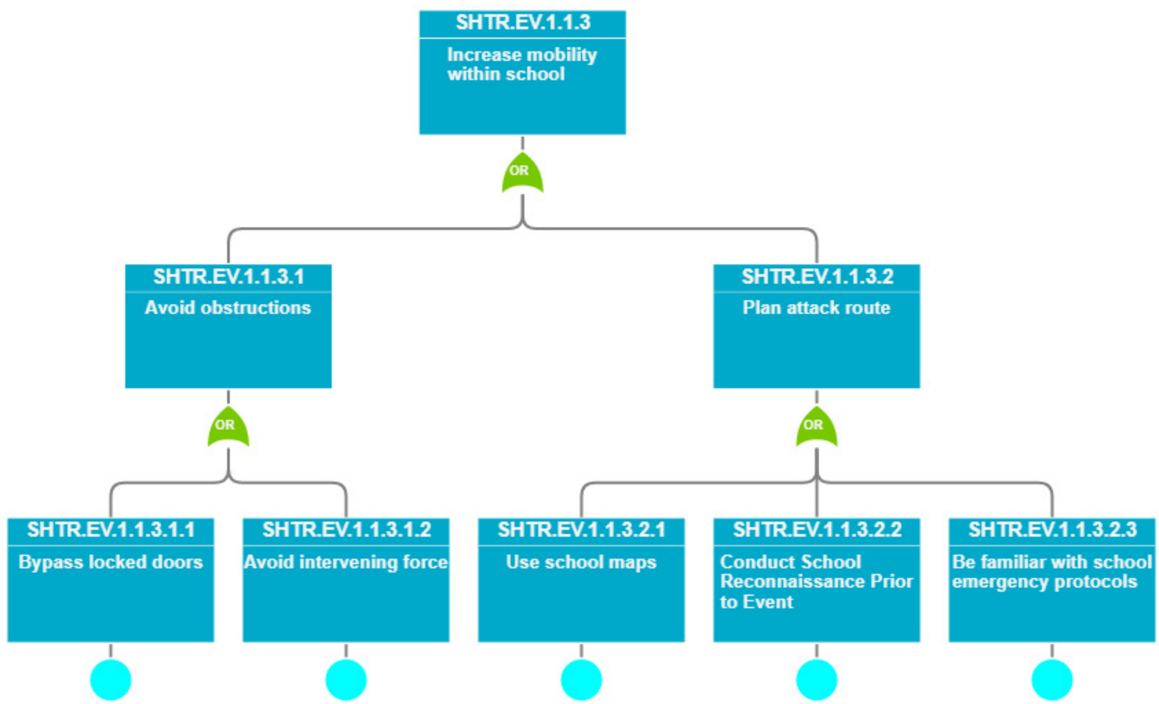

Figure 10. Increase Mobility within School

Another way to maximize engagement opportunities is by increasing the engagement area, as shown in Figure 11. Increasing the engagement area consists of increasing mobility within the school (which mirrors the decomposition of SHTR.EV.1.1.3 shown in Figure 10), positioning himself or his equipment within the school prior to starting the attack, or forcing access to areas in the school. AS mobility within the school broadens the engagement area by allowing the shooter to reach more rooms before he is forced to discontinue the attack. Additionally, as shown in Figure 12, positioning himself, his weapons, or his ammunition within the school before the attack also expands the engagement area, since the shooter will already have gained access to susceptible locations before providing indications of his intent.

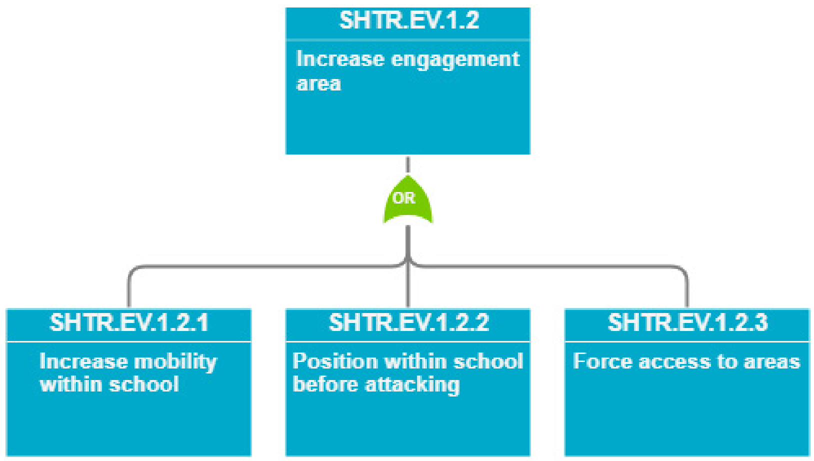

Figure 11. Increase Engagement Area

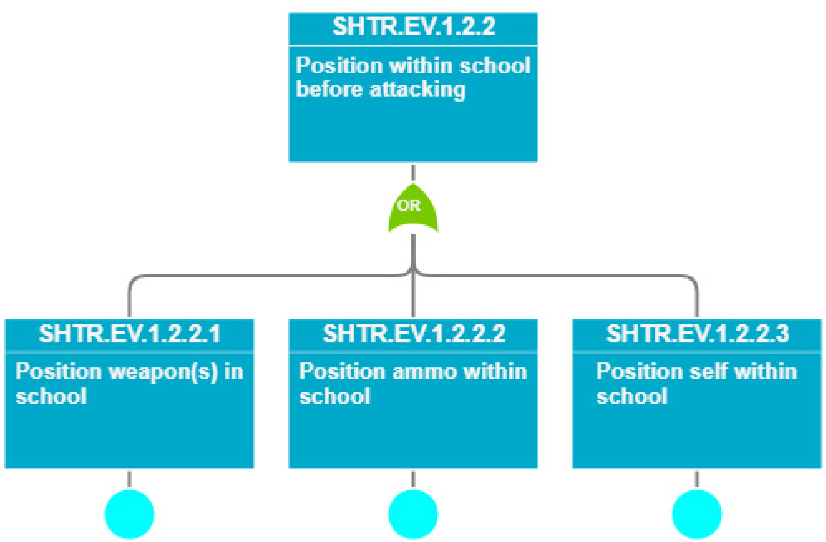

Figure 12. Position within School before Attack

Figure 13 displays the various ways AS can force access to areas in the school to increase the engagement area for his attack. The AS can attempt to overwhelm access control measures at the school by breaching weak points in the infrastructure (e.g., windows, non-reinforced doors) or destroying classroom locks. The AS can also bypass access control measures by climbing security gates or stealing security cards and keys, each of which allows the shooter to covertly enter restricted areas.

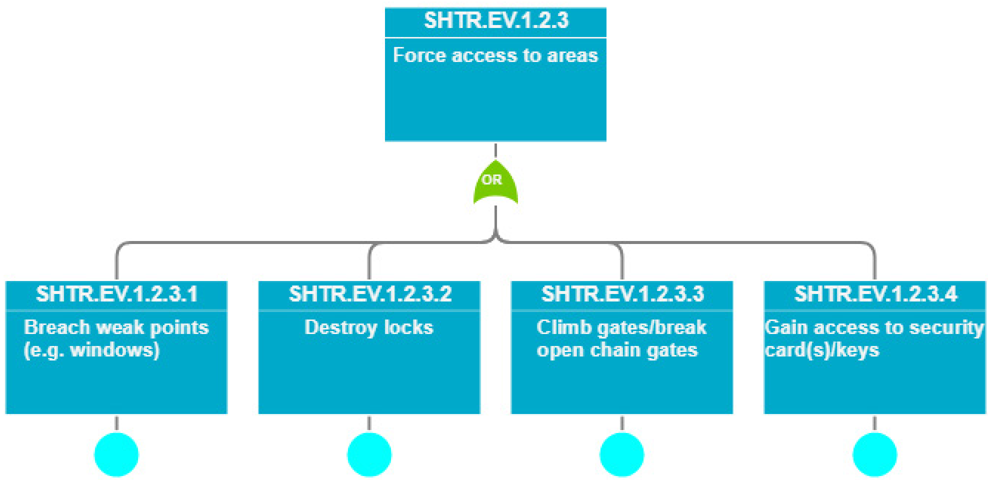

Figure 13. Force Access to Areas

Figure 14 shows means by which the AS can protect himself, which is the last subset of increasing engagement opportunities. The shooter can protect himself by wearing gear such as a bulletproof vest or a gas mask. The shooter can also defend himself by bringing emergency kits such as tourniquets, bandages, or trauma dressings to patch wounds. The protective gear and medical equipment directly enable the shooter to continue his attack on the school occupants after a non-lethal confrontation with security responders.

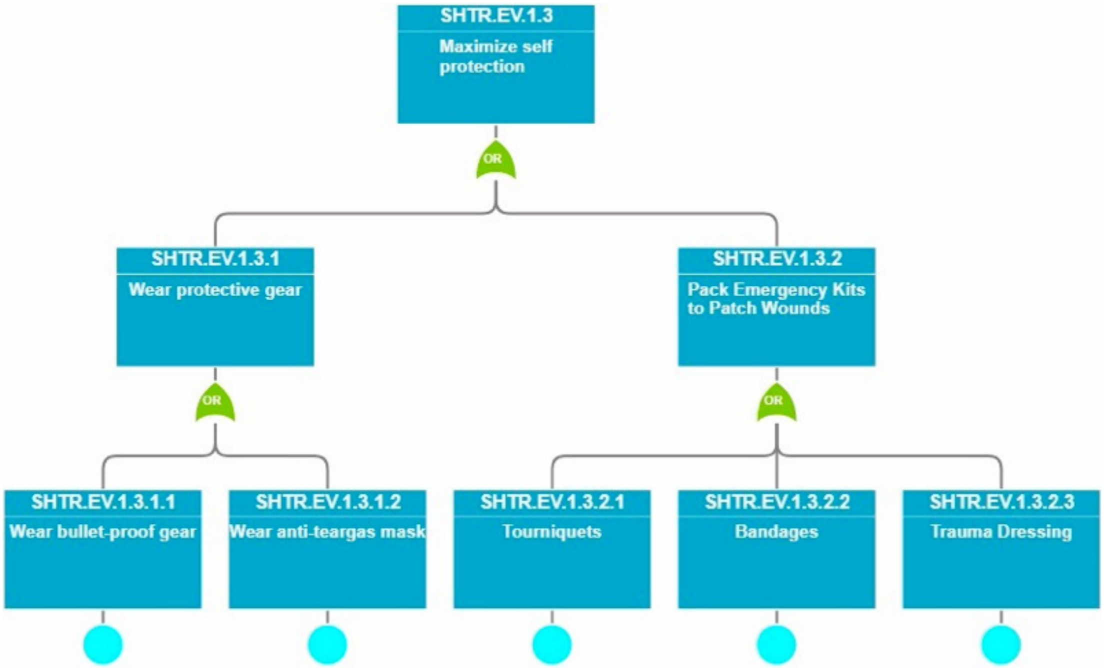

Figure 14. Maximize Self-Protection

The second way the AS can maximize casualties is by increasing lethality of individual engagements. To be able to cause the most harm to school occupants, the attack opportunities need to be effective. Figure 15 shows five primary methods that contribute to maximizing lethality: optimizing target selection, increasing engagement efficiency, preventing medical treatment to wounded personnel, optimizing weapon selection, or training with the chosen weapon(s).

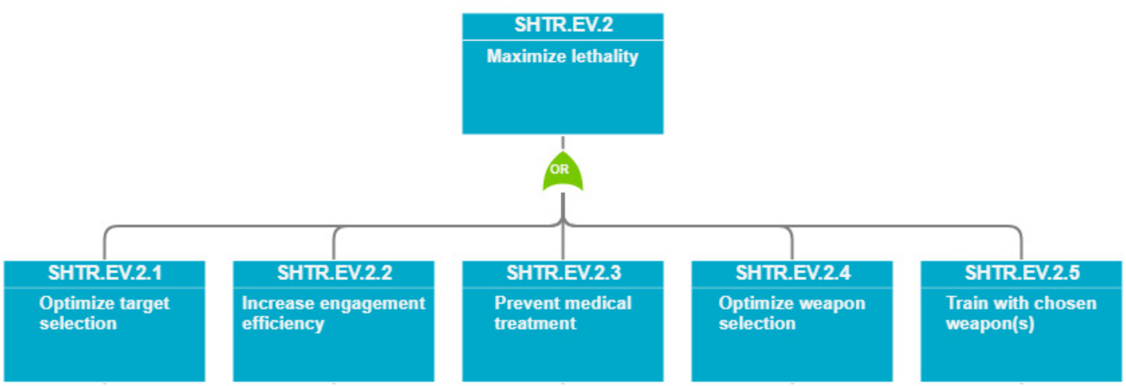

Figure 15. Maximize Lethality

Figure 16 shows that the shooter optimizes target selection either by locating target clusters or by identifying direct engagement opportunities where targets are in the line-of-sight for fire. Having a direct line-of-sight for engagement increases the shooter's probability of hitting targets, resulting in increased fatalities. The AS can identify target clusters in two ways, per Figure 17. First, the AS can force target clusters to a common area by creating a diversion (such as remote detonation), blocking egress routes to funnel targets to a desired location, or pulling the emergency fire alarm, in which case school occupants will likely proceed to hallways. Second, the AS can locate pre-existing clusters based on knowing school emergency procedures (i.e., when a fire alarm goes off) or having familiarity with the school's standard operating protocols (e.g., assemblies in the gymnasium, meal times when students will be in the cafeteria).

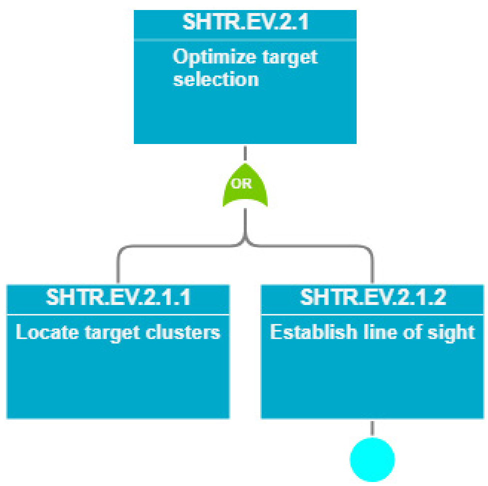

Figure 16. Optimize Target Selection

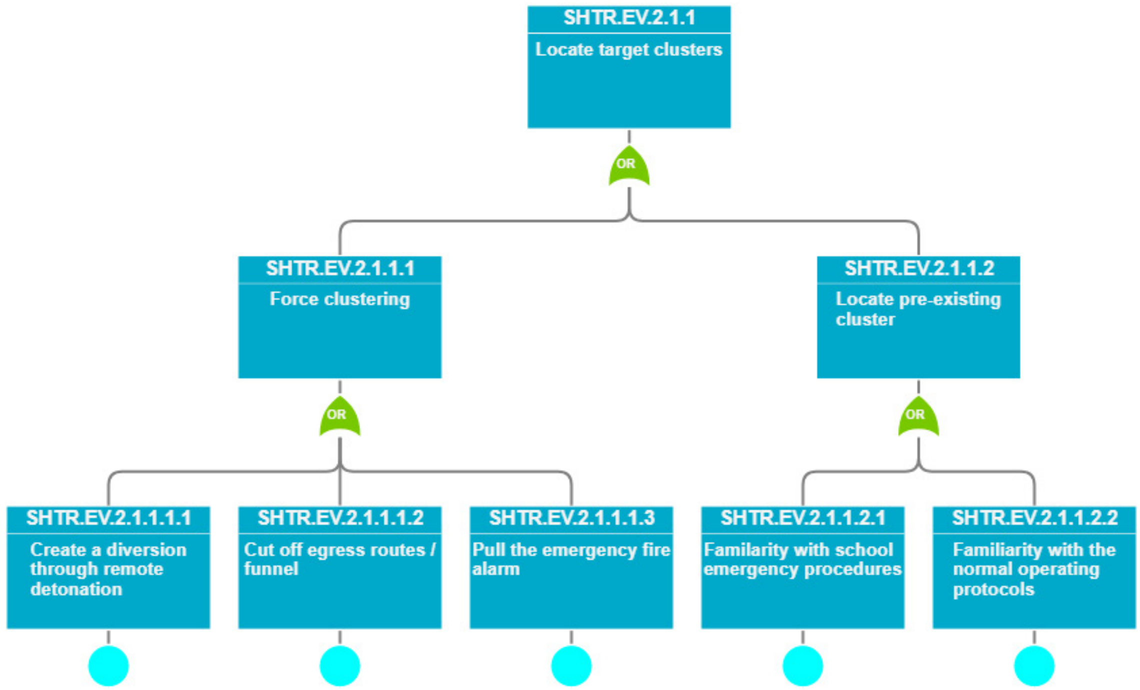

Figure 17. Locate Target Clusters

Figure 18 shows the decomposition of increasing engagement efficiency to improve the probability of death of school occupants. In this thread, the AS can target weak points (i.e., less resilient parts of the body). The AS also can minimize the engagement range with targets or increase the number of shots he fires at a given target.

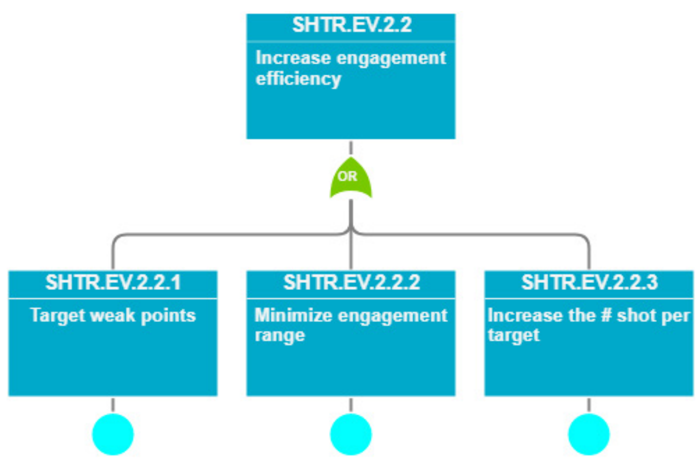

Figure 18. Increase Engagement Efficiency

Figure 19 illustrates the means by which the shooter can prevent medical treatment. When the AS prevents medical treatment, the injured victims are more likely to succumb to wounds that are not immediately fatal. The AS can prevent treatment by isolating responders so they cannot reach wounded personnel or killing responders outright. Additionally, placing barriers (or other means of deterrent) around the injured to block access or destroying emergency kits on the school premises both allow the shooter to cut the victims off from potential medical support.

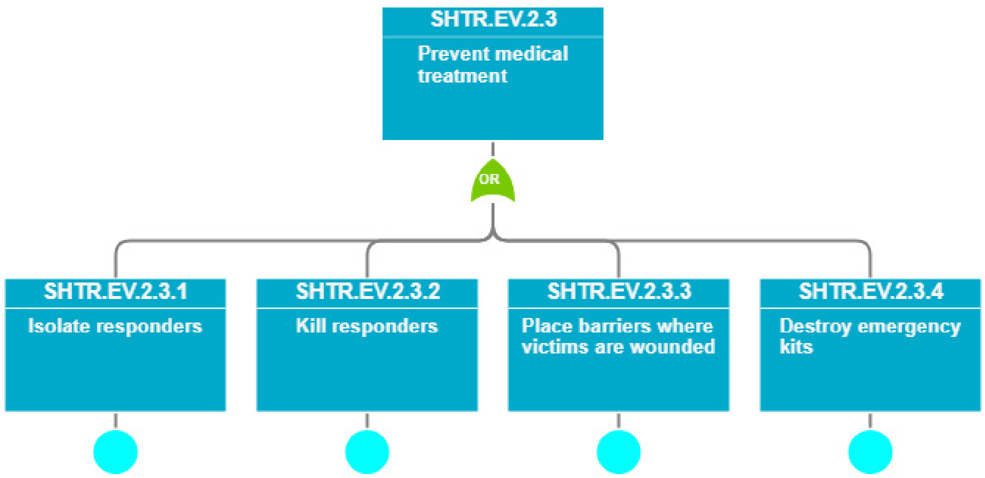

Figure 19. Prevent Medical Treatment

Optimizing weapon selection, as shown in Figure 20, entails selecting a weapon that allows the shooter to cause maximum damage during an incident. The shooter's success in killing school occupants directly relates to the weapon of choice. The AS can select weapons that have fast reload speeds, rapid rates of fire, or use inherently deadlier ammunition (e.g., larger caliber or hollow-point rounds).

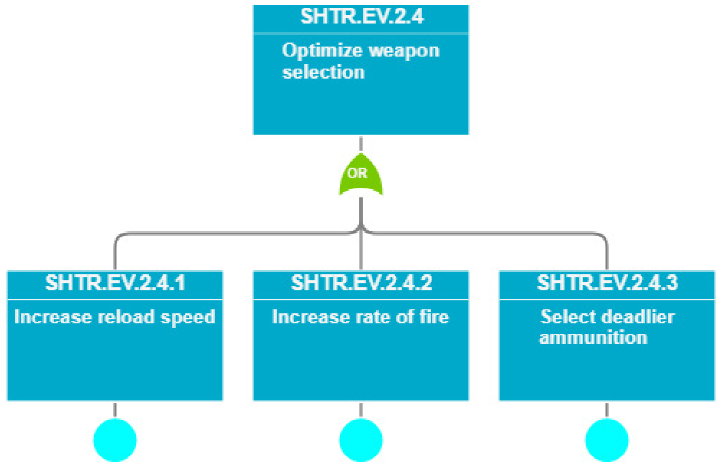

Figure 20. Optimize Weapon Selection

Figure 21 shows the decomposition of an AS training with his chosen weapons – yet another subset of increasing engagement lethality. The AS can condition himself to attack a school by playing violent video games, gain tactical knowledge by reading the weapon's technical documentation, or practice firing the weapon. He can also enroll in anti-active shooter training courses or take other online training (increasing his awareness of response protocols). The more the AS prepares for the attack, the deadlier the attack will be.

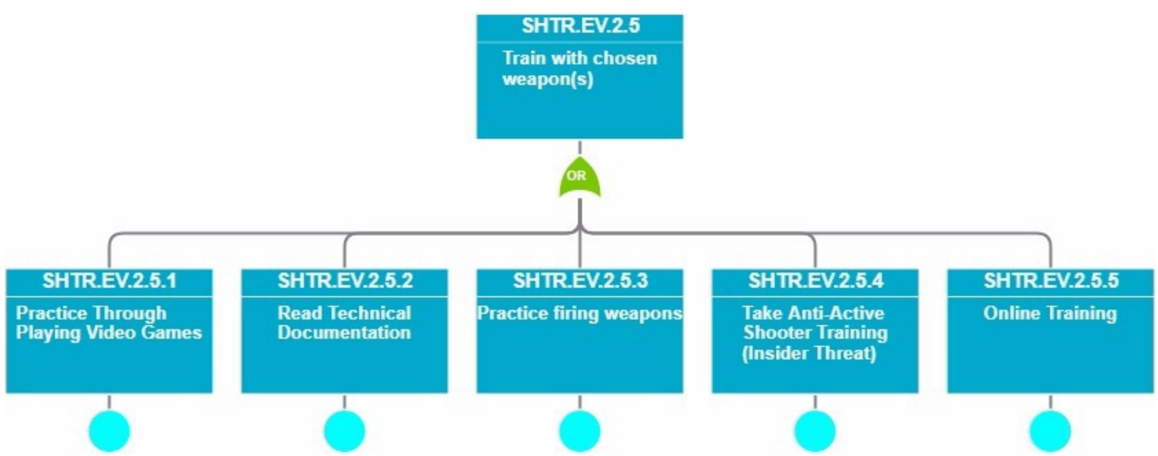

Figure 21. Train with Chosen Weapon(s)

The success tree analysis identifies the actions that an AS may perform in order to achieve his overall goal of causing as many casualties as possible during an attack. The AS does this by either increasing the number of engagement opportunities or improving the lethality of those engagements. Decomposing these efforts from the shooter's perspective provides insight into the tactics an AS may employ when attacking a school. Understanding the relationship of the underlying events allows us to determine where the system may be enhanced and intercede, breaking the chain of events that enable the shooter to kill school occupants.

3. Fault Tree Analysis

The fault tree depicts the ways the school system enhancements can fail. In this section, we examine the active shooter event relationships from the perspective of the system in order to clearly define the faults that lead up to the death of an occupant. Figure 22 depicts the top levels of the fault tree. The fault tree provides a corollary to the success tree, since the shooter's goal in the success tree is to maximize casualties during an attack incident. Conversely, the top-level failure in the FTA is the death of one or more school occupants. A death occurs when the system fails to prevent the AS from shooting occupants and fails to provide adequate medical support to injured personnel.

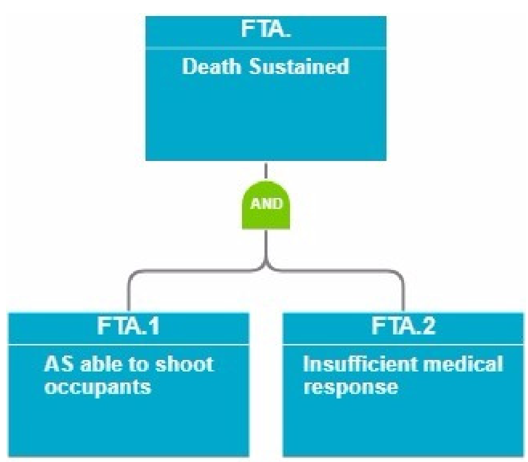

Figure 22. Death Sustained

As shown in Figure 23, three primary faults enable the AS to shoot occupants. The system fails to prevent a shooting when it fails to intervene directly, allows the active shooter to gain access to the grounds, and allows an engagement opportunity for the shooter. Figure 24 shows that insufficient intervention is a result of inadequate physical barriers and the lack of security response. Physical barriers provide a passive impediment, delaying the shooter's progress through the school, whereas security responders can intercept the AS and stop him altogether.

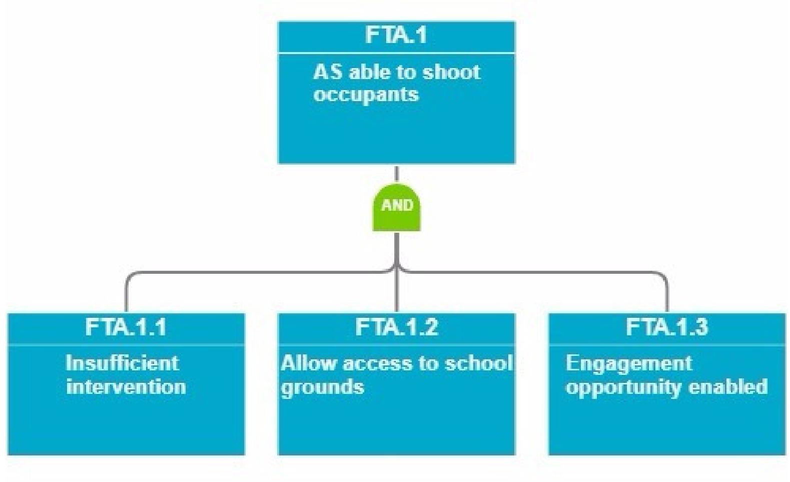

Figure 23. AS Shoots Occupants

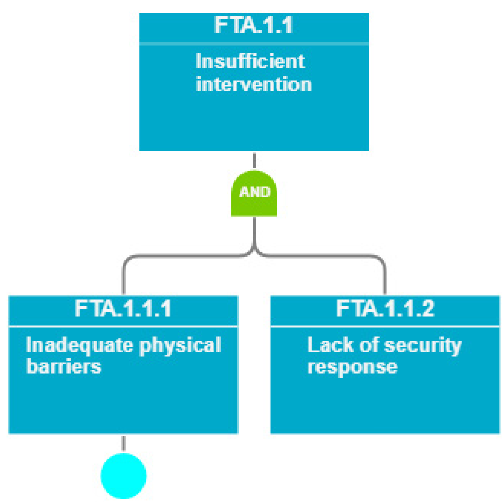

Figure 24. Insufficient Intervention

Figure 25 shows that the lack of security response is due to both external and internal responders not being able to intercede in time. External responders may not be able to intervene due to degraded communication links or the school being inaccessible, as shown in Figure 26. Degraded communications can result from cell tower jamming, an individual providing intentionally false or well-meaning but inaccurate or unhelpful information to first responders, or school staff being otherwise unable to send out notifications. Meanwhile, internal responders may not be able to intervene in time for multiple reasons, as depicted in Figure 27. The threatened area may be inaccessible (i.e., the school fails to provide alternate ingress points in the event doors are chained or marked with signs suggesting the presence of a bomb), the school may not have an on-site armed security responder assigned, or the on-site armed security responder may fail to act.

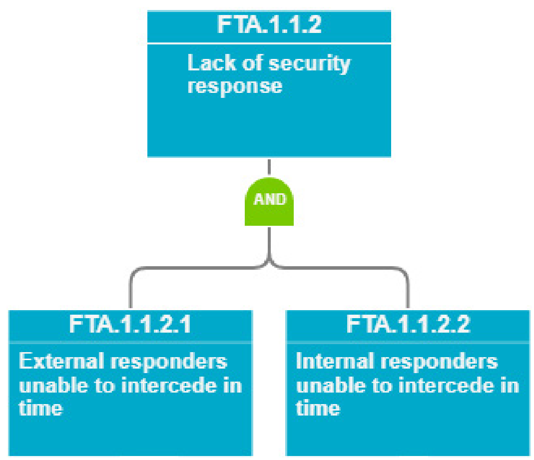

Figure 25. Lack of Security Response

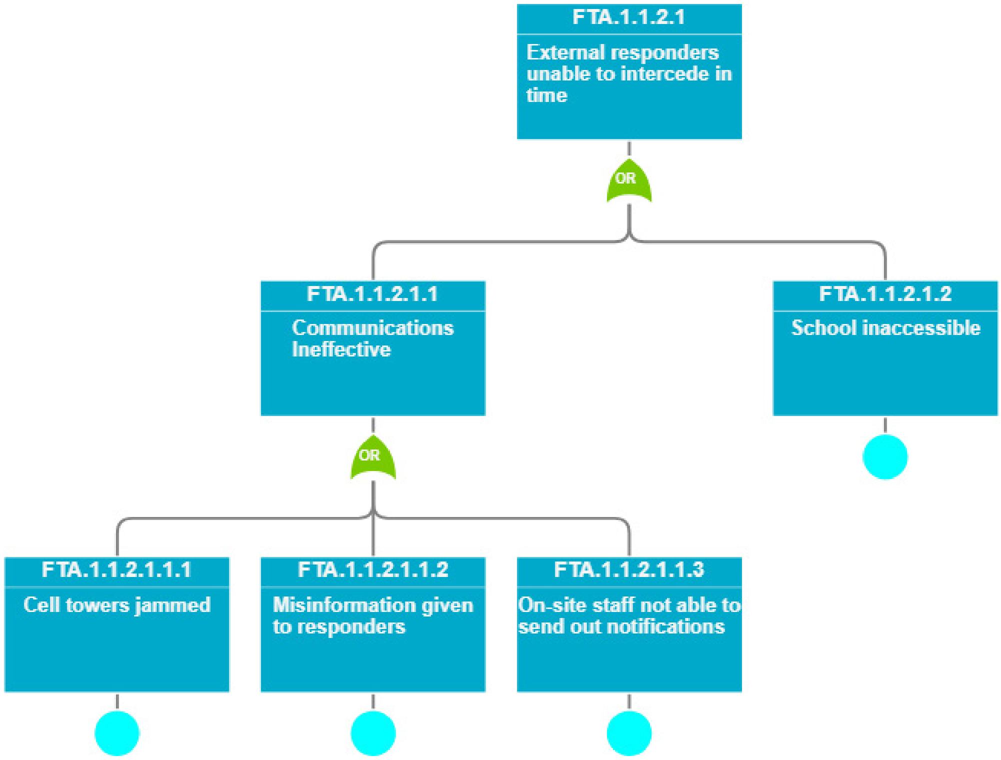

Figure 26. External Responders Unable to Intercede in Time

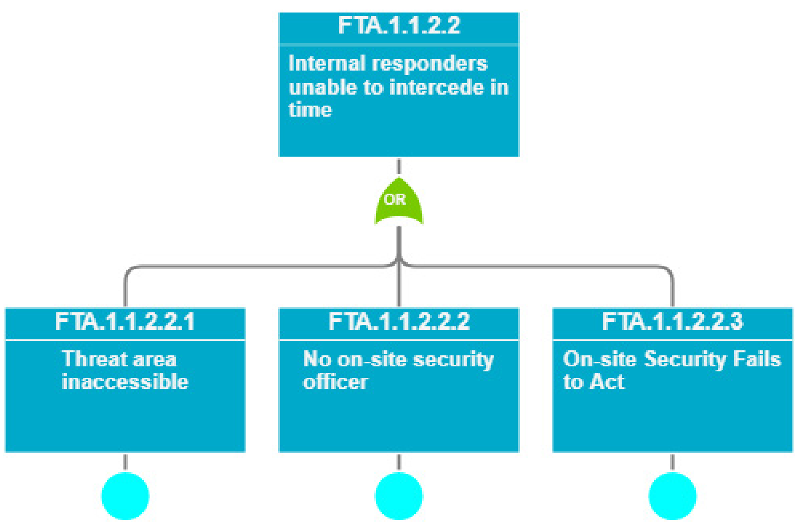

Figure 27. Internal Responders Unable to Intercede in Time

Figure 28 shows how the system fails to prevent the AS from accessing school grounds. This occurs if the system has insufficient access control measures or fails to detect the threat. Access control measures are insufficient if the school does not have effective security measures (e.g., gates, locked doors) in place or if existing security measures cannot withstand a breach attempt. If there is a deficiency in monitoring coverage for entrances into the school, or if the system cannot identify a threat that the AS has attempted to conceal while entering through a monitored access point, the system fails to detect the threat.

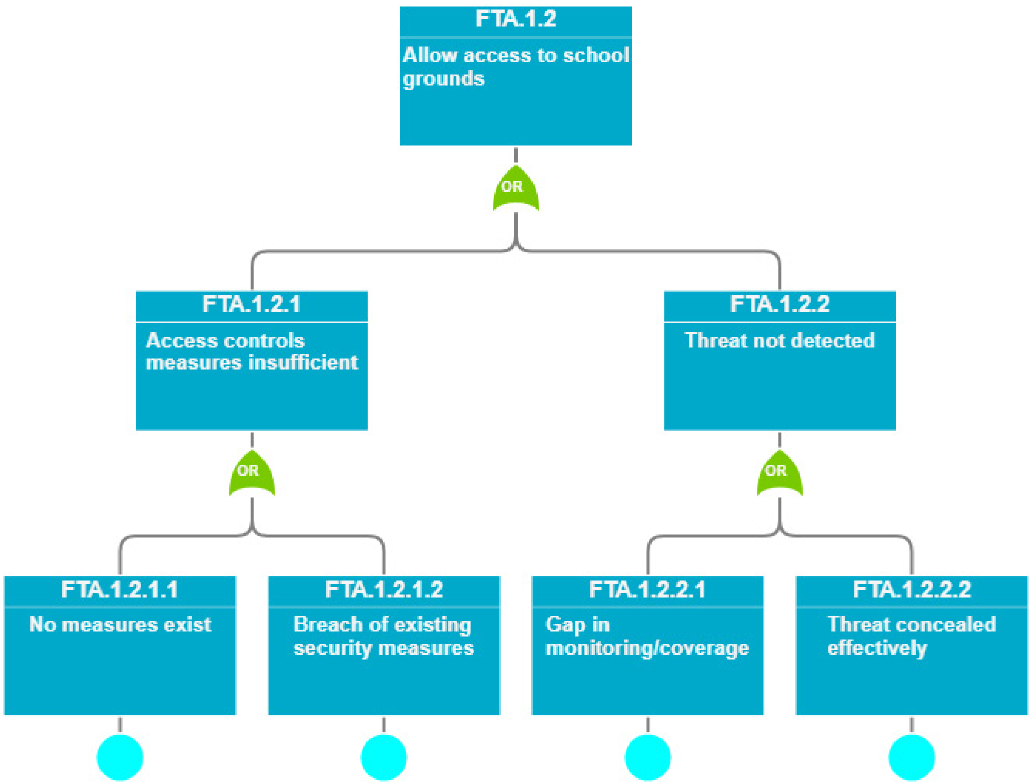

Figure 28. Allow AS to Access School Grounds

In addition to the system allowing access to the school, the system must enable the AS to discover an engagement opportunity, as shown in Figure 29. Engagement opportunities can present themselves through direct line-of-sight (LOS) targeting or proximal targeting (i.e., indirect fire). Figure 30 shows the decomposition of direct LOS targeting, where occupants are unable to exit the threat area, are unable to hide from the shooter, and are unable to fight the shooter.

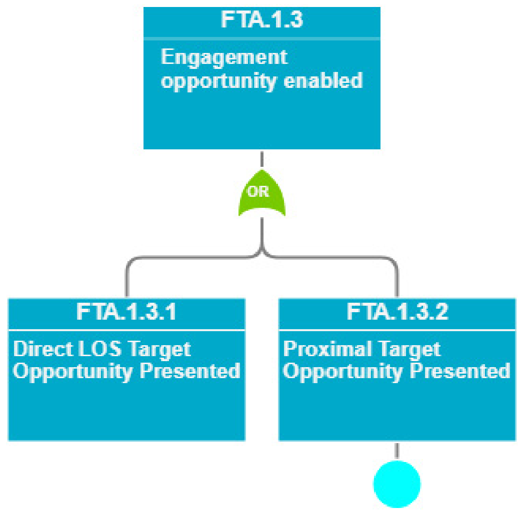

Figure 29. Engagement Opportunity Presented

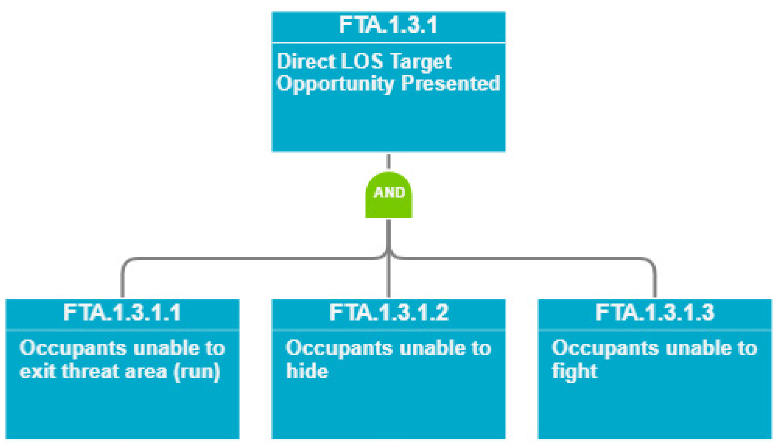

Figure 30. Direct LOS Targeting

Figure 31 shows the decomposition of the occupants' inability to run from the shooter. This issue may occur if the system allows the shooter to block school exits or access to other safe areas. The compromise of emergency protocols (i.e., escape routes available to school occupants) allows the AS to take advantage of occupant behavior during an AS incident. In lieu of running, occupants may choose to attempt to hide, as shown in Figure 32. However, they may not be able to do so if the system allows the AS to block access to secure locations without providing alternate means of access. School occupants could be unaware of the various hiding options available or there could not be enough secure places for all occupants to hide. Finally, Figure 33 shows why occupants may not be able to fight the AS effectively. This could occur if occupants who attempt to resist are unable to overpower the AS or if they do not have access to material that they can use to fight the shooter.

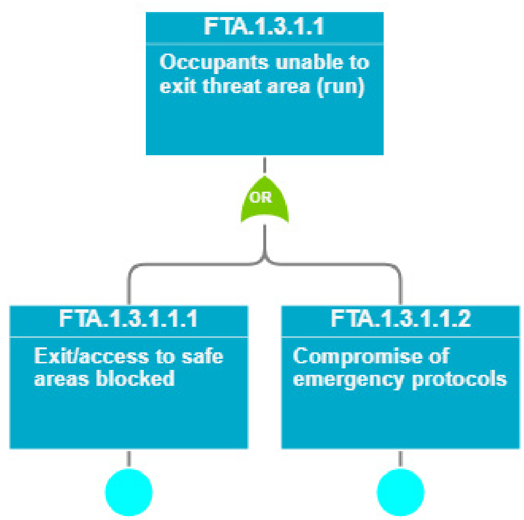

Figure 31. Occupants Unable to Exit Threat Area (Run)

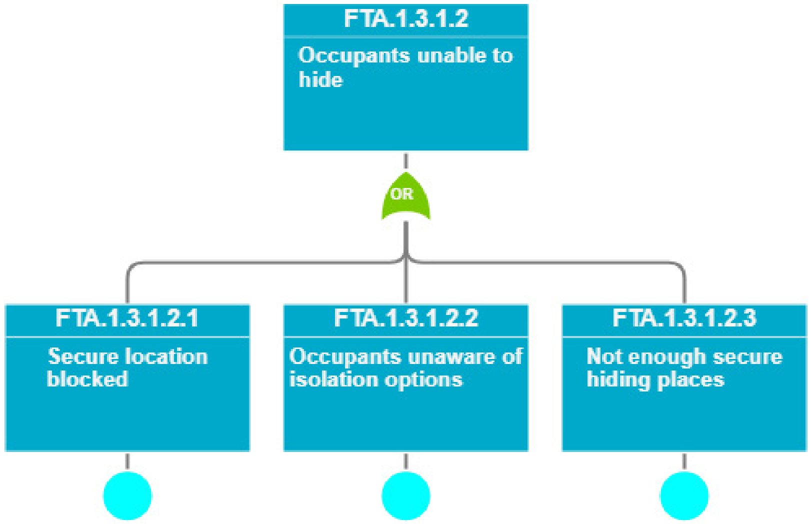

Figure 32. Occupants Unable to Hide

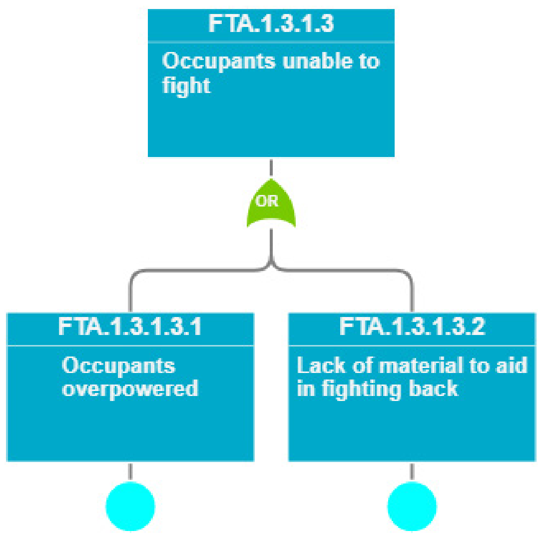

Figure 33. Occupants Unable to Fight

When the system bars the shooter's ability to directly engage potential targets, he may instead attempt to shoot school occupants indirectly (i.e., firing the weapon through doors and windows). These indirect methods become effective at causing fatalities when the system fails to keep occupants safe from shrapnel damage or ricocheting bullets. For this to occur, the system must present a proximal targeting opportunity, as shown previously in Figure 29.

Another supporting event that increases the probability of death of school occupants is insufficient medical response, illustrated in Figure 34. Three primary events that can contribute to inadequate medical response are delayed access to effective medical care, ineffective immediate medical care (i.e., school staff who attempt to provide first aid), or medical responders' unawareness of the presence of injuries.

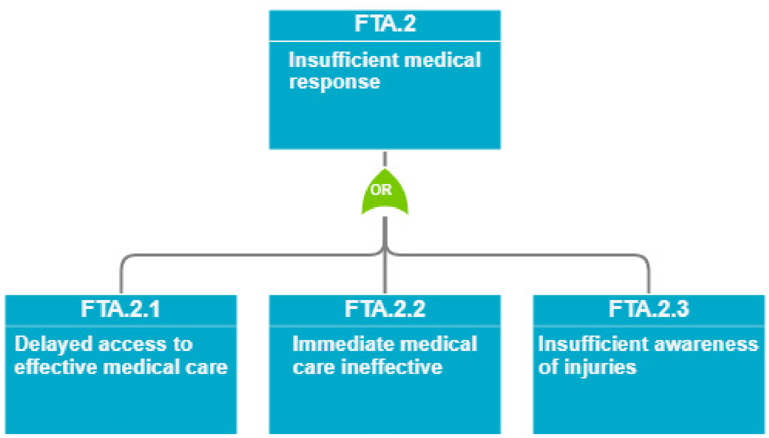

Figure 34. Insufficient Medical Response

Figure 35 shows the decomposition of delayed access to effective medical care. Belated notification, inaccessibility of injured personnel, or insufficient availability of medical responders can all contribute to delayed access to effective medical care. Notification delays can transpire when the communication links are inaccessible or degraded. Additionally, medical professionals may be unable to reach victims due to physical barriers or intentional blocking of access to the injured personnel. Finally, professional medical services may not be available to respond to the incident, which can occur if all responders are busy with other emergencies or if their dispatch locations are too far away from the school to support a timely response.

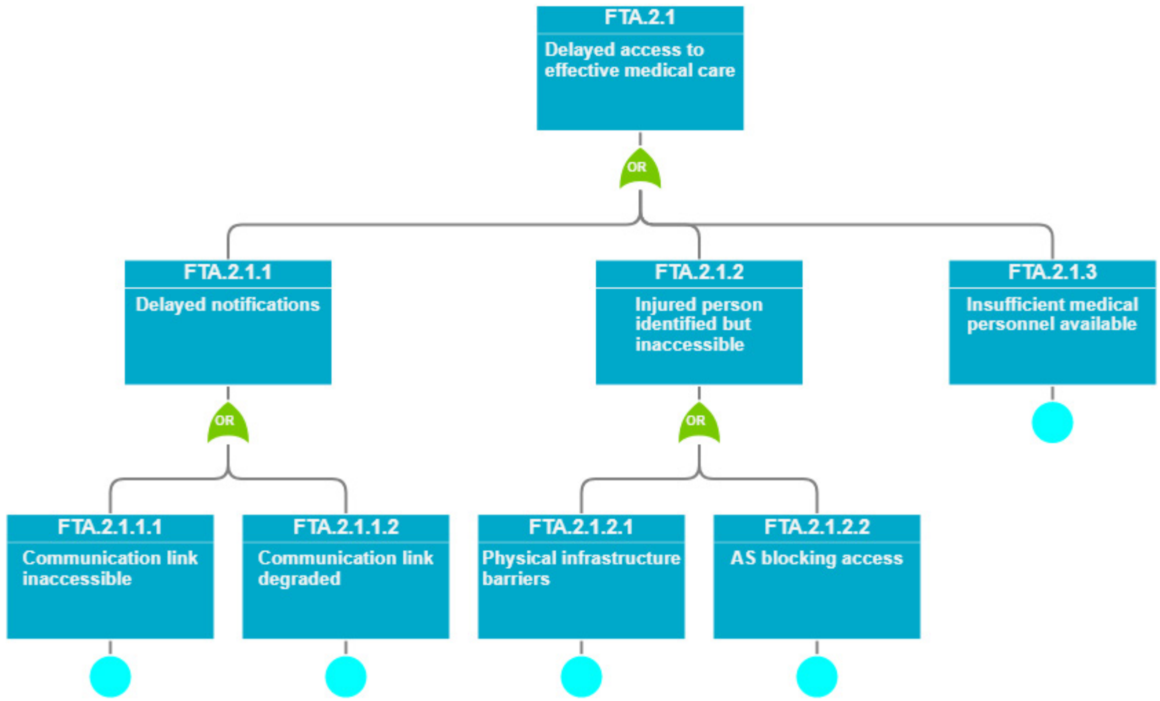

Figure 35. Delayed Access to Professional Medical Care

Figure 36 illustrates the reasons why immediate medical care may not be effective. Death of school occupants may occur despite the efforts of school staff and faculty members if first aid kits are insufficient or if staff members lack the training to properly treat injuries. First aid kits could be out of stock, could fail to have the right tools to treat gunshot wounds, or may not be located close enough to where occupants sustained injuries. Furthermore, if faculty members are not sufficiently trained, those attempting to render aid may do so incorrectly.

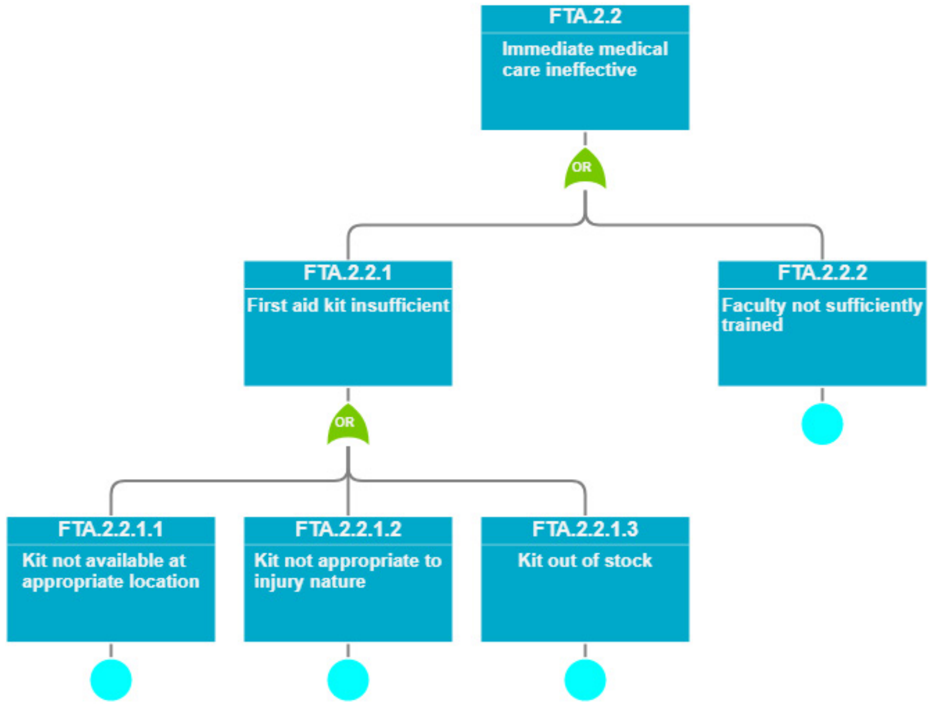

Figure 36. Immediate Medical Care Ineffective

The immediate causal factors for an insufficient awareness of existing injuries are explored in Figure 37. The injured person could be inaccessible (in which case the extent of his injuries may be unclear), school authorities may not have accounted for all personnel, or those who could provide treatment may have overlooked the injury.

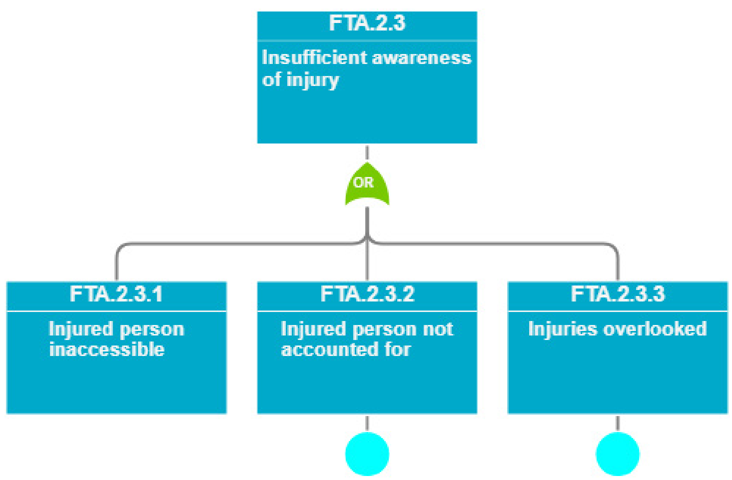

Figure 37. Insufficient Awareness of Injury

As shown in Figure 38, the injured occupant may be inaccessible because of physical infrastructure barriers or due to the AS threat not being contained. The presence of obstacles can delay first responders' arrival to the scene, thereby preventing them from being able to assess injuries and provide immediate care to occupants in need. If the AS threat has not been contained, medical responders may be unable to safely move throughout the school.

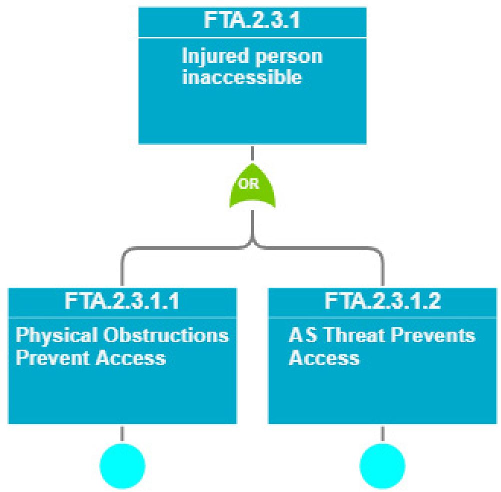

Figure 38. Injured Person Inaccessible

Delayed access to professional medical care, ineffective immediate medical care, or improperly identified injuries contribute to increasing the probability of casualties for the school occupants. The combination of the AS shooting occupants and insufficient medical response results in the death or injury of school occupants. The fault tree analysis above identifies the school system failures that can lead to lethal consequences for school occupants.

4. Capability Gaps

Stakeholder interviews provided insight into key needs and concerns, revealing critical capability gaps that prevent existing school systems from effectively countering the AS threat. Issues that stakeholders raised included inadequately protected classrooms, insufficient situational awareness during an AS incident, lack of dynamic AS training, the absence of an armed resource officer trained to handle AS situations, and the lack of coordinated efforts between first responders and school officials.

These issues address specific examples of security deficiencies in school systems; however, many of these individual concerns are interrelated. For example, both a lack of communication and insufficient situational awareness can lead to improper coordination between first responders and school officials. Likewise, shortfalls in AS response training and the absence of a robust visitor management process are each indicative of a lack of knowledge and preparation for an AS incident. With these relationships in mind, the team consolidated the diverse stakeholder concerns into the following four categories: communication, threat detection, knowledge/preparation, and access control. These categories constitute the types of capability gaps that need to be closed so that the system can counter the AS threat. Figure 39 shows these categories and the frequency of each type of gap from stakeholder interviews.

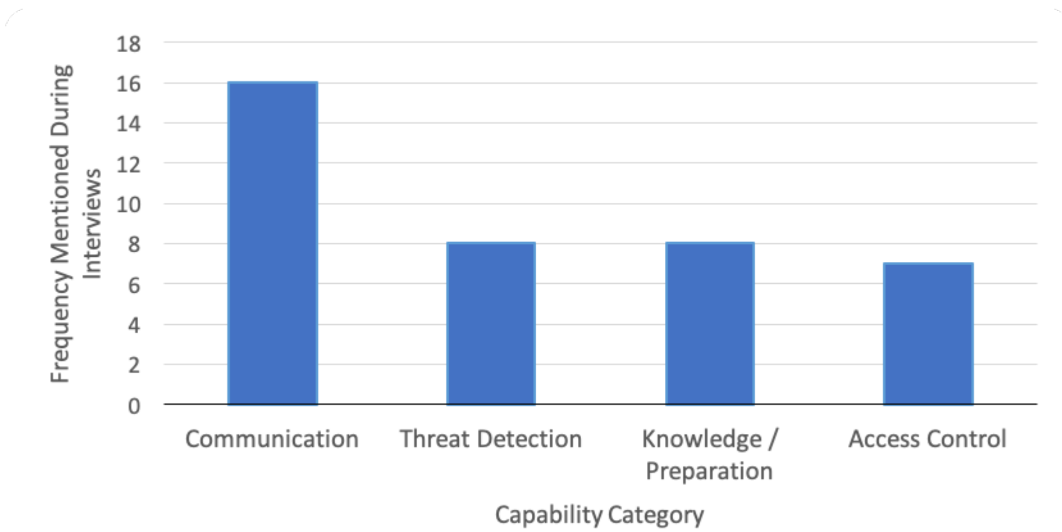

Figure 39. Frequency of Capability Gap Types Identified during Stakeholder Interviews

Communication was the leading factor identified in the interviews. Stakeholders addressed the lack of communication between first responders and school occupants in 16 separate interviews. First responders and school officials are perceived to be unable to communicate accurate, real-time information during a school shooting. This lack of shared situational awareness may lead to inefficiencies in first responders' coverage and immediate response to the event. These same deficiencies in communication also contribute to adding additional time to execute lockdowns, coordinate evacuations, and provide lifesaving care to injured individuals.

Another common stakeholder concern is the inability to detect concealed weapons or to identify active shooters. The majority of the schools we studied did not have any threat detection equipment. Schools must generally rely on personnel seeing a weapon or hearing a gunshot to detect the existence of a threat and take action. By waiting for direct observation, the AS has the opportunity to engage occupants and the school cannot respond without casualties.

Knowledge/preparation is a capability gap that concerns both law enforcement and school officials. This gap is a result of the lack of guidance and AS training for all the stakeholders. Current training (drills and emergency protocols) administered in schools focuses on older, better-known problems such as fires or bomb threats. It does not emphasize the dynamic nature of the AS threat. While option-based responses exist, not all schools have learned how to apply them.

Access control is the last capability gap and is a notable shortfall for existing school systems. Many stakeholders expressed concern about inadequate methods for preventing an intruder from entering school buildings, classrooms, and communal areas. Students and faculty are free to move within the school premises, but this same freedom allows the shooter to move easily through the school to find and attack new targets. However, restricting all mobility is not a viable option to counter the AS threat, since school systems must consider other safety issues and requirements (e.g., fire codes, emergency evacuation). Due to this, stakeholders also stressed the importance of ensuring access control measures are not so restrictive as to prevent freedom of movement for school personnel and emergency responders.

C. SUMMARY

In this chapter, we explored the problem space associated with countering the active shooter threat. The first sections of this chapter serve to define the problem and narrow the team's focus. Defining the system boundary clearly establishes the system as the school itself and differentiates it from the external actors with which it will interact, both supporting (e.g., first responders) and adversarial (i.e., the active shooter). Addressing assumptions and constraints reduces the scope of the problem at hand, allowing the team to focus on a manageable portion of a broad-reaching issue.

With the problem defined and the scope narrowed, the next segments of problem space exploration constituted a deeper analysis. The success tree and fault tree analysis allowed the team to analyze the AS threat from two opposing perspectives. These tools highlighted both what the shooter may attempt to do to maximize his effectiveness during an attack and how the system may fail to counter the shooter's efforts. Identifying and interviewing stakeholders provided the perspective of individuals who are already concerned with the AS problem and working to find solutions. Altogether, the ST, FTA, stakeholder analysis, and interviews led to the development of the system's effective needs and the capability gaps that the system enhancements must close.

The next chapter will leverage the needs and gaps identified as we transition into the solution space.

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III. SYSTEM ARCHITECTURE

A. OPERATIONAL CONCEPT (CONOPS)

The overall purpose for the school system enhancements is to minimize the lethality of a potential incident. The upgraded system can achieve this purpose by leveraging the following capabilities:

- identify threats
- restrict the threat's mobility
- separate potential targets from the threat
- notify external support entities
- enhance situational awareness for school occupants and external support entities
- facilitate medical response

The emphasis on these capabilities will shift, depending on the phase of operation. The enhanced school system's operational phases are planning, imminent, in-progress, recovery, and after-action. The capstone team selected these operational phases based on the research available, including information from case studies and stakeholder interviews. The phases represent distinct periods of time in the events leading up to, during, and immediately after an active shooter event. Due to the rapid nature of active shooter incidents, these phases may overlap.

1. Phase 1: Planning

The planning phase begins with school administrators conducting a threat assessment to identify vulnerabilities. Administrators may or may not conduct this assessment in conjunction with security professionals outside the school system. The vulnerabilities that this assessment reveals correspond to gaps in the individual school system's capabilities. Enhancing the system using improved equipment or processes will allow administrators to close these gaps. Once administrators have selected enhancements, they will implement and test equipment-based solutions to ensure operational readiness. Administrators will then need to update the school's safety plan to include operation and management of the new system enhancements. The last action in the planning phase is to conduct joint exercises with the school faculty, law enforcement, and medical personnel. The planning phase ends when the recommended product and process enhancements are operating at the school.

2. Phase 2: Imminent

The imminent phase starts with a threat approaching the school. The shooter has made plans to harm school occupants and is on the verge of executing these plans. In the imminent phase, the system will attempt to identify any approaching threats before school occupants are in danger. If the system determines that a potential suspect is carrying concealed or visible weapons, the shooter-in-progress phase begins and the system informs the appropriate personnel.

3. Phase 3: In-progress

During the in-progress phase, the threat is on the school premises and is able to attack school occupants. The starting point for this phase occurs with the first indication of a threat, such as the shooter breaching security measures or firing at school occupants. School faculty and staff notify armed security and medical responders that an AS incident is in progress and provide any available information, which will then cue responders to dispatch resources to address the incident. Once the armed security responders are on site, they will utilize the information provided by the system to help locate the threat within the school premises. The system will continue to provide any relevant information to help its occupants avoid the AS. Simultaneously, the system will employ any available enhancements to slow the AS's progress and facilitate friendly actors' movement throughout the school. This phase ends when responders have neutralized the AS or if the AS leaves the school on his own.

4. Phase 4: Recovery

The recovery phase commences when the AS is no longer able to cause further harm to school occupants. Transition to the recovery phase is contingent on a thorough assessment of the situation. Specific transition criteria will depend on the details of the individual active shooter incident.

This phase constitutes a shift in emphasis from security to personnel assessment and medical treatment. Appropriate to the situation, the school system may relax certain security protocols. For example, school administrators may lift or modify a lockdown to facilitate mobility for emergency responders and to expedite accessibility to medical care. Personnel accountability will be critical so that staff and medical responders can assess any injuries occupants have sustained and prioritize their treatment. The recovery phase concludes when personnel accountability and assessment are complete, injured personnel have received initial medical treatment, and all wounded personnel who require advanced treatment are in transit to the hospital.

5. Phase 5: After-Action Response

The after-action response follows the recovery phase. The objectives of this phase include gathering information about the incident, analyzing relevant data, and capturing any lessons learned. Pertinent information to support future improvements includes the length of time between when the incident began and when the system performed key responses (e.g., initiating a lockdown, notifying emergency responders). Once the school administrators and law enforcement have gathered information on the incident, decision makers can conduct after-action analysis and formulate lessons-learned. The purpose of this analysis will be to identify capability gaps in the school to see where the system failed to counter the AS; these gaps will then constitute the basis for system updates to counter future threats.

B. SYSTEM VIEW

Considering the operational concept, Figure 40 depicts a system view that identifies the internal and external interfaces and information exchanges of the enhanced school system.

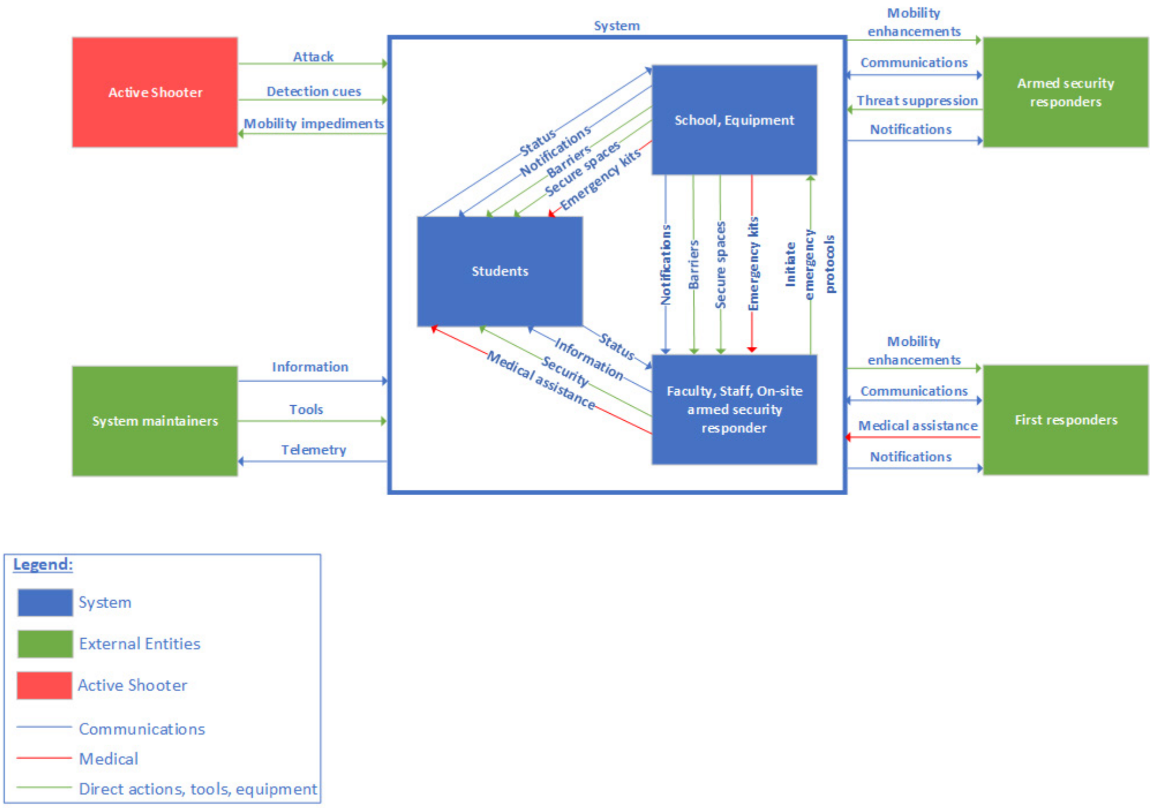

Figure 40. System View

The school system enhancements present impediments that will restrict or prevent movement of the AS within the school premises. The system will also monitor for cues that indicate when a threat is approaching or is on site. System maintainers will be responsible for providing information and tools to support system operation (e.g., manuals, procedures, upgrades, maintenance, and training curricula for system administrators and school occupants). The system, once operational, will provide telemetry data to the system maintainers at defined intervals and in response to specified cues. The system will also provide notifications and present mechanisms to enhance mobility for both the armed security responders and medical personnel (first responders). Additionally, communication between the system and external responders will continue throughout an incident. The armed security responders will provide threat suppression and guidance to affected personnel within the school, while first responders will provide medical assistance.

The system consists of three main entities: the facilities and equipment; the students; and the faculty, staff, and on-site armed security responders. The system and its associated equipment will provide notifications, barriers, secure spaces for isolation, and emergency kits to personnel within the school. Students will provide status updates to the school equipment, school faculty, and staff. The school faculty and staff will initiate emergency protocols during an incident while providing guidance and medical assistance (to the best of their ability) to students. The on-site armed security responder ensures the safety of the school occupants and engages the threat.

C. FUNCTIONAL ANALYSIS

Functional analysis defines the functions a system must perform to meet its effective needs and operational concept. Functional analysis facilitates the delineation of system requirements and provides the framework for the architectural design process. It is critical when identifying functions to focus on what the system will do, rather than how the system will do it (International Council on Systems Engineering 2011, 157–158).

1. Functional Decomposition

The functional analysis begins with identifying the top-level functions the system must perform to meet the stakeholders' needs. After identifying these functions, the team decomposed them until reaching a sufficient level of detail to support design. Figure 41 shows the functional decomposition of the highest system level function – countering an AS event. This function decomposes into the following five sub-functions: detect threat, classify threat, alert occupants and responders, monitor situation, and respond to incident.

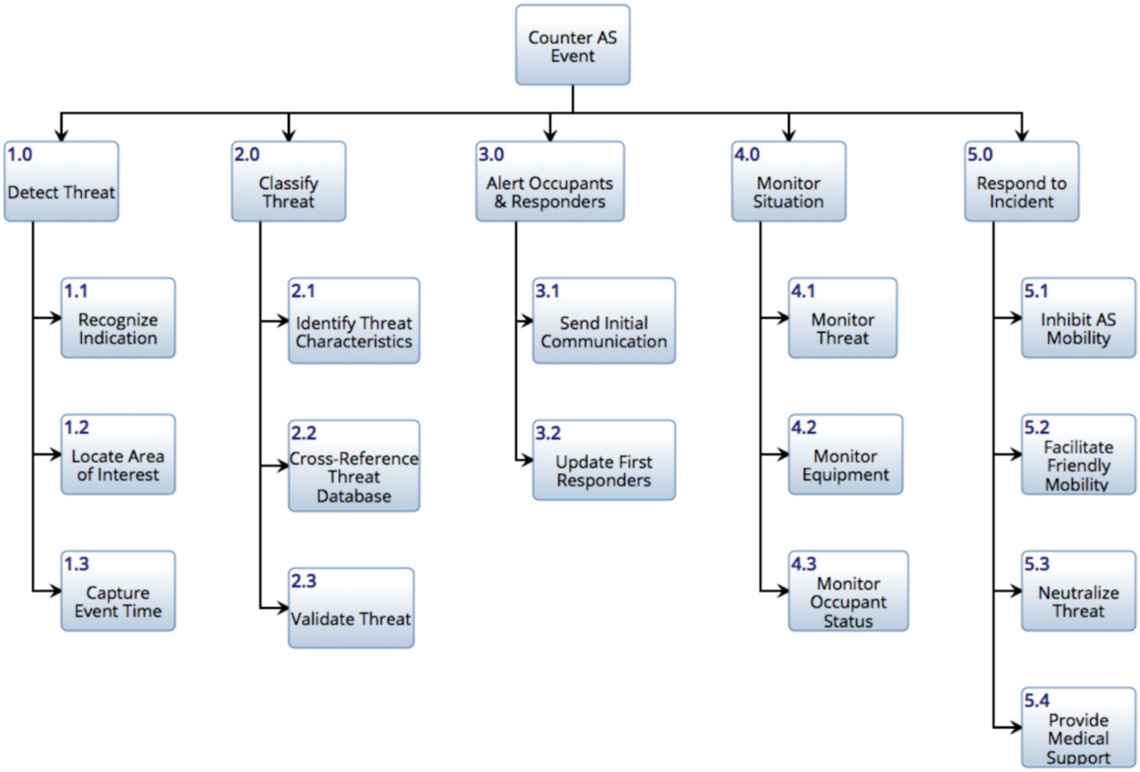

Figure 41. AS Event-Driven System Functional Decomposition

The following list defines the top-level functions and supporting sub-functions for the enhanced school system.

- *1.0 Detect Threat* – Identify potential threat attempting to access the system and capture details regarding the threat's origination.
- *1.1 Recognize Indication* – Recognize potential threat based on specific cues.
- *1.2 Locate Area of interest* – Capture potential threat's point of origination.
- *1.3 Capture Event Time* – Log the time when the system initially detects a potential threat.
- *2.0 Classify Threat* – Categorize the potential threat as an active threat if observed threat attributes meet active threat criteria.

- *2.1 Identify Threat Characteristics* – Observe and record attributes of potential threat.
- *2.2 Cross-Reference Threat Database* – Compare potential threat with threat database.
- *2.3 Validate Threat* – Mark potential threat as an active shooter, if observed characteristics associate with hostile intent/action.
- *3.0 Alert Occupants & Responders* – Provide current, valid information about the AS situation to school faculty, staff, students, and external responders.
- *3.1 Send Initial Communication* – Provide school faculty, staff, students, and external responders information about the AS situation.
- *3.2 Update First Responders* – Provide updated AS event information to external responders.
- *4.0 Monitor Situation* – Monitor and record the current status of the AS and system elements.
- *4.1 Monitor Threat* – Surveille and assess the changing threat status, to include logging significant event times.
- *4.2 Monitor Equipment* – Track the current state of installed system equipment.
- *4.3 Monitor Occupant Status* – Track status of school faculty, staff, and students (e.g., security at their location, injuries) to facilitate accountability and support.
- *5.0 Respond to Incident* – Activate measures to counter the shooter's actions.

- *5.1 Inhibit AS Mobility* – Impede the ability of the AS to enter the school or move within it.
- *5.2 Facilitate Friendly Mobility* – Enable freedom of ingress, egress, and internal movement for school faculty, staff, students, and first responders.
- *5.3 Neutralize Threat* – Nullify the AS's ability to engage school faculty, staff, students, and first responders via apprehension, incapacitation, or other methods.
- *5.4 Provide Medical Support* – Make medical kits easily accessible and usable for school occupants.

2. Measures of Performance

Based on the overarching goal of minimizing casualties from an AS event in United States K-12 schools, the team developed a value hierarchy. A value hierarchy is a structured representation of the system functions, objectives, and evaluation measures (Holness 2017). Figure 42 provides an overview of this hierarchy, while later figures show its branches in greater detail. The value hierarchy assists in identifying the major categories of metrics. Decision makers can use these metrics to assess the effectiveness of specific design options in supporting the system's overall goal. The value hierarchy starts with the system's measure of effectiveness (MOE), which is the number of casualties resulting from an AS attack. The hierarchy then connects this MOE to the top-level functions of the system as they pertain to countering an AS (detect threat, classify threat, alert occupants & responders, monitor situation, and respond to incident), as shown in the functional decomposition. Each function has allocated objectives and measures of performance (MOPs).

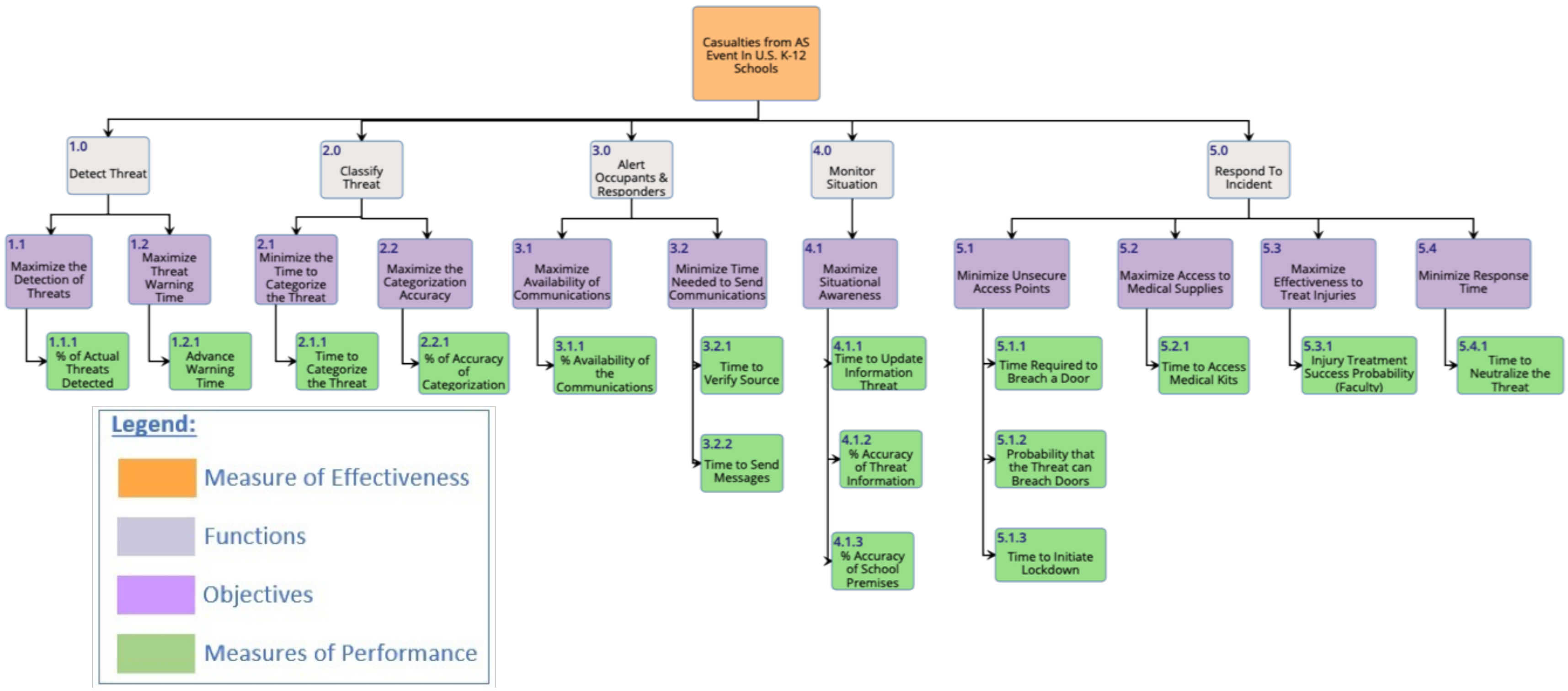

Figure 42. Value Hierarchy

Starting with Detect Threat (1.0), shown in Figure 43, the objectives are to maximize the detection of threats and maximize threat warning time. The MOP associated with maximizing threat detection is the percentage of actual threats that the system security measures detect. Advance warning time is the MOP associated with the objective of maximizing the threat warning time. This MOP measures the time the system is aware of a threat before the AS reaches the school's access points.

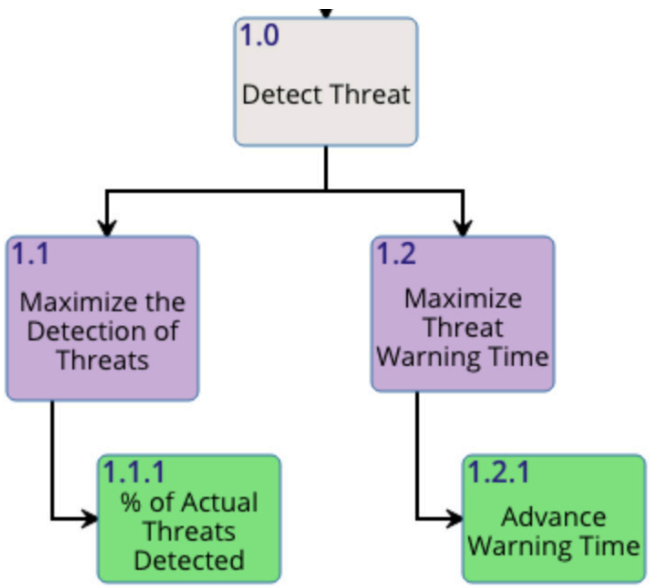

Figure 43. Value Hierarchy: Detect Threat Branch

In Classify Threat (2.0), shown in Figure 44, the objectives are to minimize the time to categorize the threat and maximize the accuracy of categorization. Classification involves determining the threat severity based on various characteristics (e.g., weapons the threat is carrying), as well as determining the potential threat's intent (i.e., whether an individual has brought weapons to the school with the intent to kill occupants or if the individual has done so inadvertently). The associated MOPs include the time to categorize the threat and percent accuracy of categorization. Since categorization is either correct or incorrect for discrete events, such as AS attacks, percent accuracy of categorization corresponds to the amount of times the system accurately categorizes the threat during simulations and other testing. Rapid, accurate classification allows faculty and staff to respond appropriately to a possible threat, ensuring that the correct tools are in place to counter the threat and protect students.

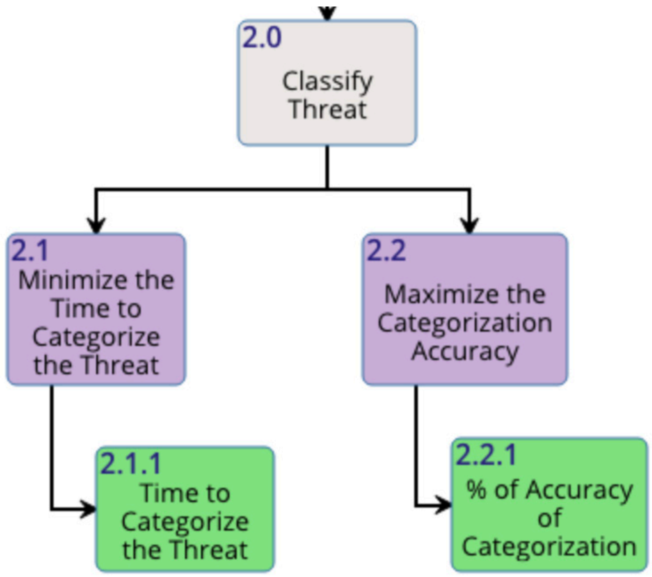

Figure 44. Value Hierarchy: Classify Threat Branch

In Alert Occupants & Responders (3.0), shown in Figure 45, the objectives are to maximize the availability of communications and minimize the time to send communications. The availability of communications objective captures the system's need to ensure all actors have accurate, current, and meaningful information about the AS incident at any time. Communications availability is measured by uptime of the communications infrastructure. The second objective entails minimizing the time to send communications. The associated MOPs are the time it takes to verify the source of the message and the time to send information. Having low-latency communications is paramount for school occupants and external responders to obtain the most recent and reliable status to aid responders and reduce further impacts to occupants.

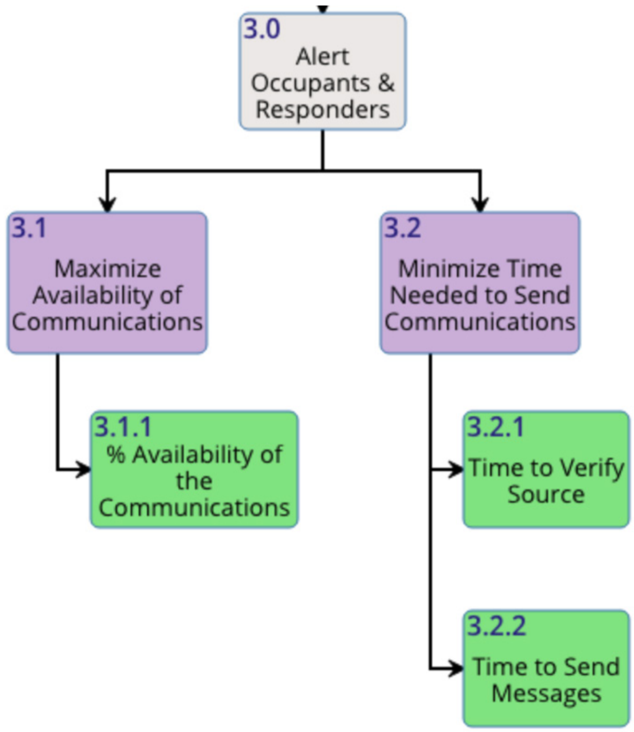

Figure 45. Value Hierarchy: Alert Occupants & Responders Branch

While the AS incident is ongoing, continual assessment of the situation is critical to ensure faculty, staff, and external responders (law enforcement and medical personnel) understand the current status and take appropriate actions based on the information available. For Monitor Situation (4.0), shown in Figure 46, the objective is to maximize the situational awareness for school occupants as well as external responders. MOPs for this objective are the time to update information on the threat, the percent accuracy of the threat information, and the percent accuracy of the school premises. Pertinent information about the school premises includes occupant status and significant layout details (i.e., have any infrastructural changes occurred since the school's initial construction or are there any temporary impediments within the school, and is information about these changes available to external responders).

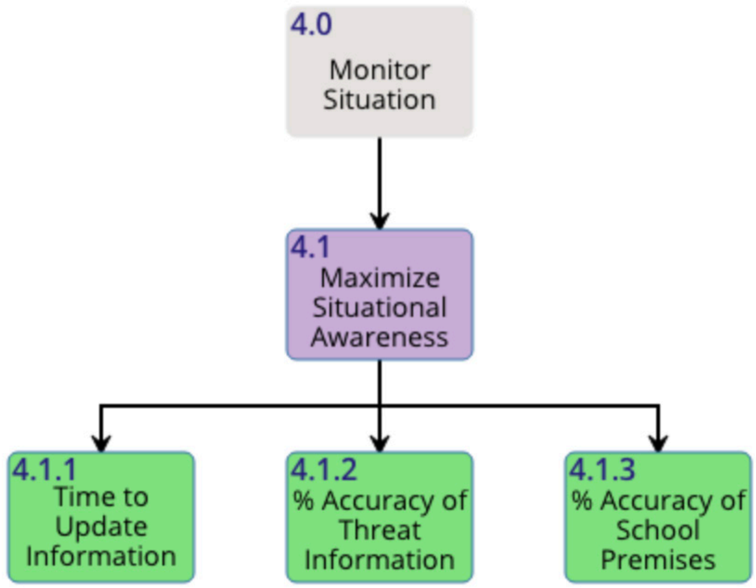

Figure 46. Value Hierarchy: Monitor Situation Branch

During the AS event, the measures in place to Respond to the Incident (5.0) will directly affect the resultant number of casualties. The supporting objectives, shown in Figure 47, include minimizing unsecured access points, maximizing access to medical supplies, maximizing the effectiveness to treat injuries, and maximizing the probability of neutralizing the threat. The MOPs that support minimizing unsecured access points are the time required to breach a door, the probability that the threat can breach a door, and the amount of time required for the school to initiate a lockdown. School hardening methods to increase the time to breach a door and lower the probability that an assailant can breach doors aid in slowing or stopping the AS.

The time it takes to access a medical kit is an MOP that relates to the objective of maximizing access to medical supplies. Faster access to medical kits allows faculty and staff to treat the wounded before the external medical responders arrive, thus reducing the likelihood of a school occupant's death due to excessive treatment delay. The success probability for faculty who respond to a medical emergency is an MOP that supports the objective of maximizing injury treatment effectiveness. The last objective in this branch of the value hierarchy is minimizing the response time during an AS incident.

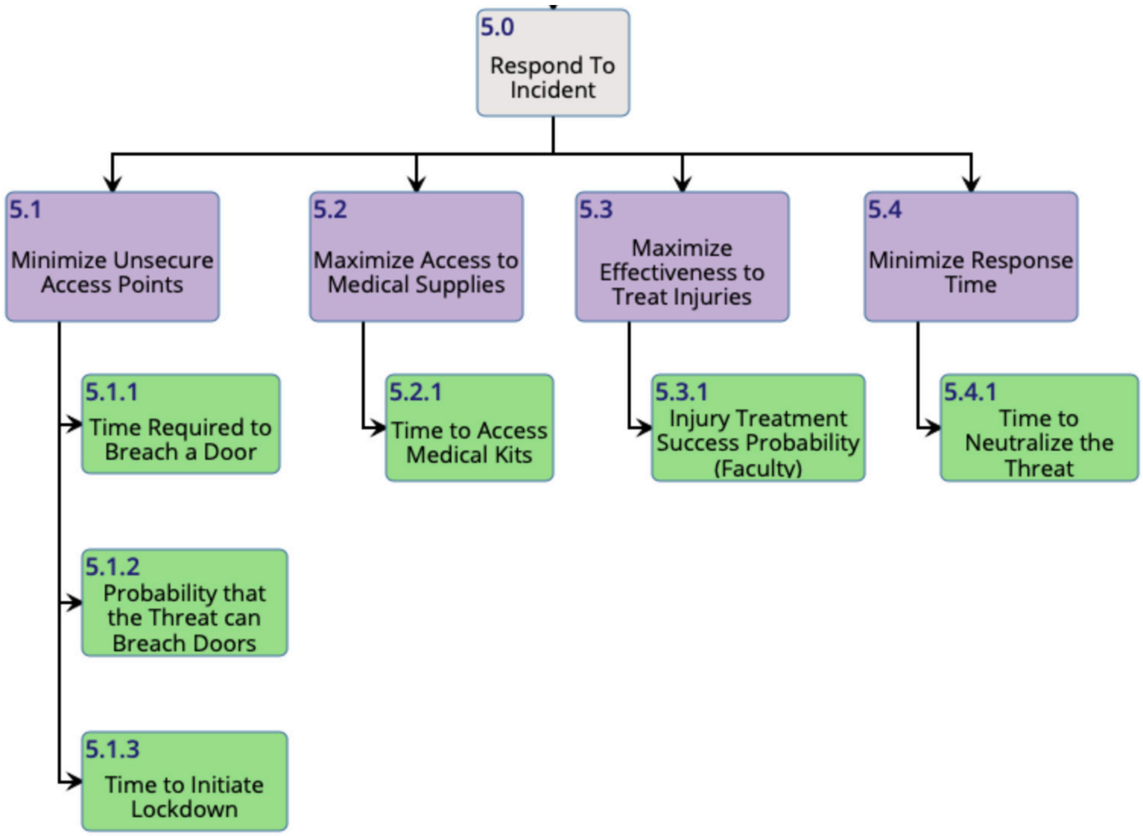

Figure 47. Value Hierarchy: Respond to Incident Branch

The needs analysis, functional decomposition, and value hierarchy determine what the system must do in order to counter an AS, organize related functionality, and provide metrics to quantify how well the enhanced system performs. These functions provide the basis for how the final system will improve survivability for school occupants, should an active shooter incident occur. To further understand how the system performs these functions, a behavior model is necessary to allocate functions to individual actors and illustrate the overall event flow.

D. BEHAVIOR MODEL

The system behavior model, developed in Innoslate, captures the high-level actions that the active shooter performs as well as key actions that the system itself and external systems will perform to counter the shooter. The model demonstrates the chronological flow for five actors involved in a shooting event: the active shooter, the school faculty/staff, the school facility/equipment, armed security responders, and medical responders. The behavior model also captures critical interactions between these actors. Ultimately, the model provides perspective on the general flow of events for an AS scenario and provides the framework for use in simulation tools. This model focuses on the imminent and in-progress phases of an AS event. Although it is important to consider the other phases when planning system improvements, these two phases provide the most apparent opportunity to directly counter the shooter. Figure 48 shows the overall structure of the behavior model. Subsequent figures focus on the separate branches.

1. Active Shooter Branch

We began the development of the behavior model with the AS branch. To appropriately model the desired system response, we need an accurate representation of the shooter's behavior in an active shooter scenario. Actions chosen for this branch, depicted in Figure 49, are those that were common to most of the AS cases we studied. This branch primarily leverages the information provided by the case studies and the shooter success tree. The team analyzed the individual event timelines from each case study and identified trends, which provided a general flow of events that most active shooters follow.

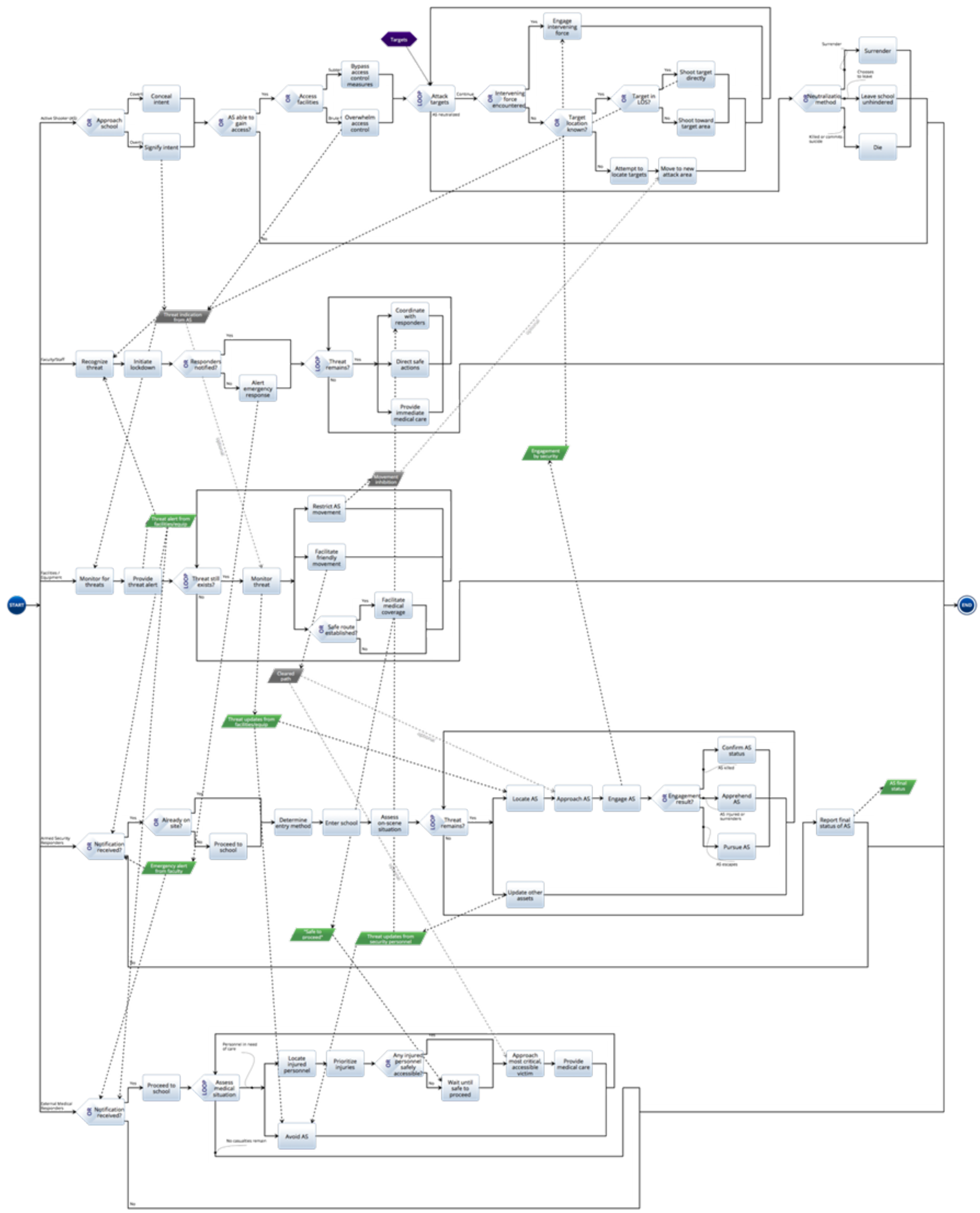

Figure 48. System Behavior Model Overview

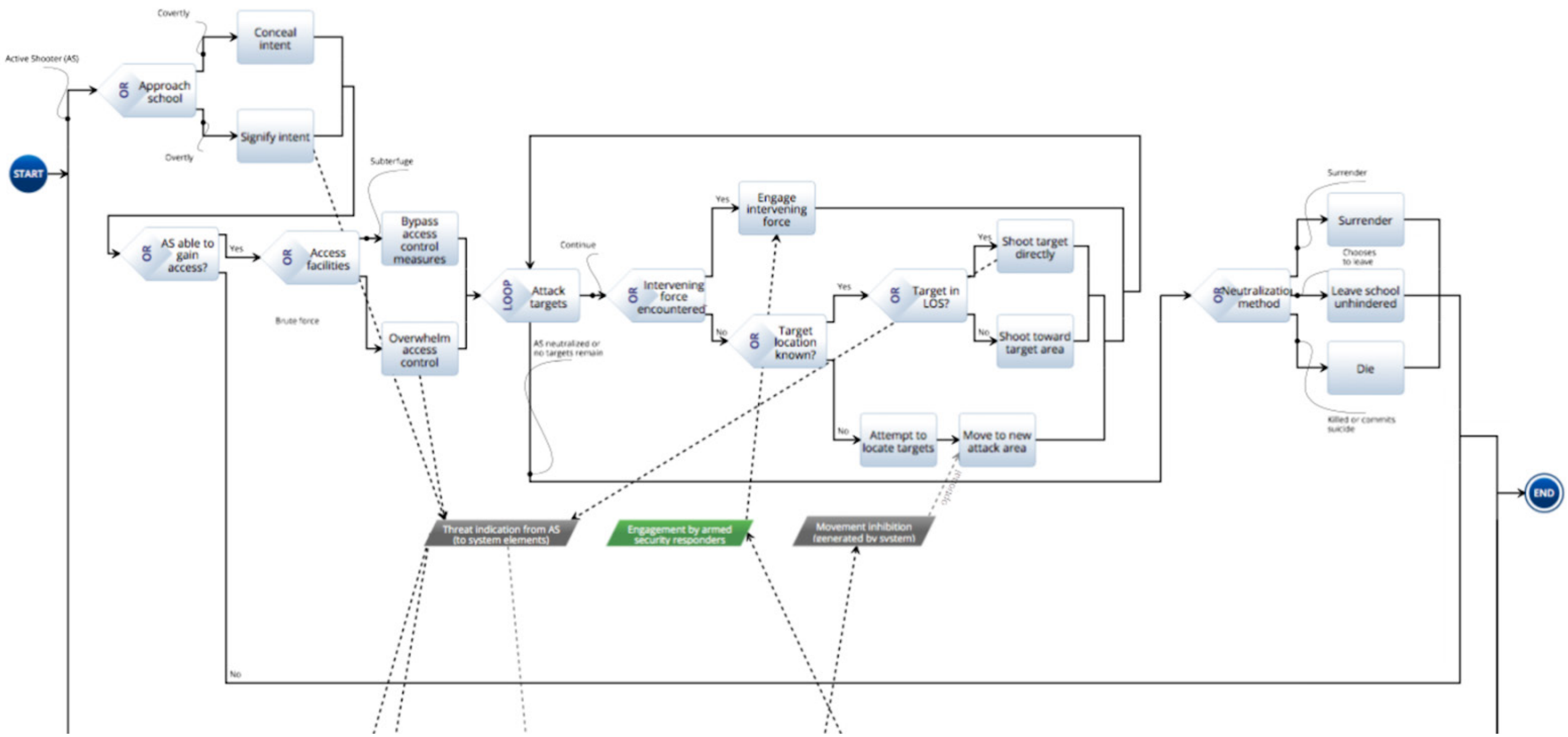

Figure 49. Behavior Model: AS Branch

First, the shooter must approach the school either covertly or overtly. A covert approach is one where the shooter is either concealing his weapon or has pre-staged it, so that there is no apparent hostile intent. An overt approach would show the shooter's intent early in the process. An overt approach provides a threat indication that the system can observe, either directly by occupants or through installed equipment.

Next, the shooter must gain access to the school premises. If the system is already secured and the shooter is unable to gain access, the shooter has no choice but to leave and no remaining threat to the school occupants exists. Otherwise, the shooter will access the school through either subterfuge or brute force. If the AS chooses to enter via brute force, he will produce a threat indication that the system can observe.

Once the shooter has gained access to the school grounds, an attack loop commences. If the shooter does not encounter an armed intervention force, he will attempt to locate potential targets, prioritizing the search based on various factors. These factors include target clustering, the proximity of likely targets to the shooter's ingress point, and the existence or absence of a direct engagement opportunity. The shooter success tree analysis explores these factors in more detail. While not directly reflected in the shooter's attack loop, these factors contribute to the time required for the shooter to conduct actions such as "attempt to locate targets" and "move to target area." These factors also contribute to the total number of targets the AS can engage during each pass through the loop and the likelihood of the shooter proceeding through a specific branch of the "OR" actions modeled. Within this loop, the active shooter receives a "movement inhibition" input from the facilities/equipment branch. This inhibition provides the system an opportunity to delay the shooter's movement, potentially increasing the time spent in the loop unable to attack potential targets. The attack loop continues until the shooter exhausts all possible targets, runs out of ammunition, or is neutralized.

A key event that did not occur in several of the case studies, but reflects an important aspect of desired system behavior, is armed security responders' engagement with the AS. This engagement creates a period when the shooter is unable to attack targets. The engagement does not necessarily have to result in the death or apprehension of the shooter, so the attack loop could continue even if the "Engage intervening force" action occurs once.

The final general event in an active shooter scenario is the neutralization of the threat. This event could entail the engagement force killing, injuring, or apprehending the active shooter. It also captures situations wherein the shooter commits suicide or leaves of his own free will. Regardless of the outcome, the threat to the school's inhabitants no longer exists and the critical phases of the active shooter event conclude.

2. Faculty/Staff Branch

The first of two branches representing system behavior is the Faculty/Staff branch, shown in Figure 50. Faculty/staff behavior commences on receipt of a threat signal, where the faculty and staff either directly observe an action the AS has performed or they receive a cue that facilities/equipment provide. These members will then initiate a lockdown and alert emergency responders (if the equipment branch has not already done so). For the remainder of the time the threat remains, faculty and staff will coordinate with responders, following their instruction and guidance, providing direction to students for safe actions, and providing immediate medical care to the best of their ability.

3. Facilities/Equipment Branch

The second branch that illustrates system-produced behavior is the Facilities/ Equipment branch, shown in Figure 51. Physical equipment passively monitors the environment for threats. When the equipment detects a threat, it will transmit a warning signal to faculty/staff and may also notify external responders. For the remainder of the time the threat exists, this asset will monitor the threat and provide updates to first responders to increase their situational awareness. The system will then restrict AS movement, which could entail any combination of active measures (e.g., automatic deadbolts) or passive measures (e.g., pre-installed, intrusion-resistant materials).

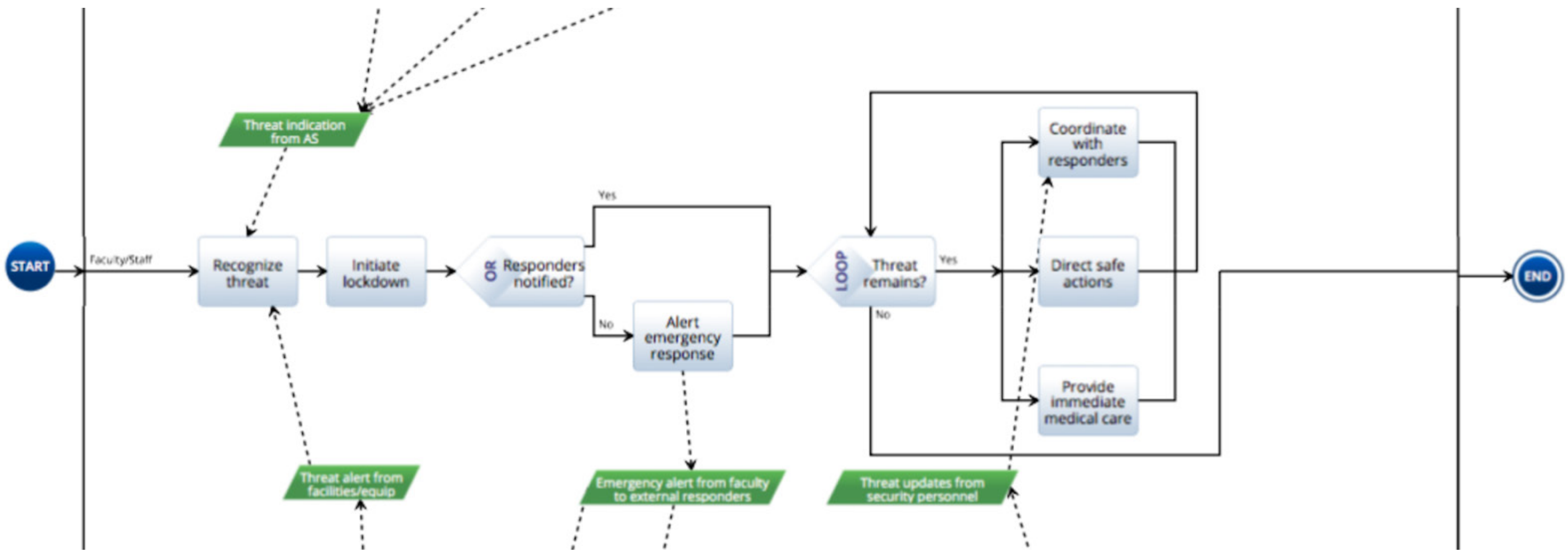

Figure 50. Behavior Model: Faculty/Staff Branch

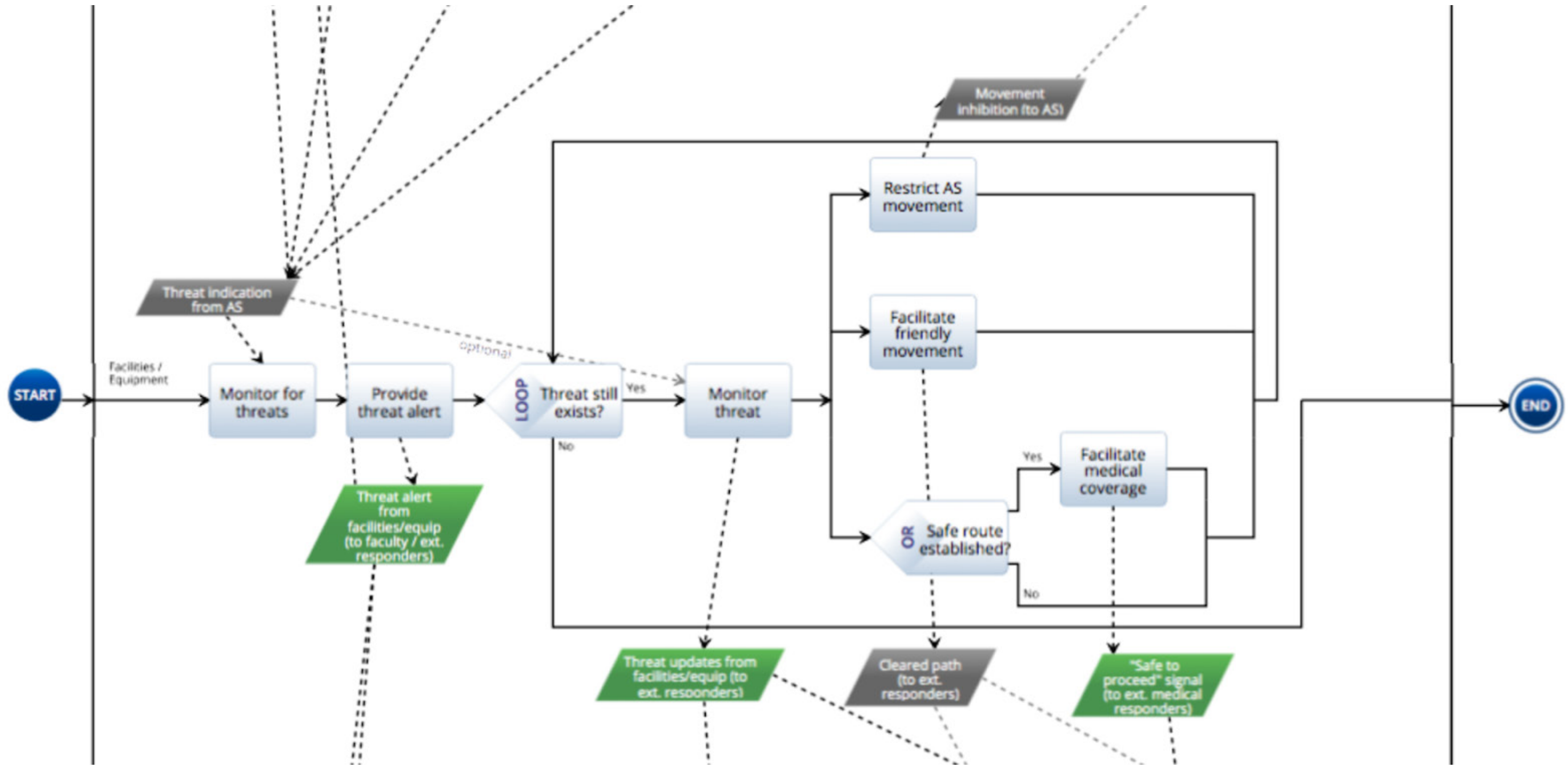

Figure 51. Behavior Model: Facilities/Equipment Branch

The system will also facilitate friendly movement, which may entail relaxing active security measures to allow freedom of motion or providing critical information about the school layout. Finally, if a safe route to injured personnel exists, the equipment installed in the system will facilitate medical coverage by providing critical information to external medical support assets about the location of wounded personnel and potential approach methods, along with verification that it is safe to proceed.

4. Armed Security Responders Branch

Figure 52 shows the expected behavior of armed security responders. If the school has a dedicated on-site armed security responder, this branch constitutes internal system behavior. Otherwise, it describes external behavior. Regardless, the action flow remains the same.

Armed security response for external assets begins on receipt of a threat signal, either from faculty/staff or equipment. On-site armed security responders may be able to observe the threat directly, which also constitutes signal receipt. If no threat signal exists, then this entire branch will not occur. Assuming security responders receive a notification, they must accomplish four actions, each of which will consume time (which in turn gives the AS more time to proceed uninhibited). If not already present, the armed security responders must proceed to the school. Upon arrival, they must determine how best to enter the school. While the previously-followed method of waiting for more capable assets such as Special Weapons and Tactics (SWAT) teams is not practical due to the prohibitive time requirements associated, the first armed responders on scene must still spend some time, however short, assessing the situation. This assessment includes determining the shooter's location, how best to approach him and what additional hazards may exist along the way. Once armed responders have completed this initial assessment, they can enter the school and conduct further investigation of the situation from inside.

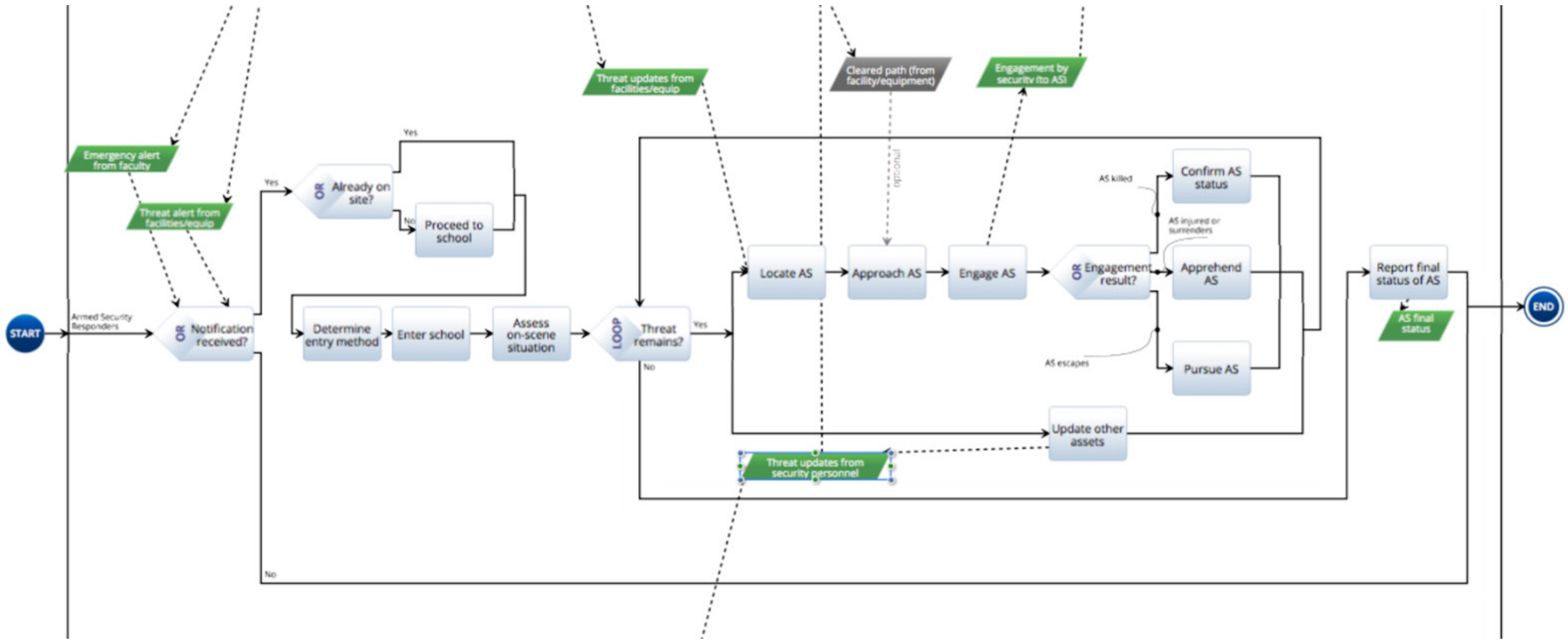

Figure 52. Behavior Model: Armed Security Responders Branch

As long as the threat remains, the armed security responders will attempt to locate, approach, and engage the AS. Depending on the result of the engagement, the armed security responders will apprehend the AS, confirm they have killed the AS, or pursue the AS if he managed to escape. Simultaneously, the armed security responders will provide updates to other assets to improve situational awareness for all involved personnel. In most cases, armed security responders engaging the AS will result in the shooter's death or apprehension. However, since it is possible for the AS to escape, this portion of the behavior model forms a loop. Once armed responders suppress the threat, they will report the shooter's final status.

5. External Medical Responders Branch

The last asset directly involved in the AS scenario is external medical responders, whose branch of the behavior model appears in Figure 53. As with the armed security responders, medical responders are dependent on some form of notification – otherwise, they do not perform any of their modeled actions.

Once notified, the medical responders will proceed to the school and begin assessing the medical situation. As long as personnel need medical care, responders will attempt to render assistance while simultaneously avoiding the AS. Their ability to avoid the AS depends on inputs from other assets, who will give updates on the threat. Providing medical care requires the responders to locate injured personnel and prioritize injuries. If it is impossible to approach any injured personnel safely, the medical responders must wait until it is safe to do so. Otherwise, they will proceed to the victim that they can safely approach who has sustained the most critical injuries (i.e., responders can reach the victim without encountering the AS). They will provide medical care as needed, then continue through this iterative process until no more victims are in need of assistance.

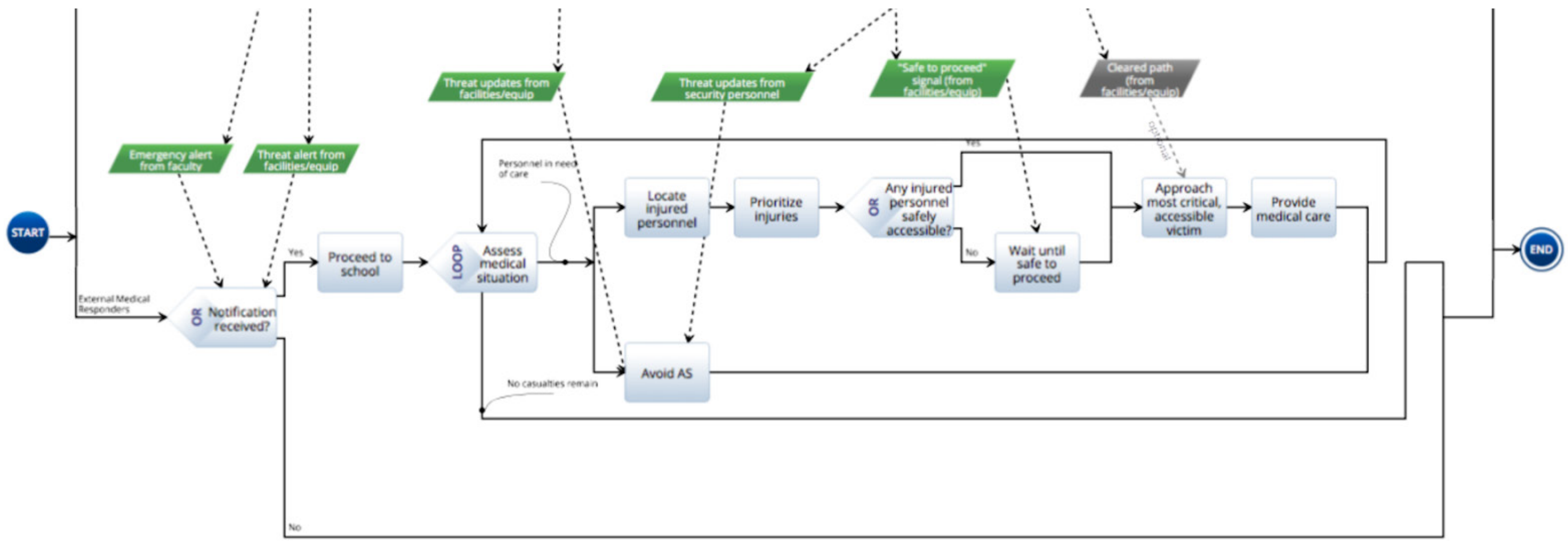

Figure 53. Behavior Model: External Medical Responders Branch

E. EXTENDSIM MODEL AND SIMULATION METHOD

To simulate system performance and to analyze possible school system enhancement options, the team developed a model using the Imagine That Inc. ExtendSim software program. This ExtendSim model is depicted in Figures 54–60. The general structure of this model reflects the behavior model previously described, with distinct branches for each actor associated with the system. Each branch creates an entity (e.g., the active shooter) that progresses through various processing blocks. These blocks cause the entity to make decisions based on available data or delay for a specified period, representing the time required for the entity to complete an action. Entities may also enter a queue block, wherein the entity waits for an external cue before continuing. The diagrams shown in Figures 54–60 adhere to the following syntax:

- Double lines indicate the path an entity will trace.
- Single lines indicate information transfer.
- Plain text describes an individual block's purpose.
- Underlined text indicates information that flows between points in the model.
- Italicized text shows where an entities path connects from one point to another if the path is not directly connected.

1. School Representation and Model Assumptions

The intent behind the ExtendSim model is to simulate the key events associated with an AS attacking a school and to determine how various system enhancements could affect the outcome of the attack. As modeled in the software, an AS attack is divided into three phases: approach, attempted access, and movement. The targeted school is a single building with classrooms equally spaced. This design supports several layout options, including a single, infinite hallway of classes, a closed loop of classrooms, or even a building with multiple floors of linear hallways. The model also assumes that every room the AS passes is a classroom and that every classroom is occupied. It is possible to have students randomly moving through the hallway when the AS arrives, which emulates normal behavior during a standard school day wherein students may be going to the restroom or administrative offices during class periods. Additional assumptions for the ExtendSim model include the following:

- The AS is a single perpetrator.
- The shooter has no specific target in mind, and will therefore begin shooting the first available target instead of waiting for a perceived ideal opportunity.
- All normal school occupants (i.e., staff, faculty, students) are present when the attack commences.
- All occupants are inside the school building when the attack commences.
- Occupants are evenly dispersed through every classroom.
- All actors that contribute to system behavior can be represented as a single entity (e.g., faculty act as a group instead of independently).
- After an initial engagement between armed responders and the AS, armed responders will either kill or apprehend the shooter, or the shooter will escape. The shooter will not have an opportunity to return to attacking occupants.
- The AS is restricted to a maximum time limit to conduct the attack.

This last assumption is based on the average time associated with active shooter events at schools and will force the simulation to a conclusion even if the AS has not encountered armed resistance. Although unrealistic to apply a seemingly arbitrary time limit to an AS attack, the purpose behind this assumption is to encapsulate the various reasons why a shooter may discontinue the attack without encountering resistance. These reasons could include the shooter running out of ammunition, the shooter deciding that he has done enough damage to meet his intent, or the shooter becoming concerned that remaining any longer would result in his own demise.

2. Active Shooter Branch

ExtendSim simulates events by creating entities that follow user-defined paths. These paths direct the entity through decision points and other logical constructs, which in turn generates results for the simulation user to analyze. Single iterations of an event simulation are known as "runs." Figures 54 and 55 show the general path an active shooter follows during a school shooting. Figure 54 focuses on the shooter's approach and entry to the target school. Figure 55 captures the shooter's looped behavior of moving through the school to find and engage potential targets, as well as the event resolution. Throughout the ExtendSim model, actions that one system actor performs often appear on a separate actor's branch, instead of appearing on the branch associated with the entity performing the action. This is because the purpose of most of the system's functions are to alter the actions and abilities of another actor. It is simpler to apply the desired effect directly to the affected actor in ExtendSim and allows for a cleaner, more understandable model.

Once the AS enters the model for a simulation run, his first choice is whether to make an overt or covert approach to the school. If the AS reveals hostile intentions early on, the model generates "AScue0," which other entities can observe and which will cause them to initiate their own action chains during the run. The shooter then approaches the school. Regardless of the approach method, this action will take some period of time. The "EarlyWarningDelay" time reflects the amount of advanced warning the system can provide, assuming its upgrades include advanced detection capabilities.

The next key event in the scenario is when the shooter attempts to gain access to the school building. If the shooter attempts to enter covertly and bypass any existing access control measures, the AS entity will follow the top branch in Figure 54. At this point, the system may detect this attempted breach. An equation block (shown on the model as a green rectangle with "y=f(x)" inside) calculates the success of this detection attempt. Detection success depends on the probability that the system is actively monitoring the access point the AS chooses to enter as well as whether the monitored access point succeeds in detecting the shooter.

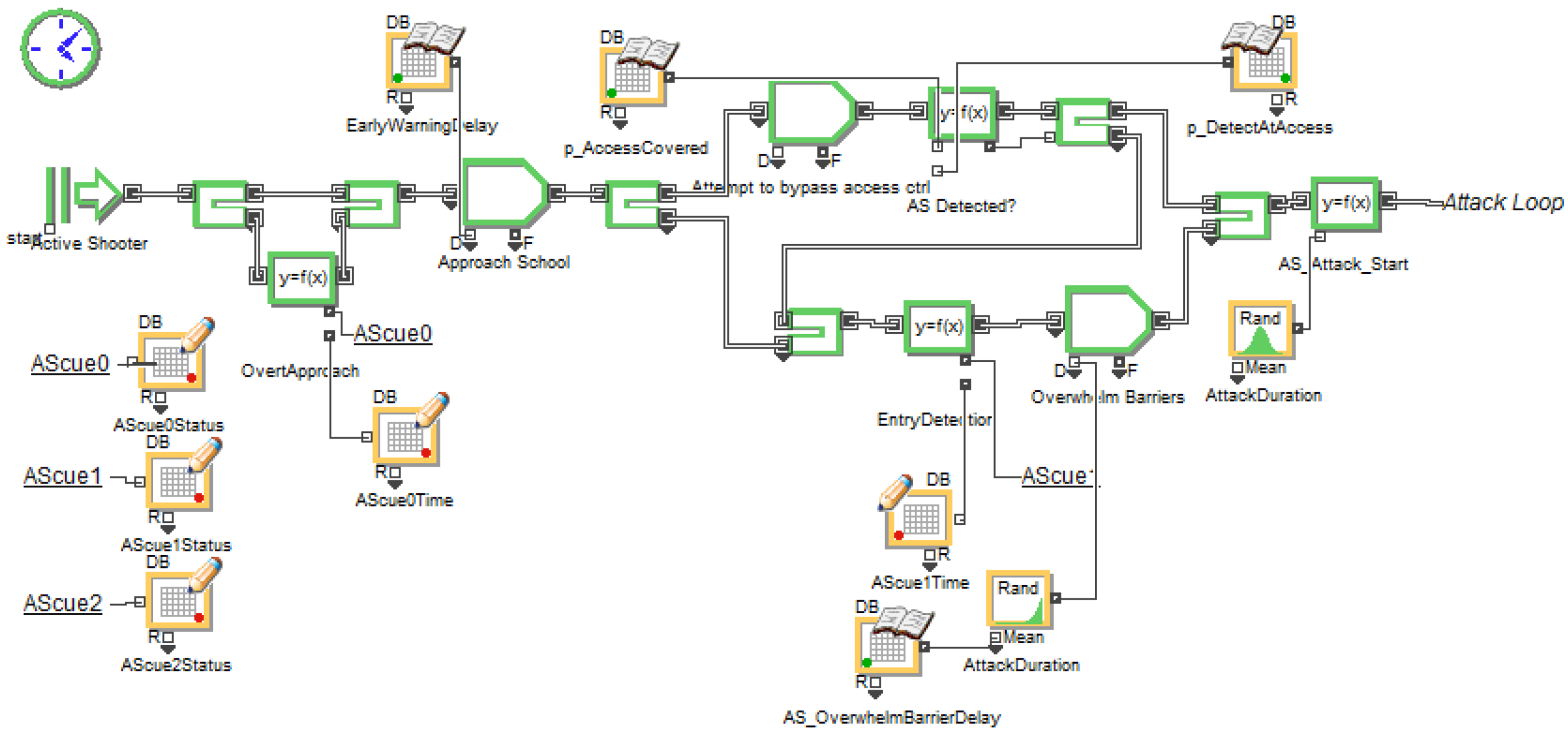

Figure 54. ExtendSim Model: AS Branch—Approach and Building Entry

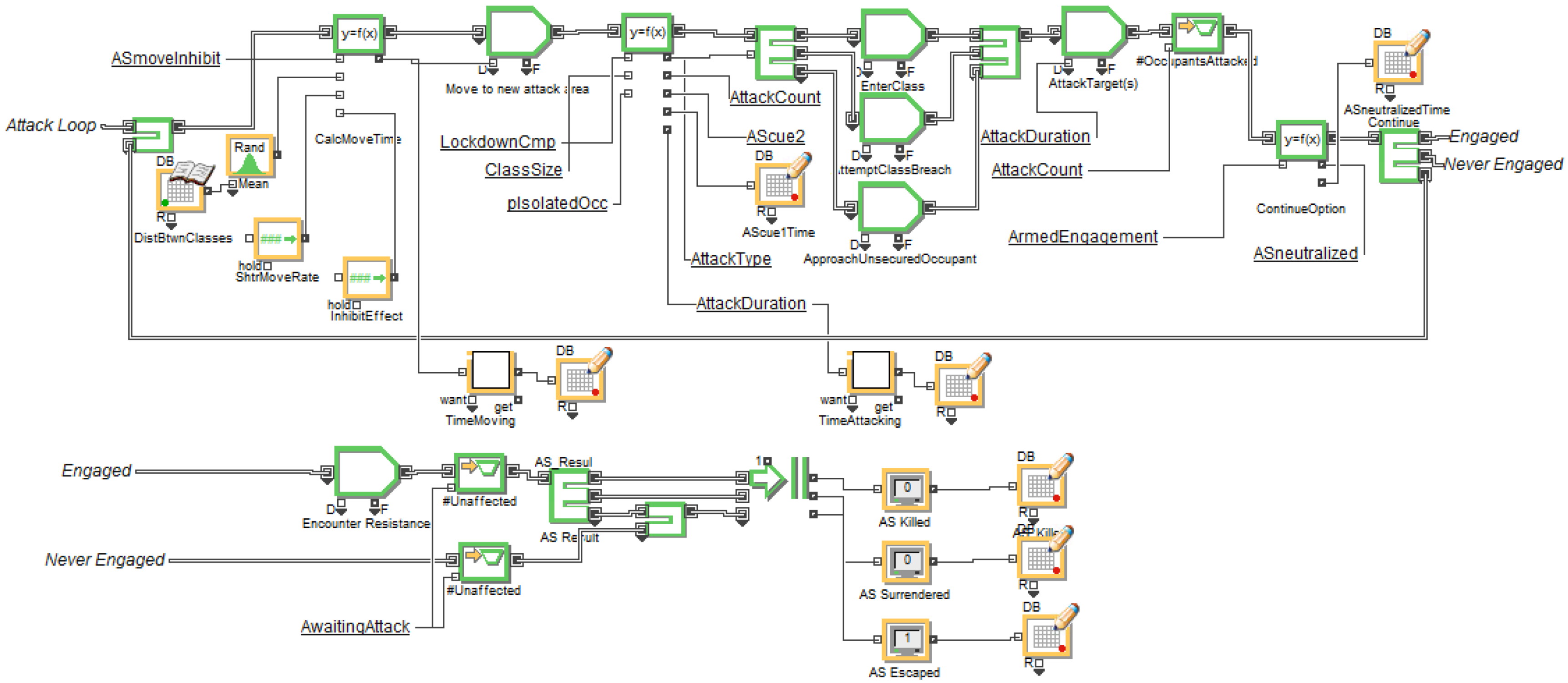

Figure 55. ExtendSim Model: AS Branch—Attack Loop and Result

If the system detects the shooter, the model generates a second cue, "AScue1," which it sends to other entity branches. The shooter must then attempt to overwhelm any existing access control measures. Once the shooter gains access to the school, the simulation notes the current time during the individual run, calculates a random time limit for the shooter's attack, and appends a designated stop time when the shooter will leave - even if the shooter does not encounter an armed responder.

From this point, the shooter's actions are shown in Figure 55, where the shooter enters the attack loop. Another equation block reads the average distance between classrooms, determines whether the system has generated any sort of inhibitions to restrict the shooter's progress through the school, then determines a time delay to account for the shooter moving to the next attack area. After reaching the attack area, the shooter passes through another equation block. This block processes several factors, such as whether a lockdown has taken effect or how likely it is for the shooter to come across an isolated occupant, then determines what type of attack the shooter will commence. The attack types are either a direct attack on an isolated target, a direct attack on a full classroom after gaining entry, or an indirect attack on a classroom (i.e., shooting through any doors/walls) after trying to gain entry to the classroom. The equation block also determines how much time the shooter will spend on this particular attack.

After completing the attack, the shooter passes through a block that releases "resources" (shown as a yellow arrow pointing to a green trapezoid). In ExtendSim, a "resource" is a control mechanism. Certain blocks within an ExtendSim model cannot perform their function unless a resource is available for use. When a model entity (e.g., the shooter) reaches these blocks, that entity must wait until a resource becomes available. Resources wait in a repository until a separate block triggers their release. Once a resource is available, the block where the entity is waiting consumes the resource and returns it to its repository. In the block that the shooter passes through after completing an attack, the released resources reflect the number of individuals that the shooter has attacked. The "School Occupant Branch" section addresses these resources in more detail.

Next, the AS entity passes through a block that determines whether the shooter has encountered armed resistance or if his previously calculated end time has arrived. If neither of these have occurred, the AS entity returns to the start of the attack loop and repeats the process. Otherwise, this branch continues to the end of the simulation. The shooter either encounters resistance or leaves the school. In either case, the model releases more resources that cue other branches that the AS will not attack any remaining occupants. The ExtendSim model then indicates the shooter's final status: killed, surrendered, or escaped.

3. School Occupants Branch

The next actors modeled are the school occupants, as shown in Figure 56. The model user can manually enter the school's population in the "create" block (two vertical lines with a right-facing arrow). ExtendSim creates a separate entity to represent every member of the school population. Each entity then proceeds to the next block, called a "queue" block, where it waits for an outside occurrence before proceeding. At any time, this queue block provides a data signal to other branches in the model to indicate how many occupants are waiting for something to happen. First, if the AS branch has released resources to correspond to the number of attacks (i.e., the AS has accumulated victims), that same number of school occupants will leave their queue and continue through their entity's branch. The queue length data signal will simultaneously adjust to show the new number of waiting occupants. If the AS branch releases resources to indicate that occupants are safe from further attack, the remaining occupants in the queue can leave and will bypass the rest of this branch.

Once the AS attacks an individual occupant, the associated entity will proceed through a number of logical constructs that determine the individual's final outcome. The equation block titled "EngagementResults" receives an input determining the type of attack (direct or indirect) the AS has conducted. This block then applies a series of Bernoulli trials to determine if the occupant was shot and whether the hit resulted in an immediate fatality. A Bernoulli trial provides a stochastic result when only two discrete outcomes are possible and a known or assumed probability of one outcome exists (e.g., whether the occupant has been shot and whether the occupant has subsequently died). If the occupant's injuries are not immediately fatal, logic elements later in this entity branch determine whether the injured occupant will need medical treatment to prevent death or if the injury is not life-threatening.

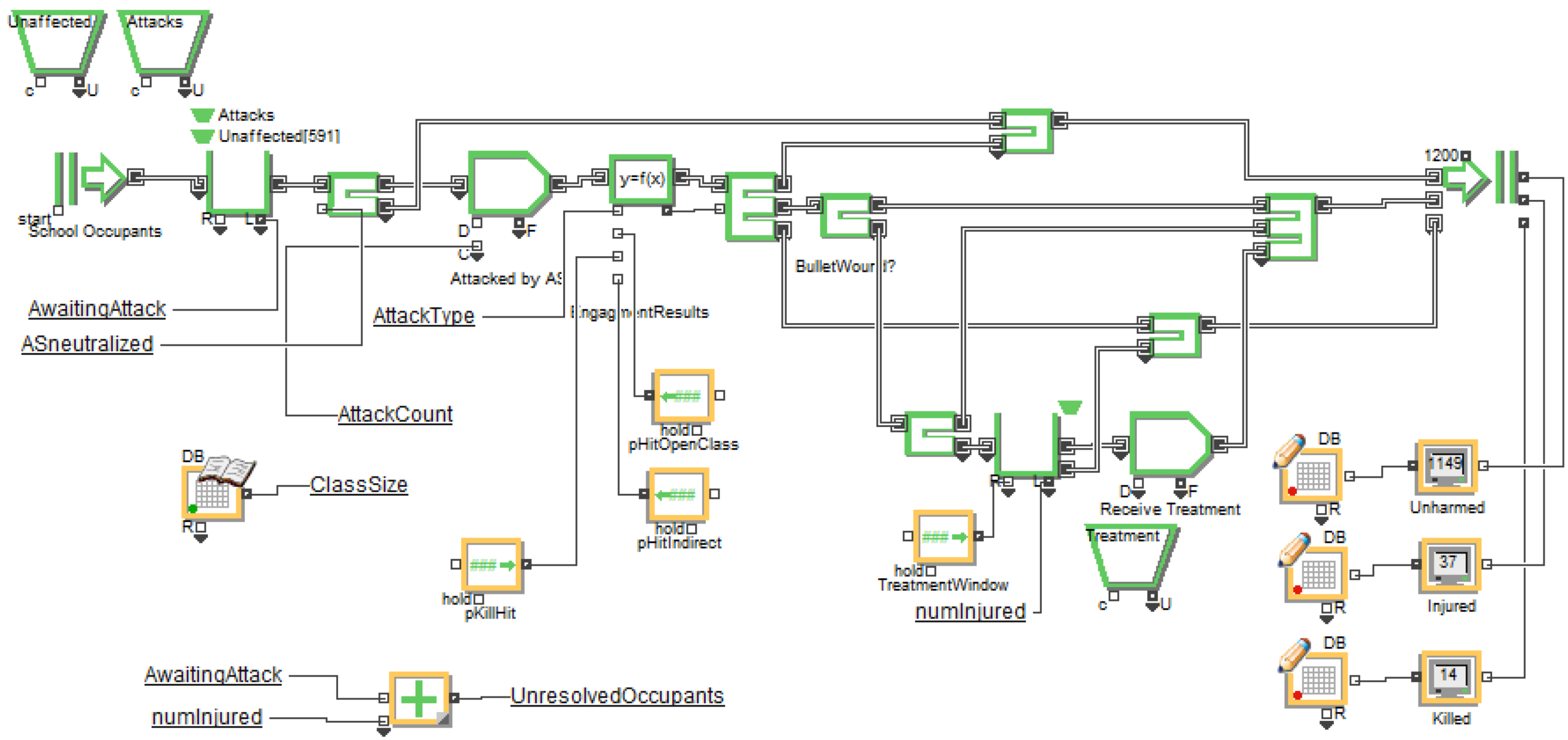

Figure 56. ExtendSim Model: Occupants Branch

If an occupant's injury is life-threatening, the occupant continues into a second queue block to await medical treatment. The model uses resources in the same manner as previously described to simulate other system actors successfully providing medical treatment. An injured occupant who receives treatment within a preset time limit continues through this branch and ends at the "injured" result. Otherwise, the injury has become fatal and the affected occupant proceeds to the "killed" result.

In addition to showing final results, this model branch also generates data that controls simulation flow. At any time, this branch tracks the status of personnel within the school to determine if any injuries exist or if any occupants have not yet been affected, which then directs the decision flow of other entities in the ExtendSim model.

4. Faculty Branch

Figure 57 depicts the model of the behavior of any staff or faculty members. The ExtendSim model treats staff and faculty as a single entity, which we will refer to as simply, faculty. Faculty immediately enter a queue where they await an indication that an AS threat exists. This indication could either be a direct observation or a cue from detection equipment. Faculty members then initiate the lockdown. If the system enhancement includes an automated lockdown process that omits faculty input, then model users can manually set the time associated for this particular activity block (titled, "Initiate Lockdown") to zero seconds and the simulation will accurately emulate this capability.

Next, the faculty entity passes through an equation block that assesses whether existing equipment enhancements sent an automated alert to any available external responders. If not, the faculty must then call 911 to get the desired support. If an automated alert capability exists, faculty can omit this step and proceed directly to the response loop within this branch.

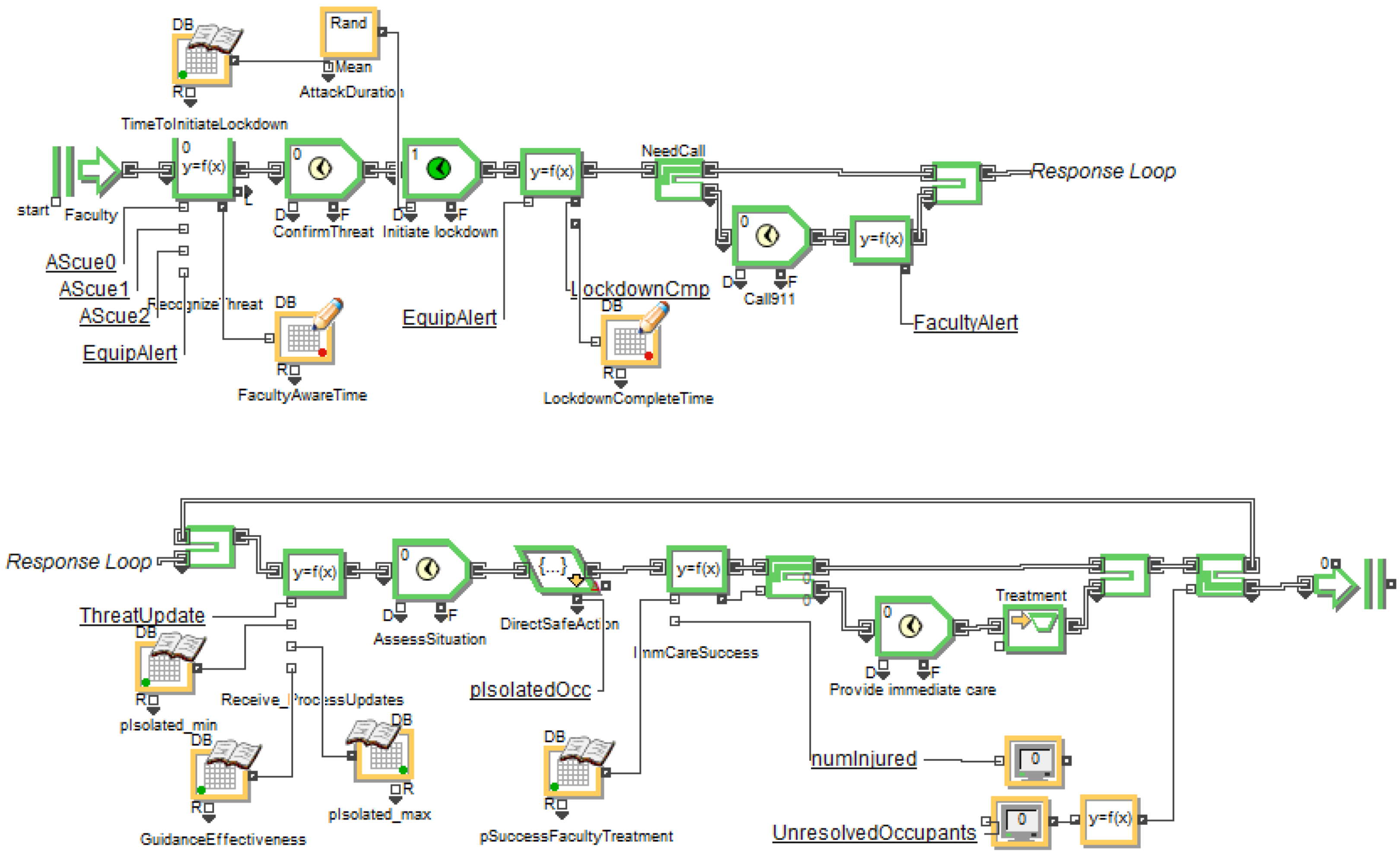

Figure 57. ExtendSim Model: Faculty Branch

In the response loop, the faculty entity attempts to gather information about the AS situation, provide guidance to students to minimize their susceptibility, and treat any students who have been wounded. The first equation block in the loop processes user-input values for the minimum and maximum probability of a student being in an unsecured area during an AS scenario, as well as an input associated with how effective the teachers' guidance is at influencing student safety. This block also measures the time delay since the faculty member last received an update regarding the threat situation, which accounts for the perishable value of guidance due to outdated information. Ultimately, the model processes this information to determine the resultant probability of a student being isolated. This probability then affects the shooter's attack type selection as previously described.

The next equation block in the loop determines whether a faculty member is able to treat an injured student. At any time, the occupant branch of the model tracks the number of occupants who are injured and awaiting treatment. If an occupant is awaiting treatment, the "ImmCareSuccess" block conducts a Bernoulli trial based on a user-determined probability to determine if the treatment was successful, which then releases a resource that allows the affected occupant to leave its associated queue.

As currently modeled, the ExtendSim software does not allow a faculty member to immediately attempt treatment a second time, nor does it account for the location of injured personnel within the school. As long as an injured occupant is in the queue to await treatment, the faculty entity will attempt to provide medical care every time it passes through its response loop. This loop continues as long as the AS is still active and injured occupants are awaiting treatment.

5. Equipment Branch

The next major system element modeled is the system equipment, shown in Figure 58. This branch is relatively simple because many system capabilities associated with installed equipment appear elsewhere in the overall model. For example, threat detection range is indirectly modeled on the active shooter branch as a time delay between when the shooter provides an initial cue and subsequently arrives at the school.

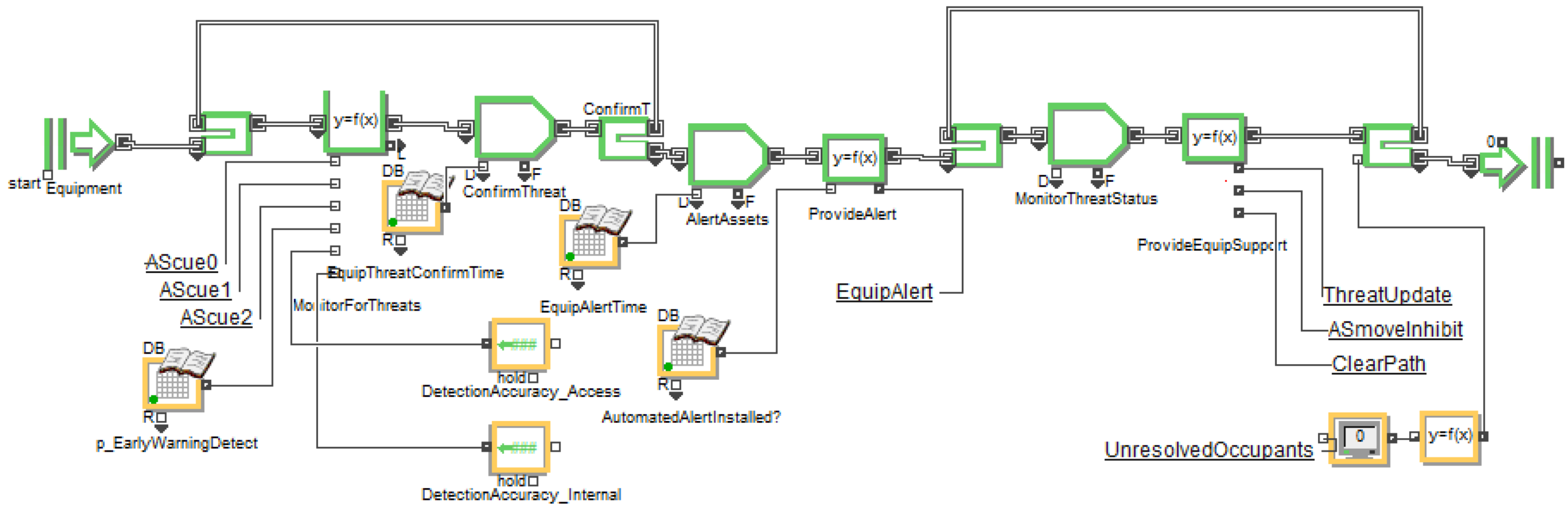

Figure 58. ExtendSim Model: Equipment Branch

The first loop shown on this branch models the equipment's ability to detect a threat. When the shooter branch generates any of the AS cues, the equipment branch will observe this cue, stochastically determine whether this cue was detected, and account for the time required for the installed equipment to process and confirm an existing threat. Detection probabilities are user-adjustable to support differentiating among various technologies and vary for different points within the shooter's attack sequence.

Once the equipment recognizes the existence of a threat, it will provide alerts to other system actors. If an automated external alert capability exists, the equipment will generate this alert to first responders so that faculty can focus on directing safe actions within the school. The equipment branch then continues into a loop to provide threat updates to other assets, facilitate friendly movement, and inhibit the shooter's movement. The model records the time when equipment generates these updates, that way other system actors know how much time has passed between update production and subsequent receipt. The effectiveness of movement inhibition or facilitation influences the speeds of other actors.

6. Armed Responders' Branch

The armed responders' branch, shown in Figure 59, represents the behavior of either an on-site armed security responder or an external armed responder. The armed responder immediately enters a queue where he waits for a threat signal. The queue block also determines whether or not the user has chosen to simulate the existence of an on-site armed security responder. The block accomplishes this by referencing a database of user-defined inputs. The "Database Characteristics" section expands on this concept.

Once notified, the armed responder proceeds to the school. If already on-site, this transit time is instantaneous. If not on-site, the model employs a Poisson distribution to determine the armed responder's arrival time based on user-input data for average response times in the school's vicinity. The team chose this distribution type for armed responders' arrival and other similar delay estimations because its probability distribution exhibits realistic possible outcomes for situations where longer expected delays entail increased uncertainty, while also precluding negative time values.

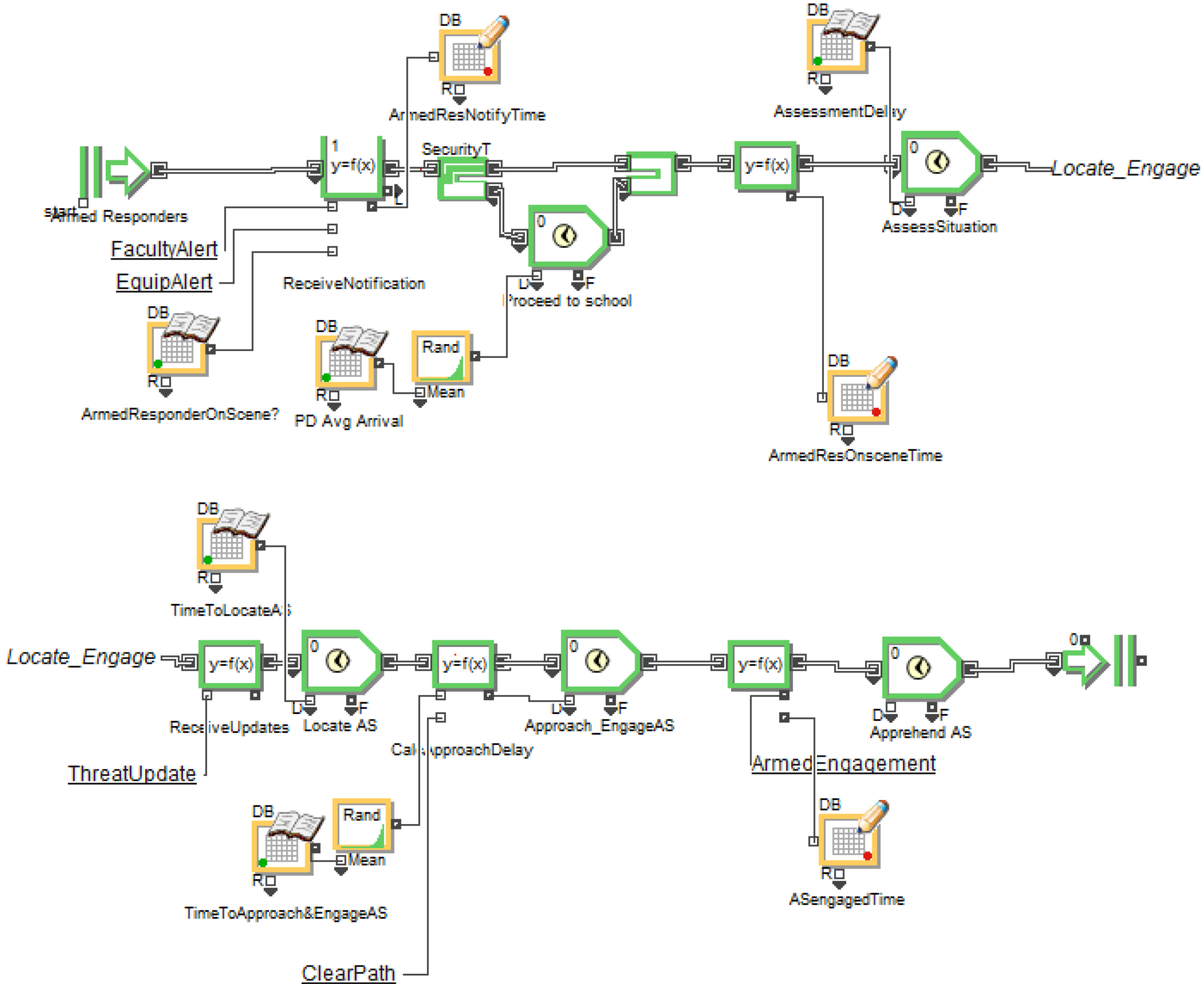

Figure 59. ExtendSim Model: Armed Responders' Branch

Upon arrival, the responder assesses the situation to determine the most effective means of finding and engaging the shooter, while also considering how to avoid any unnecessary additional danger to the school occupants. Next, the armed responder will enter the school, receive any available updates from monitoring equipment or faculty, and locate the shooter. Once the responder knows the shooter's location, the responder will approach and engage the shooter. Equipment capabilities can influence the responder's closure speed. When the engagement has finished, this branch of the model generates a data signal labeled "armed engagement" and sends it to other branches to direct their behavior. The armed responder then apprehends the shooter (if the shooter is still alive) and this branch ends. The model does not discriminate whether the shooter surrenders, dies, or escapes while simulating the armed responder's actions, since it has no impact on any other results or model behavior.

7. Medical Responders' Branch

The final branch of the model, shown in Figure 60, simulates the actions of external medical responders. The notification and transit sections of this branch are nearly identical to that of the armed responders branch, except that the model assumes that no advanced medical services (i.e., an Emergency Medical Technician or better-qualified responder) are immediately available. Once at the school, the external medical responders wait for a threat update to determine whether they can safely enter the school. They will also spend a certain amount of time prioritizing injuries to provide treatment to the most critical victims first.

After entering the school and prioritizing injuries, medical responders enter a treatment loop. A single delay occurs during each pass through this loop to account for the time required for an external medical responder to move to an injured occupant and provide treatment. Next, an equation block conducts a Bernoulli trial, similar to that of the faculty branch, to determine whether this treatment was successful in preventing an occupant's death. The treatment loop will continue as long as injured occupants exist.

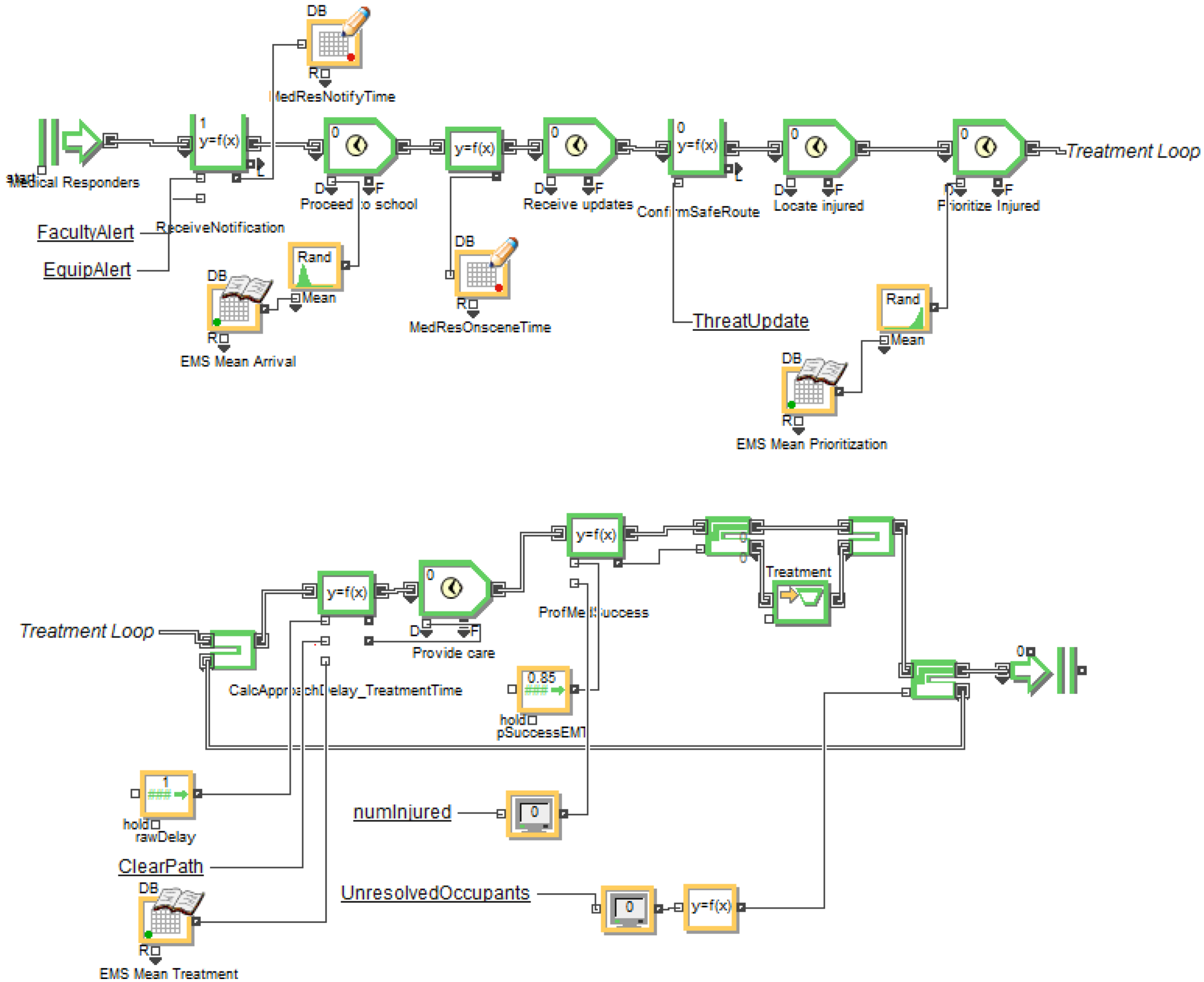

Figure 60. ExtendSim Model: Medical Responders' Branch

8. Database Characteristics

The ExtendSim model relies heavily on databases when running simulations. Databases provide flexibility to the model user, since the user can adjust key parameters (either directly within the ExtendSim software or by transferring information from the data-organization software of their choice). ExtendSim will then read these parameters during each of its simulation runs. The software also records information in output databases, which allows the user to conduct a more in-depth analysis. Database functionality is especially beneficial in that it enables the user to perform multiple runs automatically and record the results on separate rows within the output tables. The ExtendSim model uses four databases—two input databases and two output databases, as shown in Figure 61. Appendix B includes definitions for the values in each database.

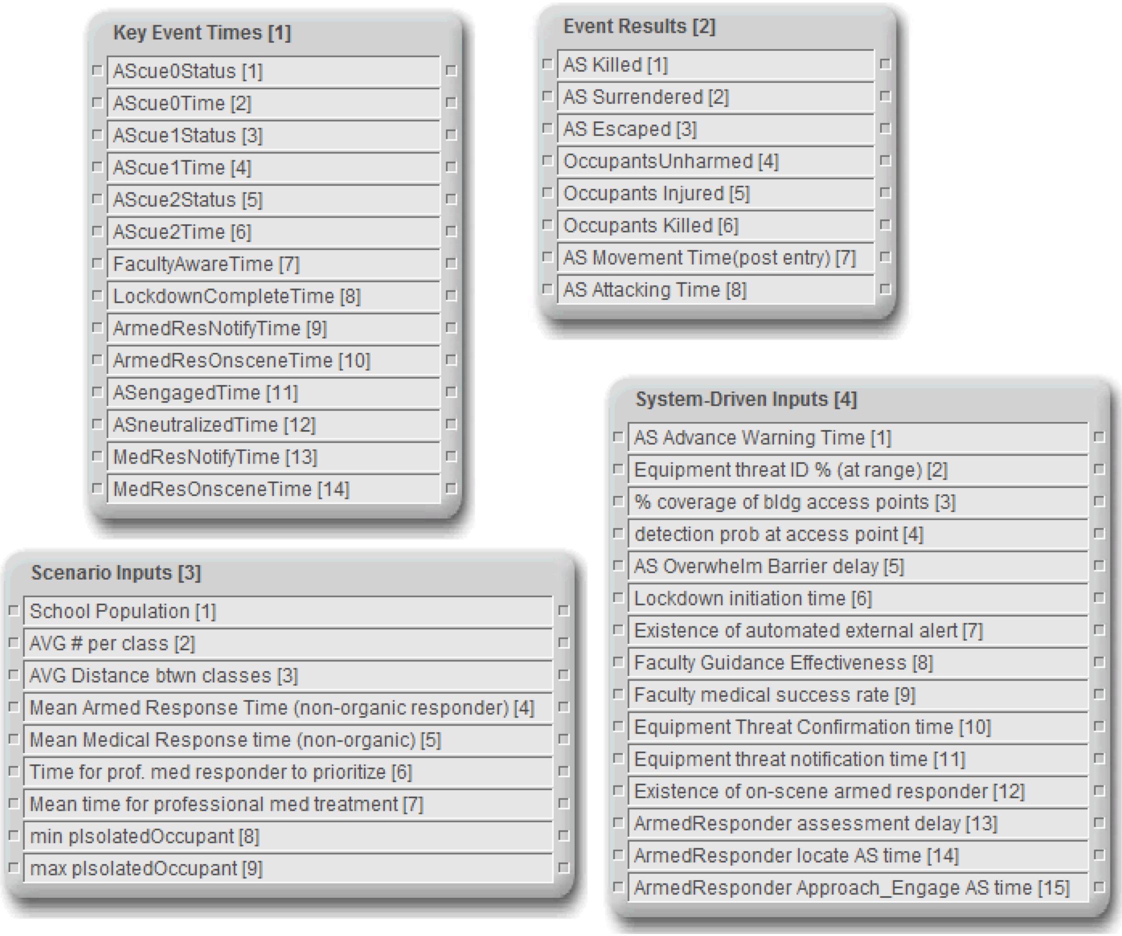

Figure 61. ExtendSim Databases

The model uses two databases for simulation inputs. The first input database, “Scenario Inputs,” accounts for the variability of schools throughout the United States. While the capstone team created a general scenario for initial testing, the assumptions that support it may not uniformly apply well to all schools. Tailoring this database allows future users to more accurately model their school’s characteristics, such as the school’s population, the distance between classrooms, and predicted emergency response times for local services. This database is not intended to capture the effects of system performance and capabilities, but is instead meant to enable decision-makers to tailor the model for their school. The second input database, “System-Driven Inputs,” captures anything that the user expects the enhanced system to be able to affect. It is associated with system MOPs and allows system designers to adjust the system capabilities after changing the scenario inputs.

Adjusting these system-driven inputs allows system designers to determine which capabilities will have the best chance of improving the final result.

Two additional databases record simulation outputs. The first output database, "Key Event Times," supports diagnostics and model validation. This database records when the model generates certain cues as well as when various entities recognize these cues and perform their assigned actions. These recorded timestamps allow the model user to identify logical errors, such as if external armed security responders arrive before the shooter has produced any cues. The second output database, "Event Results," records the final status of the shooter as well as the total number of occupants who are dead, injured, and unharmed at the end of the simulation. It also records the amount of time after commencing the attack that the AS was moving between attack areas versus how much time the AS spent actually attacking occupants.

9. Data Sources for Model

The validity of the ExtendSim model relies on the metrics and values model users apply. To provide meaningful outputs that allow users to evaluate the effectiveness of school system enhancements, the model will require data collected from AS incidents. Toward this end, we populated our model with data ascertained by evaluating case studies, reviewing research papers, interviewing stakeholders, and researching web statistics. These sources produced approximately 54% of the values we used in the ExtendSim model, as shown in Figure 62.

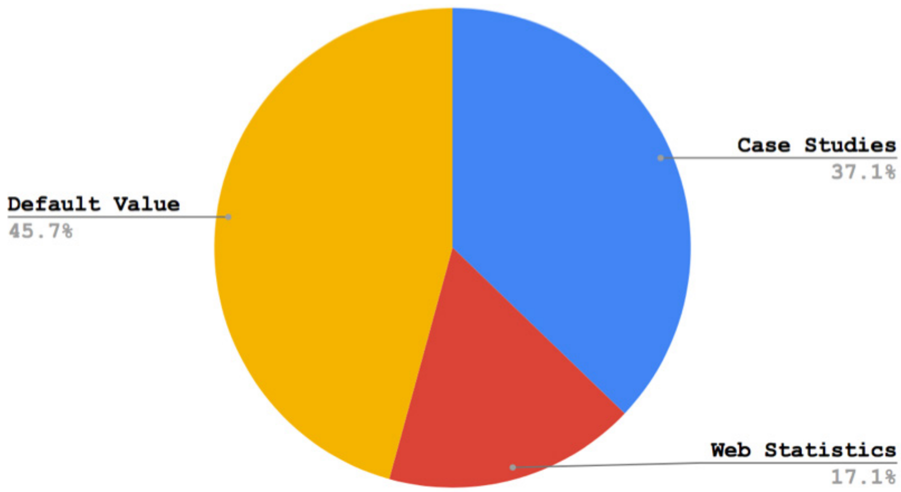

Figure 62. ExtendSim Data Sources

To generate the remaining 46% of the input values, we used our best judgment. An example of a default value employed in the model is the shooter's transit time between attack areas. The values for the time required to walk to a class, the playground, school offices, and through hallways are directly related to the size and shape of the school. Since average data, for all schools, does not exist, the team chose average values. We attempted to validate these values by timing a team member walking between classrooms, offices, and playgrounds at a local school. Individual transit times are shown in Table 4. The overall average time for all transit scenarios was 48 seconds. For the ExtendSim model, the team rounded this time up to 60 seconds to account for variations in school size and other real-world delaying factors.

Table 4. Default Value Determination for Transiting between Key Areas

Actions	Iteration # 1 (sec)	Iteration # 2 (sec)	Iteration # 3 (sec)
Classroom to Classroom	50	40	55
Classroom to Playground	47	45	43
Parking lot to Office	50	55	51
Total Average	48 sec <= 60 sec Default Value		

10. Model Limitations

While the ExtendSim model simulates several complex interactions and their associated effects, there are several more system behaviors and nuances that we were not able to incorporate. For example, the model cannot accurately account for the ability of a teacher to direct a safe course of action. Ideally, there would be a decaying value associated with the time lapse between updates to faculty, both from monitoring equipment or other assets, as well as from faculty to students. This lapse in time would lead to more realistic effects such as a variable range for the probability of the shooter finding an isolated occupant or even extensions in the movement delay associated with the shooter trying to find targets (indicative of situations where school occupants are able to avoid the shooter's location).

Another notable model limitation involves the ability of faculty and medical responders to find and treat injured occupants. Realistically, if the AS shoots an occupant, the victim will be in a specific location and in many cases will be unable to move to another area. Because of this, not every faculty member can treat every victim and some victims will be much harder to find; therefore, potential medical service providers may not even know that the injury exists. While it is possible that ExtendSim can append attributes (similar to the event times already discussed) that could address some of these issues and simulate their effects on the overall scenario, our model does not incorporate these features.

The ExtendSim model contains structure for various planned functionality that the team was unable to incorporate. An example exists where the equipment branch creates threat updates that, theoretically, would allow other assets to find the shooter faster, avoid the shooter if they know shooter's location, or move through the school faster. While some of these features are not fully functional in the current version of the model, the framework exists for follow-on work.

IV. ANALYSIS OF ALTERNATIVES

With the establishment of the ExtendSim model that simulates activities during an AS incident, we can now investigate specific school system enhancements and their effect on the outcome of the incident. Because our system of interest already exists but needs improvements in order to more effectively counter an AS, we chose to analyze various system enhancements as opposed to alternative system designs. For the following discussion, we will use the term "enhancement alternative" to refer to the category of enhancements that support the improvement of a specific capability (e.g., Advance Warning Time). Figure 63 depicts the framework the team used for the selection and evaluation of potential enhancements. First, we determined evaluation criteria to assess alternatives. Next, we selected enhancement alternatives to analyze. We then determined the method to evaluate enhancement alternatives and assess their effects on the simulation results.

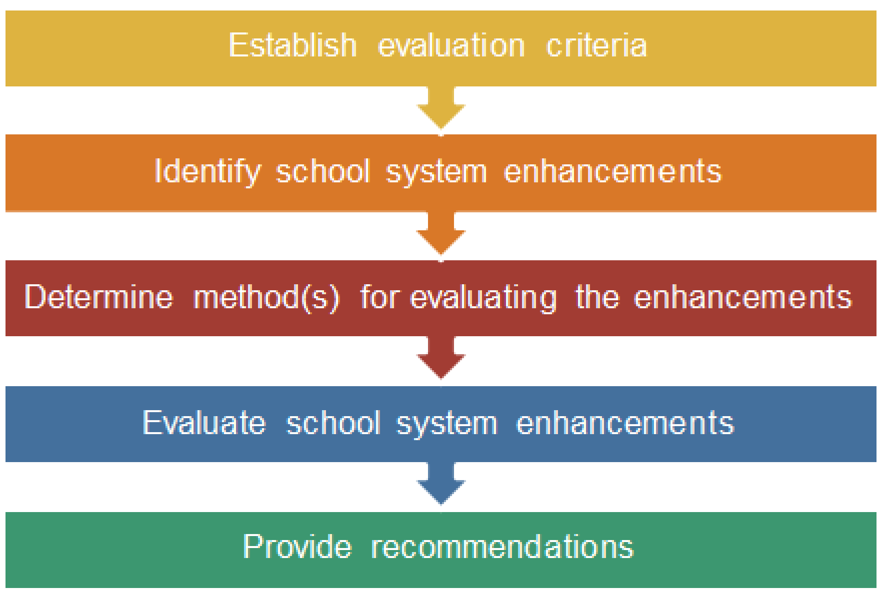

Figure 63. Framework for Evaluation

The activities leading up to this point lay the foundation to evaluate the enhancement alternatives, providing the basis for improvement recommendations for an individual school. The ultimate goal of this analysis is to illustrate the use of the ExtendSim model as a tool for analyzing alternative enhancements. We will apply the model to an example test scenario, demonstrating how school administrators can tailor the model to reflect their school's unique needs and environment. Tailoring enables more accurate simulations that local decision makers can use to make their school safer.

A. EVALUATION CRITERIA

The purpose of school system enhancements is to minimize casualties during an AS incident. As such, the primary evaluation factor – our system's sole MOE – is the total number of casualties resulting from an AS attack. This equates to the sum of occupants that end up injured or killed. A favorable enhancement is one that decreases the total number of casualties. Enhancements are also favorable if they decrease the total number of occupant deaths, but do not manage to reduce the total number of injuries.

In the previous chapter, we developed a value hierarchy to demonstrate how the enhanced system's functionality connects to performance-based objectives and measurable evaluation criteria. This hierarchy allowed us to derive several MOPs, such as Advance Warning Time and Time Required to Breach a Door. These MOPs provide decision makers information about how effectively system enhancements support specific functions. However, meeting target thresholds for individual MOPs is a means to support the overall system purpose, which is to minimize casualties. Therefore, for the analysis that follows, we will consider the effect of enhancement alternatives at a high level, treating the MOPs from the value hierarchy as inputs when simulating our test scenarios. This will indicate how enhancement alternatives that correlate to individual MOPs impact the performance of the system as a whole.

B. SELECTION OF TEST ALTERNATIVES

In the ExtendSim model, the "System-Driven Inputs" database represents system capabilities that result once schools have implemented enhancement alternatives. The effectiveness of the chosen enhancements corresponds to the assigned input values for simulation runs. For example, if school administrators have selected enhancement alternatives to increase the amount of the school's entrances they can simultaneously observe, the model user would apply a higher input value for the Percent Coverage of Building Access Points (system-driven input #3). The current version of the ExtendSim model accounts for fifteen possible types of enhancement alternatives. Table 5 lists the system-driven inputs that correspond to these enhancement alternatives, tracing these inputs to specific MOPs, design factors, and their associated top-level functions. Numbers in brackets correspond to the associated entity numbers in Figures 42 and 61, where we introduced the system MOPs and ExtendSim model inputs. Appendix B includes definitions for each of the system-driven inputs, which correspond to the enhancement alternatives in Table 5.

Table 5. Enhancement Alternatives Mapped to MOPs and Design Factors

Enhancement Alternatives	***MOP / Design Factor***	***Supported Top-Level Function***
[1] AS Advance Warning Time	[1.2.1] Advance Warning Time	[1.0] Detect Threat
[2] Equipment Threat ID % (at range)	[1.1.1] % of Actual Threats Detected	[1.0] Detect Threat
[3] % Coverage of Building Access Points	% of School Premises that is Monitored[a]	[1.0] Detect Threat
[4] Detection Probability at Access Point	[1.1.1] % of Actual Threats Detected	[1.0] Detect Threat
[5] AS Overwhelm Barrier Delay	[5.1.1] Time Required to Breach a Door	[5.0] Respond to Incident
[6] Lockdown Initiation Time	[5.1.3] Time to Initiate Lockdown	[5.0] Respond to Incident
[7] Existence of Automated External Alert	[3.2.2] Time to Send Messages	[3.0] Alert Occupants & Responders
[8] Faculty Guidance Effectiveness	[4.1.2] Percentage Accuracy of Threat Information	[4.0] Monitor Situation
[9] Faculty Medical Success Rate	[5.2.1] Time to Access Medical Kits [5.3.1] Injury Treatment Success Probability (Faculty)	[5.0] Respond to Incident

[a]Denotes design factor. Remaining items in column constitute MOPs.

Table 5. (Con't) Enhancement Alternatives Mapped to MOPs and Design Factors

Enhancement Alternatives	***MOP / Design Factor***	***Supported Top-Level Function***
[10] Equipment Threat Confirmation Time	[2.1.1] Time to Categorize the Threat	[2.0] Classify Threat
[11] Equipment Threat Notification Time	[3.2.1] Time to Verify Source [3.2.2] Time to Send Messages	[3.0] Alert Occupants & Responders
[12] Existence of On-scene Armed Responder	# of On-site Armed Responders[a]	[5.0] Respond to Incident
[13] Armed Responder Assessment Delay	[4.1.1] Time to Update Information [4.1.2] % Accuracy of Threat Information	[4.0] Monitor Situation
[14] Armed Responder Locate AS Time	[4.1.1] Time to Update Information [4.1.2] % Accuracy of Threat Information [4.1.3] % Accuracy of School Premises	[4.0] Monitor Situation
[15] Armed Responder Approach Engage AS Time	[5.4.1] Time to Neutralize the Threat	[5.0] Respond to Incident

[a]Denotes design factor. Remaining items in column constitute MOPs.

While the system-driven inputs account for the majority of the MOPs developed in the value hierarchy, there are some exceptions. The MOPs that do not directly correspond to system-driven inputs are as follows:

- [2.2.1] % Accuracy of Categorization
- [3.1.1] % Availability of the Communications
- [5.1.2] Probability That the Threat Can Breach Doors

For these MOPs, the ExtendSim model assumes values that simplify the event flow. For example, the model assumes that the AS will eventually breach an access point (MOP 5.1.2) but allows the user to determine how much time the shooter will need to do so.

Given the limitations associated with the ExtendSim model, the team determined that it would not be practical to assess the overall effects of every individual enhancement alternative. Therefore, we chose to omit several options for subsequent performance analysis and evaluation. One reason for omission was the inability of the ExtendSim model to accurately account for the effects of a certain enhancement (e.g., Faculty Guidance Effectiveness). Another basis for omission was if, as modeled, an input would not have any effect. An example of this is Equipment Threat Confirmation Time. The ExtendSim model generates an AS cue when the shooter either approaches overtly or when the system detects the shooter attempting a covert approach. The model does not differentiate between potential sources for an AS cue. Since the equipment and faculty members both respond to the same AS cues, the time required for automated equipment to process a threat indication is insignificant. Another actor will have already initiated the appropriate response. This same model limitation impacts the Equipment Threat ID % (at range) enhancement alternative. Because of this, we assume that equipment will be unable to identify potential threats at range in all of our test scenarios. In the end, we chose to explore the effects of enhancement alternatives corresponding to the following seven system-driven inputs: AS Advance Warning Time, Percent Coverage of Building Access Points, Detection Probability at Access Point, AS Overwhelm Barrier Delay, Lockdown Initiation Time, Equipment Threat Notification Time, and Armed Responder Locate AS Time.

C. METHOD FOR EVALUATING ALTERNATIVES

After determining which enhancement alternatives to analyze, we established a method to evaluate these options. It is important to note that the alternatives are not related to specific products, but instead represent capability ranges. The purpose of this analysis of alternatives is to determine the overall improvement to system performance by implementing specific categories of enhancement alternatives, as represented through the system-driven inputs. The top seven enhancement alternatives in Table 6 represent what we tested for optimization, while we did not further explore the remaining eight alternatives for the reasons described in Section B.

Table 6. Capability Ranges for Enhancement Alternatives

		Values		
	Enhancement Alternatives	***Worst case***	***Baseline***	***Best case***
Enhancements Alternatives Tested for Optimization	[1] AS Advance Warning Time (s)	0	30	300
	[3] % Coverage of Bldg Access Point (%)	0	0.7	1
	[4] Detection Probability at Access Point	0	0.5	1
	[5] AS Overwhelm Barrier Delay (s)	10	60	120
	[6] Lockdown Initiation Time (s)	∞	180	90
	[11] Equipment Threat Notification Time (s)	180	45	3
	[14] Armed Responder Locate AS Time (s)	60[a]	30	10
Enhancement Alternatives Not Tested for Optimization	[2] Equipment Threat ID % (at range) (%)	0	0	0
	[7] Existence of Automated External Alert	False	True	True
	[8] Faculty Guidance Effectiveness (%)	0	0.5	1
	[9] Faculty Medical Success Rate (%)	0	0.3	1
	[10] Equipment Threat Confirmation Time (s)	5	5	5
	[12] Existence of On-scene Armed Responder	False	True	True
	[13] Armed Responder Assessment Delay (s)	∞	60	45
	[15] Armed Responder Approach/Engage AS Time (s)	90	60	30

[a]Enhancement Alternative #14, Armed Responder Locate AS Time, excludes the time required for armed responders to approach and engage the shooter. See Appendix B for definitions.

Each enhancement alternative has three values assigned: worst-case, baseline, and best-case. The values selected for the enhancement alternatives facilitate allocation to products that either currently exist or are in development. The worst-case values indicate that the enhancement alternative is either nonexistent or is performing at a suboptimal level. For example, zero seconds for AS Advance Warning Time implies no enhancements are in place to support advanced notification, therefore the system is unable to detect a threat until the AS has already reached an access point. In some instances, the worst-case values force the model to behave in a certain way. For example, using 99,999 seconds as an input value for Lockdown Initiation Time (shown as ∞ in Table 6) delays the completion of a lockdown until after the entire simulation ends, capturing the effects of when the system fails to initiate a lockdown during the AS event. Contrary to the worst-case, the best-case values account for optimal parameters for the enhancement alternatives, such as having full coverage of school access points. Baseline values for individual enhancement alternatives capture moderate performance and provide nominal midpoints between best- and worst-case capabilities.

To evaluate the effectiveness of the enhancement alternatives, we developed and simulated ten test scenarios. These scenarios are shown in Table 7. For the first three test scenarios, we set all fifteen enhancement alternatives to their respective worst-case, baseline, or best-case value. The remaining test scenarios represent a single-factor analysis of the seven enhancement alternatives that the team selected for analysis. For these test scenarios, we set an individual enhancement alternative to its best-case value while holding the remaining 14 enhancement alternatives at their baseline. Each of the seven enhancement alternatives we tested falls into one of the following categories: Detect Threat, Alert Occupants and Responders, Monitor Situation, and Respond to Incident. Each of these categories represents a key capability gap and mirrors the top-level functions of the school system during an AS event.

We simulated the test scenarios identified in Table 7 on a notional school by defining site-specific values in the "Scenario Inputs" database of the ExtendSim model. This theoretical school has a population of 1200 occupants and an average class size of 25 students. Additionally, the average distance between classrooms is 50 feet. As a final scenario input, the chance that the AS will find an isolated occupant outside of a classroom after the lockdown is complete ranges between 5–25%. In these test scenarios, an armed on-site security responder and automated AS alert system are in place at the school; test scenario #1 is the only exception, since it represents the worst-case situation.

Table 7. Simulation Test Scenarios

Test Scenario #	Category	System Enhancement(s)	Input Value
1	N/A	All	Worst Case
2		All	Baseline
3		All	Best Case
4	Detect Threat	[1] AS Advance Warning Time (s)	Best Case
5		[3] % Coverage of Bldg Access Point (%)	Best Case
6		[4] Detection Probability at Access Point	Best Case
7	Respond to Incident	[5] AS Overwhelm Barrier Delay (s)	Best Case
8		[6] Lockdown Initiation Time (s)	Best Case
9	Communicate	[11] Equipment Threat Notification Time (s)	Best Case
10	Assess Situation	[14] Armed Responder Locate AS Time (s)	Best Case

D. SCHOOL SYSTEM ENHANCEMENTS EVALUATION

For each of the test scenarios, we applied the inputs as previously discussed and conducted 100 simulations. Each simulation provided results for the shooter's final status (killed, surrendered, or escaped) and the resultant number of casualties (injured or killed). Table 8 shows the average results of these simulation runs. The AS status results indicate the percent of simulations where each result occurred (e.g., 38% of the baseline test scenarios resulted in the shooter's death). Occupant statuses represent simple averages, with the total casualties equaling the sum of occupants injured and killed. Percentages shown directly below the occupant status results (rightmost columns in the table) indicate relative improvement as compared to the system baseline (test scenario #2).

Table 8. Comparison of Enhancement Alternatives (1200 students)

Test #	Category	Enhancement Alternatives	AS Killed (%)	AS Surrender (%)	AS Escaped (%)	Occupants Injured	Occupants Killed	Total Casualties
1	**Worst Case**	All	0	0	100	39.16	22.82	61.98
2	**Baseline**	All	38	58	4	7.60	2.80	10.40
3	**Best Case**	All	38	56	6	0	0	0
4	**Detect Threat**	[1] AS Advance Warning Time (s)	44	50	6	0 {100%}	0 {100%}	0 {100%}
5		[3] % Coverage of Bldg Access Point (%)	50	44	6	7.00 {7.9%}	2.56 {8.6%}	9.56 {8.1%}
6		[4] Detection Probability at Access Point	48	46	6	4.12 {45.8%}	1.66 {40.7%}	5.78 {44.4%}
7	**Respond to Incident**	[5] AS Overwhelm Barrier Delay (s)	56	40	4	6.82 {10.3%}	2.76 {1.4%}	9.58 {7.9%}
8		[6] Lockdown Initiation Time (s)	52	48	0	0.94 {87.6%}	0.42 {85.0%}	1.36 {86.9%}
9	**Communicate**	[11] Equipment Threat Notification Time (s)	38	52	10	6.68 {12.1%}	2.94 {-5.0%}	9.62 {7.5%}
10	**Assess Situation**	[14] Armed Responder Locate AS Time (s)	40	44	16	6.40 {15.8%}	2.20 {21.4%}	8.60 {17.3%}

Percentages in { } indicate improvement for result in the shared cell relative to baseline (test scenario #2). Negative values indicate degraded performance relative to baseline.

The results of test scenarios 1–3 provide a frame of reference for assessing the remaining seven scenarios. No single enhancement alternative should produce better or worse results than the best- or worst-case scenarios, respectively. Data that falls outside of these boundaries should be considered anomalous and requires further investigation. The baseline (test scenario #2) provides the datum against which we will compare the results of enhancement alternatives to assess their impact on overall system performance. For the baseline scenario, the AS escaped 4% of the time, leaving 7.60 occupants injured and 2.80 occupants killed with a total of 10.40 casualties.

Individual test scenario results are organized based on their corresponding enhancement category. Threat detection improvements include three optimized enhancement alternatives: AS Advance Warning Time, Percent Coverage of Building Access Points, and Detection Probability at Access Point. Maximizing the AS Advance Warning Time (test scenario #4) resulted in no occupant casualties, while the shooter only escaped 6% of the time. These results indicate an improvement of 100% over the baseline. Maximizing Percent Coverage of Building Access Points (test scenario #5) ensures that every ingress point at the school has an AS detection capability but does not guarantee successful detection. Simulations of this alternative resulted in an average of 7.00 occupants injured and 2.56 occupants killed, for a total of 9.56 school casualties. These findings revealed an 8.1% decrease in casualties compared to the baseline. Maximizing Detection Probability at Access Point (test scenario #6) provided the third best results among the threat detection alternatives. Maximizing detection probability while leaving coverage percentage unchanged resulted in 4.12 occupants injured and 1.66 occupants killed, for a total of 5.78 school casualties. This represents a 44.4% reduction in casualties over the baseline scenario.

The response time to an AS incident encompasses two system enhancement alternatives: increasing the amount of time needed for the AS to overwhelm barriers and decreasing the time required to initiate lockdowns. Increasing the time the AS spends attempting to overwhelm a barrier (test scenario #7) resulted in 6.82 occupants injured, 2.76 occupants killed, and 9.58 total casualties. The number of casualties decreased by 7.9% in comparison with the baseline test scenario. Minimizing Lockdown Initiation Time (test scenario #8) resulted in an average of 0.94 occupants injured, 0.42 occupants killed, and 1.36 total school casualties. This represents a decrease of 86.9% in the overall casualties.

We analyzed one enhancement alternative related to alerting responders and occupants – the Equipment Threat Notification Time. By minimizing the amount of time for the equipment to provide an alert (test scenario #9), the resulting number of occupants injured was 6.68, the number of occupants killed was 2.94, and the total number of school casualties was 9.62. For this test scenario, the number of occupants killed increased by 5% from the baseline value of 2.80. This anomalous result, implying that adding an enhancement could lead to more deaths, suggests that the difference in results between the baseline and test scenario #9 may not be large enough to be statistically significant. Conducting more runs for the test scenarios would potentially yield slightly higher averages for the baseline and ensure that the average results for each enhancement alternative reflect improvement, as expected.

To address the impact of enabling assessment of the AS situation, we used our model to analyze one supporting enhancement alternative: minimizing the time it takes the armed responder to locate the AS (test scenario #10). Minimizing this amount of time resulted in 6.40 occupants injured, 2.20 occupants killed, and 8.60 total casualties. Compared to the baseline scenario, the overall number of casualties decreased by 17.3%.

Overall, we believe this model is especially useful for predicting the effect of individual enhancements on the resultant number of casualties. However, the model still requires further refinement in predicting whether armed responders stop the AS or if the AS escapes. For the notional school that our test scenarios represent, the most effective enhancement alternatives were those that allow the system to maximize AS Advance Warning Time, minimize Lockdown Initiation Time, and increase Detection Probability at Access Points. Figure 64 shows the relative improvement of each alternative in comparison to the baseline test scenario. Maximizing AS Advance Warning Time proved to be the most critical factor, with a 100% improvement in overall casualties. Increasing the amount of time that the system was aware of a threat before the AS gained access was the best way to minimize the casualties since it allowed the school to respond before the AS had a chance to shoot any occupants. The next best enhancement was reducing the Lockdown Initiation Time once a threat was detected, with an 86.9% reduction in total casualties. Completing lockdowns faster decreased the amount of time during the attack when the AS could directly shoot large groups of students. Finally, increasing the Detection Probability at Access Points showed a 44.4% improvement in resultant casualties. Maximizing detection at school access points provided additional time for the system to initiate lockdown before the AS entered the school, thereby reducing the amount of occupants that the shooter could engage directly.

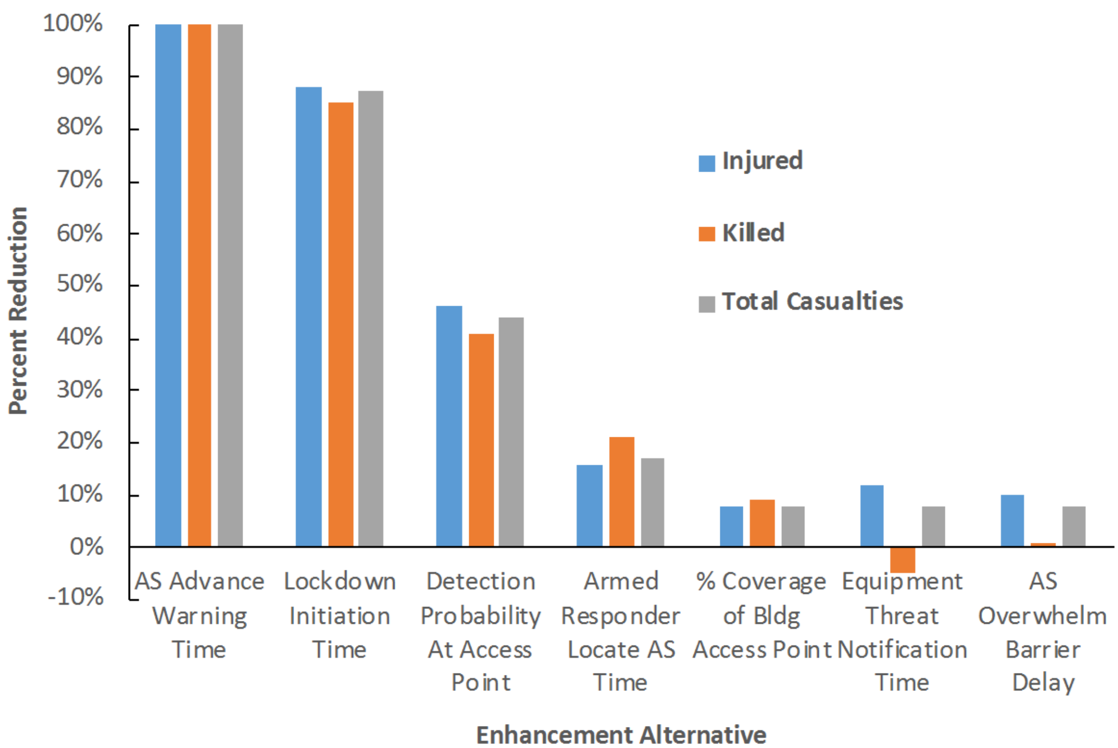

Figure 64. Percent Improvement of Enhancement Alternatives Relative to Baseline

The test scenarios presented show the results of implementing various enhancements for a notional school system. Every school has unique components that apply to its environment, therefore, the optimal improvements for one school may not be ideal for another. By adjusting the model's inputs to match the specifications of their own schools, decision makers can execute tests similar to those presented in this section. The decision makers can then use the results to determine which enhancement alternatives would be most effective.

E. EXPLORATION OF PHYSICAL SECURITY ALTERNATIVES

Many products are available to schools that may improve their ability to counter active shooters. We based our initial exploration of products on the results of the test scenarios. To support threat detection, existing solutions such as armed security responders patrolling the school premises, metal detectors, and x-ray machines that scan individuals and their belongings are options to support identifying the AS before he commences his attack. Emerging technology will also support threat detection. Scientists and engineers are developing an artificial intelligence (AI) that can work with commercial off-the-shelf (COTS) security cameras to detect and confirm threats. Deep North is one company developing AI technology to identify weapons, analyze threatening behavior, and send out automatic alerts when a threat is detected. Although AI is still in its infancy, school districts in Texas, Florida, and California are experimenting with AI-powered security systems. AI can be harnessed to aid in identifying threatening behavior and physical distress in individuals (Wiggers 2018).

Lockdown initiation time directly impacts survivability during an AS incident. Training with school faculty, staff, and students can expedite this process, but hardware solutions are available that can improve both lockdown initiation speed and lockdown effectiveness. An example is the Door Lockdown Device, shown in Figure 65, which its user can operate during an incident within five seconds (Door Lockdown Device n.d.). The Door Lockdown Device protects classrooms and office spaces from individuals trying to breach the door.

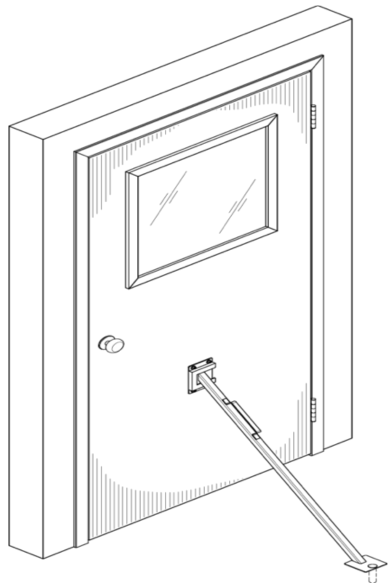

Figure 65. Door Lockdown Device. Source: Door Lockdown Device (n.d.).

Although the enhancement we categorized under Alert Occupants and Responders did not result in a significant casualty reduction compared to the baseline case, communications was a significant capability gap identified in our needs analysis. The Active Shooter Response System (ASR), shown in Figure 66, is a solution that helps fill that void (ASR Alert Systems n.d.). The Jupiter police department in Palm Beach, Florida, invested in this technology, which incorporates the use of text messaging, email, and strobe alerts to notify specific individuals or groups of people automatically (DiPaolo 2018). This functionality directly supports several system enhancement alternatives that the capstone team did not explore through test scenario simulations (e.g., the existence or absence of an automated alert system), while indirectly facilitating others. For example, rapid dissemination of threat information within the school will help expedite the lockdown process and help armed responders locate and engage the AS faster.

Figure 66. ASR Threat Alert System. Source: ASR Alert Systems (n.d.).

F. CHAPTER SUMMARY

In our analysis of alternatives, we focused on modifying the system parameters in ExtendSim to simulate AS events and observed the results. The results allowed us to determine which alternatives would yield the greatest impact on casualty reduction. To accomplish this, we established a single-factor evaluation criterion that focused on the overall goal of reducing casualties during an AS event. We then determined which system-driven inputs in our ExtendSim model could support our analysis, created a series of test scenarios, and then executed these scenarios based on a notional school environment (test scenario). With this analysis, we demonstrated the utility of our ExtendSim model in supporting decision makers when applied to a unique school setting. Finally, we identified a few current products, such as the Door Lockdown Device or the ASR, that support the enhancement alternatives that our simulations indicated would be most beneficial.

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V. CONCLUSIONS AND RECOMMENDATIONS

In this thesis, the capstone team demonstrated the use of a systems engineering approach to aid United States K-12 institutions in countering the AS threat. After an AS attack, the natural tendency is for people to rush to an answer without fully analyzing the problem itself. The proposed answers are frequently driven by bias instead of supported by evidence or scientific rigor. Applying the systems engineering process and treating the school and its occupants as a system, we avoid this tendency by examining the problem as a whole, then identifying the necessary functions and capabilities that will enable the system to minimize casualties resulting from an attack.

A. SUMMARY OF PROCESS

We began by reviewing several case studies of school shootings to ascertain commonalities among AS events and to identify capability gaps in the system's ability to counter the shooter. We interviewed stakeholders to determine the shortfalls in school security measures. We used their inputs to define the system's effective needs. From this, we analyzed an AS attack from two opposing perspectives: the shooter's, as seen through a success tree that explores how the shooter maximizes the number of occupants he can kill, and the system's, shown through a fault tree analysis that determines how system failures at various levels allow the shooter to kill occupants. Conducting these interviews and perspective-based analyses allowed us to further refine our understanding of the problem space.

We then defined the operational concept to portray how the system, once enhanced to rectify these gaps, will leverage its capabilities and interaction with external assets to counter an AS attack. Afterwards, the team developed a functional decomposition, which illustrated the top-level functions and supporting sub-functions for the enhanced school system. Next, the team developed a value hierarchy to associate these system functions with objectives and measures of performance that decision makers can use to assess the effectiveness of the enhanced system.

With the primary system functions and assessment metrics identified, the team developed a behavior model in Innoslate to illustrate the system's desired actions during an AS attack. In this behavior model, we depicted the overall event flow by allocating key system functions to individual actors inside and outside the system boundary. We then transposed the behavior model to ExtendSim in order to simulate the effectiveness of various school system enhancements in minimizing occupant casualties during an AS attack.

To demonstrate traceability between the ExtendSim model and the system architecture, the team mapped fifteen system-driven inputs to system MOPs and top-level functions. Due to model limitations, we could not test enhancement alternatives that support every one of the system MOPs. We selected seven enhancement alternatives to test after omitting those that the model could not adequately represent. We simulated the behavior of systems that incorporate these alternatives and conducted a single-factor analysis to compare their respective effectiveness to each other and to a baseline reference. For this analysis of alternatives, we defined a notional school scenario and identified applicable assumptions affecting simulation inputs. By incorporating school-system specific specifications as simulation inputs, decision makers can use the tailored process model to determine which enhancements will be most effective for their school.

B. RECOMMENDATIONS FOR FUTURE WORK

Through the extensive research and analysis conducted for this capstone, we created a model that simulates an AS event and allows decision makers to compare enhancement alternatives. However, further work is needed to develop this model before it will be ready for widespread implementation. We recommend the following efforts to further improve the fidelity and credibility of the model, ultimately making it a reliable tool to support the decision-making process.

1. Creation of a Centralized Database

The capstone team collected a significant quantity of data to support initial development of the model. Through this process, it was apparent that no centralized database exists that consolidates key attributes and statistics for AS events at United States

K-12 schools. These attributes include items such as school data (e.g., population, layout, existing security measures), the weapon used during the attack, response times for external support, and effectiveness of security measures. A centralized database ensures this type of information is readily available, which will assist in continual verification and validation of the model. Such a database would also highlight any new trends that alter the paradigms of an AS attack and provide justification to modify the assumptions that drove the architecture we created for this system.

2. Prototype Testing of Potential Solutions

For the test scenarios that we used to evaluate our model's utility, the team chose to apply nominal capability ranges as simulation inputs. However, with specific test data to use for model inputs, it is possible to simulate the effects of specific technical solutions. Isolated, prototype-style testing will provide valuable data about how each potential solution affects its related MOP without requiring large-scale event simulations. For example, testing the Door Lockdown Device described in the previous chapter will show how its use reduces lockdown initiation time.

3. Model Validation through Live Simulation

Despite the prevalence of school shootings in the United States, specific information available about these shootings is limited to general overviews. This is due, in part, to the inherent sensitivity of the topic and lack of data collection methods. Fine details, such as event timelines and periodic snapshots representing occupant statuses, are generally absent in the literature. While our event model represents the logical flow of an AS attack, we were unable to directly validate the model through comparison to the progression of an actual event. Live simulations of an AS attack, using non-lethal weapons (e.g., paintball guns) and conducted under close observation, would provide critical statistical data necessary for model validation.

4. Model Improvements

Although the ExtendSim model captures the key activities during an AS event, as well as the effect of school system enhancements, there are assumptions and limitations to the model, as highlighted in Chapter III. Improving the model so that it accounts for the following real-life factors will enhance its utility:

- *Diverse K-12 school layouts:* Schools across the nation have a variety of layouts, ranging from single-buildings to sprawling complexes with unequally-spaced classrooms. Improving the model to account for more complicated layouts will increase its utility.

- *Distribution of school occupants:* Depending on the time of the day when an AS attack occurs, the location of school occupants will differ. For example, during lunch time, most of the students will be in cafeterias instead of classrooms. The shooter's effectiveness at killing occupants can change based on the actual distribution of occupants during the attack. Accounting for these alternate occupant distributions will allow decision makers to determine how the effectiveness of enhancements may change throughout the school day.

- *Advanced behavior for system actors:* The ExtendSim model includes complex interactions between the actors involved when the AS event is in its imminent, in-progress, and recovery phases. Modifying the faculty's ability to treat injured occupants based on their location relative to injured personnel, rather than assuming faculty have access to all injured occupants, will enhance the accuracy of the simulations.

5. Advanced Test Methods

The capstone team adjusted the model inputs to determine how associated enhancements would improve resultant casualties, but we assessed these effects in isolation and did not explore interaction effects - either detrimental or beneficial. Realistically, enhancements that improve one MOP can simultaneously reduce the system's performance for another MOP. For example, access restrictions are beneficial in that they reduce the shooter's mobility, but they also reduce the occupants' ability to escape. Therefore, we recommend investigating the trade-offs that correspond to system enhancements that affect multiple MOPs in order to find optimized values when MOP are coupled. Additionally, future ExtendSim testing should include multi-factor analysis. As multiple system-driven inputs affect each area of interest (e.g., threat detection, lockdown time, and responder notification time), the team recommends a design of experiments that will explore multiple inputs at once. Doing this will reveal the constructive interaction between input factors, which will identify emergent qualities and support design recommendations.

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APPENDIX A. INTERVIEW QUESTIONS

Questions posed to school staff/administrators:

1. Are there any programs, positions, and/or physical security measures that the school has investigated but chosen *not* to implement for any reasons (e.g., funding, ethical or political reasons), and why?

2. How does the school prepare for an active shooter incident across various roles? What actions are different faculty members and students expected to take?

3. During an active shooter incident, what is the school's response protocol (e.g., lockdown, notification to local authorities, guiding students outside the buildings)?

4. What is the school's emergency response plan? Was it created at the school level, district or state?

5. Has the school conducted active shooter response drills, and if so, what deficiencies have been noted as a result (e.g., communications delays, breached/bypassed access points)?

6. Has the school hosted or conducted joint training with local law enforcement or other organizations?

7. Does the school have any measures in place to detect concealed weapons on school property?

8. What school protocols have changed based on lessons learned from active shooter incidents or drills (whether internally or drawn from outside situations)?

9. In the event of an active shooter incident, who is authorized to initiate emergency protocols and what technology is utilized to update faculty, staff, and law enforcement as the situation progresses?

10. Any additional information that might be helpful?

Questions posed to private security professionals:

1. What types of private security solutions and services have schools/districts requested? What technical solutions have they rejected, and why?

2. Does your [firm, company, organization] conduct active shooter training with local schools? If so, how often, or why not?

3. Has your [firm, company, organization] conducted a physical security assessment of local schools – such as noting the locations and physical characteristics of entrances?

4. What services offered to K-12 institutions are being revamped based on lessons learned from recent school shootings?

5. What are the common security technology gaps that exists in K-12 schools?

6. What are the most effective security solutions that are currently recommended for schools?

7. What technological solutions could be implemented to detect possible threats approaching the school and prevent access, while still maintaining the approachability and comfortable appearance necessary for a learning environment?

8. What technological solutions, if implemented, would enable faculty and staff to minimize the risk of injury or death *after* a shooter has already gained access to the facility?

9. What barriers (such as fire codes) have been encountered that prevent the implementation of a theoretically “ideal” security system?

10. Any additional information that might be helpful?

Questions posed to law enforcement officials:

1. What is the current active shooter protocol during and after an incident?

2. What difficulties have been encountered during active shooter events or drills?

3. What tools/systems, if implemented at individual schools, would augment law enforcement response capabilities? What effect would these tools have?

4. How do police agencies utilize technology to enhance their response to an active shooter? How is technology used for training the officers (i.e., simulations, drills, etc.)?

5. Any additional information that might be helpful?

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APPENDIX B. DATABASE TABLES

The ExtendSim model uses four databases to support simulation input and to record results. The databases are scenario inputs, system-driven inputs, key event times, and event results. The following lists define the values associated with each table, with the names in quotation marks showing the exact verbiage used in the model.

Scenario Inputs:

1. "School Population" – the total number of occupants (students, faculty, staff, on-site armed responders) present during a normal school day.

2. "AVG # per class" – the average number of occupants in a classroom during a normal class period.

3. "AVG Distance btwn classes" – the average distance between two adjacent classrooms on the same floor of the school.

4. "Mean Armed Response Time (non-organic responder)" – predicted average response time for local armed emergency response personnel (excludes any on-site responders).

5. "Mean Medical Response time (non-organic)" – predicted average response time for local emergency medical responders (excludes any on-site responders).

6. "Time for prof. med responder to prioritize" – expected amount of time required for a professional medical responder to perform triage before beginning treatment on the highest-priority victim.

7. "Mean time for professional med treatment" – expected amount of time required for a professional medical responder to provide treatment to an injured occupant.

8. “min pIsolatedOccupant” – minimum probability that an occupant will be outside of a secured area once the school has initiated a lockdown.

9. “max pIsolatedOccupant” – maximum probability that an occupant will be outside of a secured area once the school has initiated a lockdown.

System-Driven Inputs:

1. “AS Advance Warning Time” – amount of time available before the AS reaches an access point that the school is aware of the potential threat; corresponds to detection range.

2. “Equipment threat ID % (at range)” – probability that the system will detect an AS before the shooter reaches an access point.

3. “% coverage of bldg access points” – percentage of access points at the school with the means to detect an AS.

4. “detection prob at access point” – probability that an access point with the means to detect an AS will successfully do so.

5. “AS Overwhelm Barrier delay” – expected amount of time required for an AS that the system has detected to overcome access-control security measures intended to keep the shooter out of school buildings; does not apply to barriers within the school that separate classrooms.

6. “Lockdown initiation time” – expected amount of time required for the system to complete lockdown of all internal rooms; does not guarantee that all personnel are within a secure space.

7. “Existence of automated external alert” – true/false value that indicates whether the system can automatically transmit an alert to external responders without user input.

8. “Faculty Guidance Effectiveness” – measure of how likely faculty guidance is to minimize the probability of an isolated occupant, based on a

linear function (i.e., if minimum and maximum isolation probabilities are 5% and 25%, and effectiveness is 50%, resultant probability of an isolated occupant equals 15%).

9. “Faculty medical success rate” – expected probability that a faculty/staff member will be able to stabilize a gunshot victim (i.e., the wounded occupant remains injured but will not die before being transported to a hospital).

10. “Equipment Threat Confirmation time” – expected amount of time required for installed equipment to classify a potential threat as an actual threat.

11. “Equipment threat notification time” – amount of time required for automated alert equipment (if installed) to process and transmit data to external responders.

12. “Existence of on-scene armed responder” – true/false value that indicates whether system enhancements include the presence of a dedicated on-site armed responder who is capable of responding to an AS attack.

13. “ArmedResponder assessment delay” – expected amount of time for an armed responder to assess the situation prior to entering the school and finding the shooter.

14. “ArmedResponder locate AS time” – expected amount of time for the shooter to determine the shooter’s general location within the school, after the armed responder has already enter the building.

15. “ArmedResponder Approach_Engage AS time” – expected amount of time for armed responders to navigate throughout the school to the shooter’s location; dependent on system enhancements that improve the responders’ situational awareness and familiarity with the school layout.

Key Event Times:

1. “AScue0Status” – indicates whether the AS provided an overt cue prior to reaching an access point at the school.

2. “AScue0Time” – indicates the simulation time when the shooter produced an early cue.

3. “AScue1Status” – indicates whether the AS provided an overt cue at an access point (to include system detection).

4. “AScue1Time” – indicates the simulation time when the shooter produced a cue at an access point.

5. “AScue2Status” – indicates whether the AS provided an overt cue once already inside the school; this value should always be “true,” unless the simulation times out before the shooter can access the school.

6. “AScue2Time” – indicates the last simulation time when the shooter produced a cue while inside the school; this time is overwritten during every iteration of the the shooter’s attack loop.

7. “FacultyAwareTime” – indicates the simulation time when faculty/staff observed the shooter’s cue or received a notification from monitoring equipment.

8. “LockdownCompleteTime” – indicates the simulation time when the school lockdown was complete.

9. “ArmedResNotifyTime” – indicates the simulation time when armed responders received notification about the AS.

10. “ArmedResOnsceneTime” – indicates the simulation time when armed responders arrived on site.

11. “ASengagedTime” – indicates the simulation time when armed responders engaged the AS.

12. “ASneutralizedTime” – indicates the simulation time when armed responders neutralized the AS or when the AS escaped the school.

13. “MedResNotifyTime” – indicates the simulation time when external medical responders received notification about the AS.

14. “MedResOnsceneTime” – indicates the simulation time when external medical responders arrived on site.

Event Results:

1. “AS Killed” – indicates whether the current simulation run resulted in the AS’s death.

2. “AS Surrendered” – indicates whether the current simulation run resulted in the AS surrendering to armed responders.

3. “AS Escaped” – indicates whether the current simulation run ended with the the AS leaving the school (i.e., escaped from armed responders or armed responders never engaged AS).

4. “OccupantsUnharmed” – indicates the number of school occupants that were not injured or killed.

5. “Occupants Injured” – indicates the number of school occupants injured, but alive, at the end of the simulation; accounts for both occupants who received life-threatening injuries but received adequate treatment and occupants whose injuries were not life-threatening.

6. “Occupants Killed” – indicates the number of school occupants that the AS killed.

7. “AS Movement Time(post entry)” – records the total amount of time, after gaining access to the school building, that the shooter spent moving between classrooms.

8. “AS Attacking Time” – records the total amount of time, after gaining access to the school building, that the shooter spent attacking occupants.

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