Proceedings of the 2021 Winter Simulation Conference
S. Kim, B. Feng, K. Smith, S. Masoud, Z. Zheng, C. Szabo and M. Loper, eds.

INVESTIGATING AN ACTIVE SHOOTER DEFEAT SYSTEM WITH SIMULATION AND DATA FARMING

Charles V. Lovejoy

Recruiting Command
United States Army
Fort Knox, KY 40121, USA

Mary L. McDonald
Thomas W. Lucas
Susan M. Sanchez

Department of Operations Research
Naval Postgraduate School
Monterey, CA 93943, USA

ABSTRACT

This research uses simulation and data farming to explore and quantify the effectiveness of an active shooter defeat system at reducing fatalities over a breadth of conditions. An agent-based simulation is created to model a hypothetical active shooting event at a school building in West Point, New York. The simulation is data farmed to explore factors that influence the number of fatalities with and without the employment of a prototype active shooter defeat system known as the "Joint Active Shooter Protection and Response" (JASPR) system. Factors explored include the shooter's entry point, whether the shooter suicides, the shooter's rate and accuracy of fire, the number of bystanders in each section of the building, post-dispatch response time, and whether JASPR is present. Based on 45,000 simulated active shooting events, our results suggest that a well-designed system can significantly reduce fatalities. We present the conditions under which JASPR may be most effective.

1 INTRODUCTION

Active shootings have become increasingly common in the United States, and as the number of active shootings has increased, so too has their associated casualty count (Blair and Schweit 2014). A number of efforts have proposed solutions to counter this increase. Some model-based study approaches include stochastic simulation (Abreu et al. 2019; Gunn et al. 2017; Beaudwin et al. 2018), contagion modeling (Towers et al. 2015), closed-form equations (Sporrer 2020), and agent-based simulation (Anklam et al. 2014; Hayes and Hayes 2014; Briggs and Kennedy 2016; Stewart 2017; Lee et al. 2018; Xi and Chan 2019). Other studies (e.g., Ergenbright and Hubbard 2012; Graves 2018) have suggested implementing a system designed to detect and defeat an active shooting once such an event has started. Simulating an active shooter defeat system in the context of an active shooting event (e.g., Gunn et al. 2017; Beaudwin et al. 2018) is less common. Our primary contribution is to investigate the utility of a prototypical active shooter defeat system using agent-based simulation (ABS) coupled with large-scale data farming (Sanchez and Sanchez 2017).

ABS provides us with a useful tool for simulating active shooter defeat systems. There are several advantages to this approach. We can specify and explore a diverse set of entity motivations, behaviors, and capabilities during a simulated shooting. Simulation complements costly and limited live exercises involving subjects playing scripted roles. With simulation, it is feasible to investigate varied behavior patterns by entities at the individual or group levels. We can conduct thousands of efficiently designed experiments via data farming, enabling us to achieve broad and potentially unexpected insights into active shootings and defeat systems. Moreover, these experiments can be replicated numerous times so that we can measure and understand variability. Finally, using simulation, we can handle complex spatial and temporal relationships without needing to make restrictive simplifying assumptions, as is often required to obtain closed-form solutions (Lucas et al. 2015).

This paper describes results of a study of an active shooter defeat system called the "Joint Active Shooter Protection and Response" (JASPR) system. JASPR uses a variety of sensors, communication links, and smart devices to enable early detection and rapid response when an active shooting commences, as well as providing measures to protect potential victims. The main purposes of this system are to reduce the time required to alert bystanders and to notify and orient first responders to the presence of an active shooter. To evaluate this project, the Department of Defense (DoD) conducted a live exercise using a JASPR prototype at the U.S. Military Academy Preparatory School (USMAPS) in West Point, New York. In tandem, and to supplement what was learned in the live exercise, the DoD requested modeling and analysis assistance from the Naval Postgraduate School's Simulation Experiments and Efficient Designs (SEED) Center for Data Farming (https://harvest.nps.edu).

2 SIMULATION MODEL

This section describes the main features of the simulation developed and used as the basis for data farming.

2.1 Modeling Environment

Pythagoras is the government-owned, stochastic, time-stepped, agent-based modeling environment we used to create our active shooter simulation scenario. Pythagoras was originally developed by Northrop Grumman for the U.S. Marine Corps as a medium-resolution simulation environment for use in modeling tactical military operations. Due to its modularity and flexibility, it was easily adapted for simulating an active shooter incident. The modeling environment captures key aspects of terrain as well as agent behavior and movement, agent resources and attributes, and agent-to-agent interactions and communication.

Pythagoras's agent-based environment allows multiple individual entities to make decisions while interacting with each other and the environment based on their local situational awareness, using organic sensors and communication links, as well as behavioral rules that can adapt as a function of triggering events. Leader agents can give orders to subordinate agents, and subordinates may respond in a heterogeneous fashion, i.e., some may not follow the order or may attempt to follow the order but with varying speed or effectiveness. Further details about Pythagoras can be found in Henscheid et al. (2006).

2.2 Agent Types, Behaviors, and Triggers

Pythagoras users define agent classes as groups of entities holding initially similar physical and behavioral characteristics while accommodating a degree of stochastic heterogeneity within agent classes. The agent classes used in our model include the active shooter, the bystanders (students, faculty, staff, etc.) within the building, the first responders, and the active shooter defeat system components.

During each simulation run, the active shooter agent traverses a predetermined path of waypoints, with some stochastic variability over how closely the path is followed, and with some autonomy to move off the path to shoot or move toward bystanders.

Bystander agents in the simulation are placed randomly within different sections of the building, and their concentration within each section is varied in our experiments. When alerted to the presence of an active shooter, bystanders attempt to seek cover or run. Without a clear signal alerting them to the presence of an active shooter, bystanders may believe a fire drill is occurring and pour into a hallway. Alternatively, they may carry on as usual until the active shooter is closer to their location, at which point the sound of gunshots and/or bystander responses becomes unmistakable.

First responder agents enter the building from a main door located in the northwestern section of the building. If the active shooter defeat system is present, they move directly to the active shooter's position. The first responders carry a smart device loaded with building floor plans that receives updates on the shooter's location from live camera feeds and gunshot detectors. However, if the active shooter defeat system is not present, first responders proceed in the general direction of the active shooter, though at a slower pace and with some possibility for error, relying more on what they can see or hear and their ability to communicate with each other.

JASPR's components are also modeled as an agent class and include: (1) alert beacons that generate an unambiguous audible tone (so as not to be mistaken for a fire alarm), (2) marquees that display textual information, (3) pan-tilt-zoom cameras that can be remotely controlled, (4) gunshot detectors, (5) panic buttons that can be pressed to activate the system, and (6) remotely enabled, selectively controlled, door locks. Many of these components are networked and designed to aid in a collective response to the presence of an active shooter. For example, a bystander may activate the nearest panic button if they recognize hostile intent prior to the first gunshot, or the panic button may serve as a backup when a gunshot detector is unable to detect a gunshot signal. Additionally, the camera feeds and building floor plans are accessible to the first responders in real time, even while en route to the location. JASPR may also inhibit the shooter's progress by automatically closing and locking doors after a gunshot detector registers a gunshot.

One of Pythagoras's most powerful features is its ability to "trigger" the agents just described into pre-defined alternate behaviors, based upon the occurrence of a triggering event. This feature allows entities to adapt their physical and behavioral attributes in response to what they perceive via their own sensors, such as their eyes, or via communication links. For example, at the start of the simulation, first responders are not aware of any reason to dispatch. However, in cases where the defeat system is employed, the shooter firing his weapon triggers the gunshot detector to send an automatic emergency alert to the building's alert beacons and first responders. This communication triggers a behavioral state change in both the first responders and the bystanders who hear the signal from the beacon. When triggered, the first responders are dispatched to the area and begin their travel time. The bystanders are triggered to either take cover within rooms whose doors have been locked, or they attempt to escape through an egress point if in a large open area such as the cafeteria. If a remote-control camera sends a communication to first responders, the first responders enter a behavior in which they can move more quickly and efficiently to the active shooter since they have access to a tablet with the building's layout as well as the camera feed. A snapshot portion of Pythagoras's graphical user interface where alternate behaviors are created is shown in Figure 1.

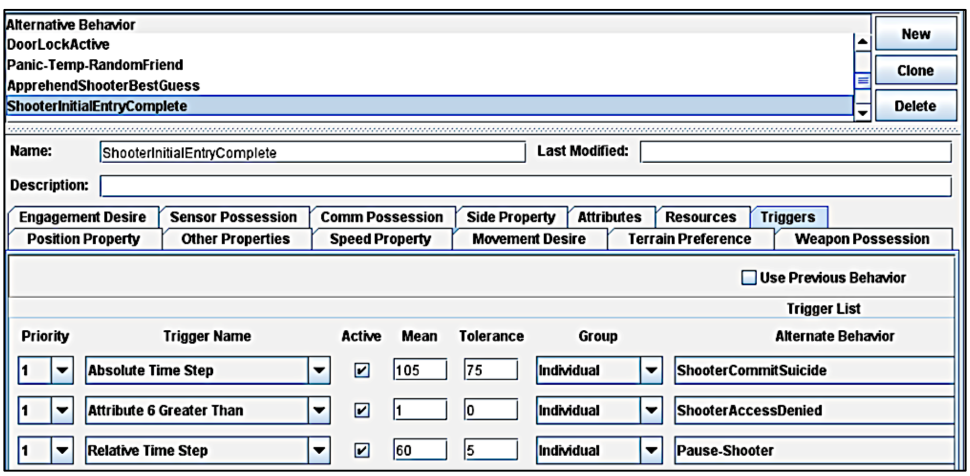

Figure 1: Pythagoras' graphical user interface allows users to define triggering events.

Figure 1 highlights in blue a behavior entitled *ShooterInitialEntryComplete*, which reflects the active shooter's entrance to the building, weapon at the ready, with the shooter actively seeking potential victims. From the selected *Triggers* tab for this behavior, there are three possible triggering events that cause the shooter to assume a different alternate behavior.

The first trigger name, *Absolute Time Step*, represents the passage of time in absolute terms, referring to the time on the simulation clock. For simulation runs with a shooter suicide, when the time step reaches a value drawn from a uniform (30, 180) distribution, the shooter suicides. In this simulation, one time step represents two seconds, so the shooter suicides at a time between one and six minutes. For runs in which the shooter does not suicide, the uniform distribution's mean value and "tolerance" (Pythagoras terminology for the plus and minus value around the mean that defines the lower and upper limits of the uniform) are set such that the event will not occur.

An alternate way out of the *ShooterInitialEntryComplete* behavior, with trigger name *Attribute 6 Greater Than*, occurs if the shooter receives at least one unit of "*Attribute 6*", which happens when the automatic door locks are activated. Generic "attributes" in Pythagoras provide flexibility to modelers in controlling agents' behaviors and capabilities. They are often used to capture some type of symbolic interaction that would trigger an agent into an alternate behavior.

A final possible triggering event is *Relative Time Step*, signifying the passage of relative time since the shooter entered the *ShooterInitialEntryComplete* behavior. Here, the shooter is triggered into a *Pause* behavior every 60 time steps, or every two minutes, representing the shooter pausing travel along their path to look around and refocus on engaging individual targets for a brief period of time. The alternate behavior that the triggering event sends the shooter to in each case is shown in the Alternate Behavior section. For example, if "attribute 6" is received, indicating that the automatic door locks have been activated, then the shooter will trigger into its *ShooterAccessDenied* alternate behavior (not shown here), in which their ability to pass through locked doors is curtailed.

2.3 Map / Playboard

The second floor of the USMAPS building at West Point, NY provides the physical backdrop for the simulation scenario – as it did for the live exercise to which the simulation is calibrated to. The building contains three different sections, multiple entrances and exits, two sets of stairwells, and corridors. Each section is defined by a unique configuration of walls and open space. The three sections are (1) classrooms, (2) cafeteria with kitchen, and (3) dormitory rooms. Figure 2 illustrates this layout, with the classrooms, cafeteria and kitchen, and dormitory rooms highlighted in blue, green, and purple, respectively with possible entrances and exits into the building highlighted in neon green.

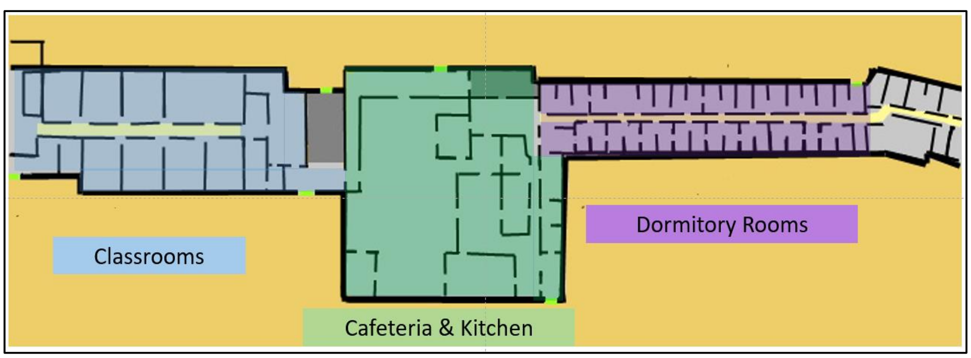

Figure 2: The three sections of the 2nd floor of the USMAPS building.

The cafeteria occupies a central location and is the largest room within the building. Together with the kitchen area in the lower right corner of the central space, it holds the potential for the largest groups of people to congregate. There are two possible cafeteria ingress/egress locations, one at the top of Figure 2 and one at the bottom. For all simulation runs where the active shooter enters the building via the cafeteria, ingress occurs from the top entry point. Bystanders can attempt to escape through either egress point.

The dorm rooms are the smallest in the building, with the least potential for large groups to congregate, and are composed of visually and (mostly) audibly-isolated rooms. They are connected by a single long hallway. Just one ingress/egress exists for the active shooter, located at the far right side of the dorm rooms.

The classrooms are located on the left side of the map, and provide a middle-ground between the cafeteria and dorm rooms, with respect to potential for groups to congregate, population density, and room size. For the runs in which the active shooter enters via the classroom section of the building, they enter at the far left end of the classroom hallway.

The DoD JASPR team designated where to place individual JASPR components, and these locations are depicted with a legend in Figure 3.

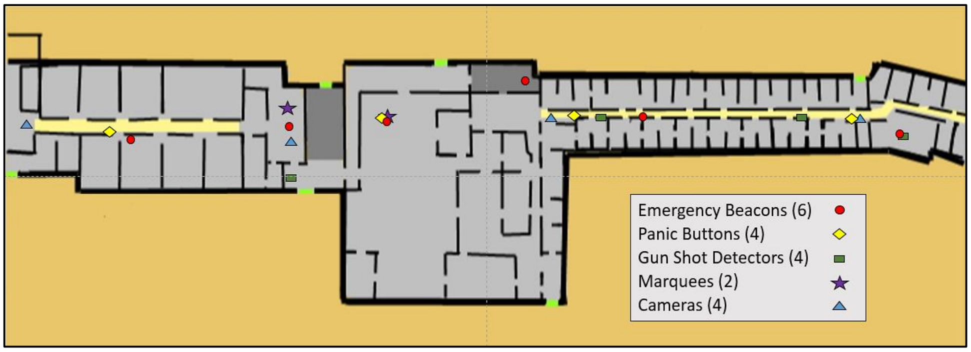

Figure 3: Locations of the JASPR active shooter defeat system components.

3 DATA FARMING THE ACTIVE SHOOTER SIMULATION

Data farming is a metaphor for generating simulation data through designed experiments. The use of large-scale efficient experimentation allows us to effectively "grow" simulation output data, enabling the discovery of broad and rich insights that would otherwise be unobtainable. The first step in designing an experiment is determining the factors to be varied and their respective ranges or levels.

The eight factors listed in Table 1 were varied in order to quantify their effect, individually or together, on the main response of interest, *Total Deaths*. The table includes the range (if numeric) or levels (if categorical) over which each factor was varied. For example, the first factor represents the active shooter (AS) entrance location, with levels of West (classrooms), Central (cafeteria), or East (dorms).

Table 1: Factors varied during simulation.

	Factors	**Minimum**	**Maximum**	**Levels (categorical)**
1	*AS Entrance Location*	-	-	West, Central, East
2	*AS Suicide*	-	-	Yes, No
3	*JASPR Presence*	-	-	Yes, No
4	*AS Firing Rate*	45 rnds/min	60 rnds/min	-
5	*AS Probability of hit*	0.25	0.75	-
6	*Bystanders in Cafeteria*	10 people	240 people	-
7	*Bystanders in Classrooms*	0 people	40 people	-
8	*First Responder Response Time*	0 min	30 min	-

We took care to use valid and reasonable ranges and levels for our factors. We were fortunate to be able to personally walk through the interior of the USMAPS building at West Point and verify that our simulated model matched the physical layout of the school, as well as verify room occupancy limits for the cafeteria and typical student seating in the classrooms. We obtained several months of data on first responder response times at West Point from the military police. We also relied heavily on prescribed rates of fire for the DoD standard issue M4 carbine, including a rapid semiautomatic firing rate at 45 rounds/min (United States Army 2016), and reasoned that 60 rounds/min was the upper threshold for effective, aimed, automatic fire, though 700-900 rounds/min is the hypothetical maximum automatic firing rate for the M4 (Army Technology, 2021; Global Security, 2021).

There are two other model characteristics that are not held constant across all simulation runs, but are functions of other input factors. We fixed the total population at 340, and all bystanders not initially placed in either the cafeteria or the classrooms are initially placed in the dorm rooms. We also consider the cognitive delay, i.e., the time required for bystanders to recognize that an active shooter is in the area. We set the cognitive delay to 0.0 seconds if JASPR is present, otherwise it is uniformly distributed between 0 and 30 seconds. The 0.0 cognitive delay assumption was based on the fact that the activation of the JASPR gunshot detector or the pressing of a panic button immediately sends a signal to the dispatch center, but this could certainly be treated stochastically or varied in a future experiment.

The factors are systematically varied via a designed experiment. We start with a full factorial for the three categorical factors. A full factorial design contains all possible combinations, yielding 12 ($3 \times 2 \times 2$) design points (DPs). A 125 DP second order nearly orthogonal Latin hypercube (NOLH) design (MacCalman et al. 2017) samples the remaining numerical factors. The use of the second order NOLH provides an efficient exploration of the design space, with negligible multicollinearity among input factors and their second order effects, and allows us to fit many diverse metamodels. Additionally, the second order NOLH provides space-filling properties that enables the identification of thresholds and change points (MacCalman et al. 2017). The maximum pairwise correlation between any two columns in the second order regression matrix is 0.0411, indicating near orthogonality. Due to these properties, even complicated metamodels can be fit with minimal confounding effects.

Crossing the 12 DPs from the full factorial with the 125 DPs from the second order NOLH yields 1,500 DPs (12×125). Thirty independent replications were conducted at each DP, yielding 45,000 active shooter simulation runs. Of note, thirty replications of each design point required approximately 141 CPU days to run, which only took approximately 19 hours using the 180 nodes available for this job on our high performance computing cluster. As a point of comparison, and to illustrate the power of an efficient design of experiment, a full factorial design that tests every possible combination of the factors, assuming ten levels for each continuous factor, would have taken 625 days to complete, given the same computing cluster. Each replication of the model produces a time series of deaths as well as a cumulative total.

4 ANALYSIS

Our analysis utilizes stepwise regression and graphical displays to quantify the effect of the experiment's factors on *Total Deaths*. Lovejoy (2020) explores other metamodeling approaches and visualizations. We note that any insights obtained from this experiment should not be extrapolated beyond the experimental region. We use JMP statistical software for our analysis (SAS Institute Inc. 2020).

We first summarize each of the 1,500 DPs by the mean of *Total Deaths* over the replications. We then ran a stepwise regression on the summarized output to capture relationships between the experiment's factors and the summarized response. Main effects, two-way interactions, quadratic terms, and three-way interactions for all factors—as well as quadratic and cubic terms for the quantitative factors—were eligible for inclusion in the stepwise model. The initial regression model fit indicated that a square root transformation of the response makes the residual variance more homogenous. The final fit has an R-squared value of 0.85. The actual versus predicted plot displayed in Figure 4 shows the regression line in red coupled with a 95% confidence interval in the shaded red area. The square root of mean *Total Deaths* at each DP is indicated by a point and a horizontal blue line indicates the overall mean of the square root of the response.

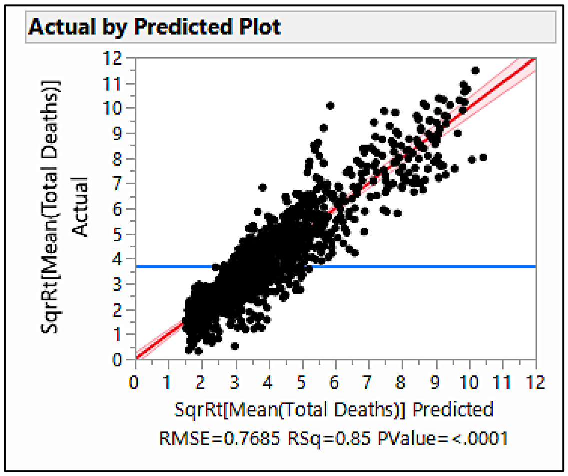

Figure 4: Actual versus predicted plot for square root transform fit of mean *Total Deaths*.

Figure 5 contains the model's sorted parameter estimates, in descending order of significance. The main effect *JASPR Presence* is the term with the largest absolute value *t*-ratio and is therefore deemed the most significant predictor. *Shooter Ingress* and *Shooter Suicide* are the next most influential terms. Only two of the numeric factors, *Response Time* and *AS P(Hit)*, entered the metamodel.

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
JASPR Presence[No]	1.0337292	0.020001	51.68	<.0001*
Shooter Ingress[Classrooms]	-0.945328	0.028286	-33.42	<.0001*
Shooter Suicide[No]	0.6331359	0.020001	31.65	<.0001*
Shooter Ingress[Dining]*JASPR Presence[No]	-0.81703	0.028286	-28.88	<.0001*
Response.Time (min)	0.0507541	0.002293	22.13	<.0001*
JASPR Presence[No]*Shooter Suicide[No]	0.3461098	0.020001	17.30	<.0001*
AS P(hit)	1.9385093	0.136923	14.16	<.0001*
Shooter Ingress[Classrooms]*JASPR Presence[No]	-0.326551	0.028286	-11.54	<.0001*
JASPR Presence[No]*(Response.Time (min)-15.008)	0.0232239	0.002293	10.13	<.0001*
Shooter Ingress[Dining]*JASPR Presence[No]*Shooter Suicide[No]	-0.261759	0.028286	-9.25	<.0001*
Shooter Suicide[No]*(Response.Time (min)-15.008)	0.0168615	0.002293	7.35	<.0001*
Shooter Ingress[Dining]	0.180361	0.028286	6.38	<.0001*
Shooter Ingress[Classrooms]*(AS P(hit)-0.49992)	-1.152506	0.193639	-5.95	<.0001*
JASPR Presence[No]*(AS P(hit)-0.49992)	0.6799759	0.136923	4.97	<.0001*
Shooter Ingress[Dining]*(AS P(hit)-0.49992)	0.87602	0.193639	4.52	<.0001*
Shooter Ingress[Classrooms]*JASPR Presence[No]*Shooter Suicide[No]	-0.110631	0.028286	-3.91	<.0001*
Shooter Ingress[Classrooms]*Shooter Suicide[No]	-0.109668	0.028286	-3.88	0.0001*
Shooter Ingress[Dining]*Shooter Suicide[No]	-0.070031	0.028286	-2.48	0.0134*

Figure 5: Sorted parameter estimates for square root transform fit of mean *Total Deaths*.

JMP's Prediction Profiler, shown in Figure 6, illustrates the magnitude and direction of the regression's main effects. In interactive mode, the cross-hairs at each of the independent factors can be moved left or right to illustrate how one-at-a-time changes affect mean *Total Deaths*. With the cross-hairs at the settings shown in the figure, the expected mean *Total Deaths* is approximately 17.9.

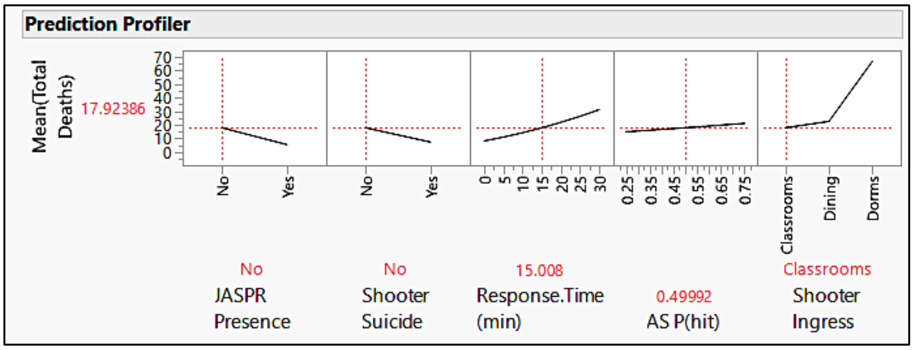

Figure 6: Prediction profiler for square root transform fit of mean *Total Deaths*.

The fit indicates that the main effects *JASPR Presence* and *Shooter Suicide* reduce mean *Total Deaths*, as expected. Increases in *Response Time* and *AS P(Hit)* increase mean *Total Deaths*, also as expected. Perhaps most notably, an active shooter entering the building via the dormitory section is associated with a sharp increase in mean *Total Deaths*.

Figure 7 visually depicts the two-way interaction between *JASPR Presence* and *Response Time*. The horizontal axis represents *Response Time* in minutes and the vertical axis represents mean *Total Deaths*. The blue line represents the cases in which JASPR is present. When JASPR is present, the blue line is nearly horizontal, indicating very little effect of increased response time. This is because JASPR includes automatic door locks that quickly contain the shooter and keep them out of most of the rooms where bystanders are located, even while first responders are still en route to the scene. The red line represents cases in which JASPR is not present. For these cases, the line has positive slope, indicating that increased response time results in more deaths. To summarize, the presence of JASPR reduces the importance of quick response time, but the absence of JASPR makes quick response time critical.

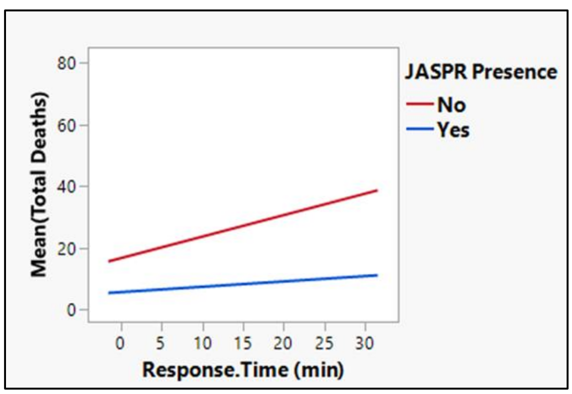

Figure 7: The interaction between *JASPR Presence* and *Response Time*.

Because the regression model indicates that the effects of all categorical factors (*JASPR Presence*, *Shooter Ingress*, *Shooter Suicide*) are significant, with seven of the ten most significant terms incorporating one or all of these, we explore the effect of these three on *Total Deaths* via the boxplots in Figure 8. This figure uses all 45,000 individual end-of-run values rather than the design point summaries.

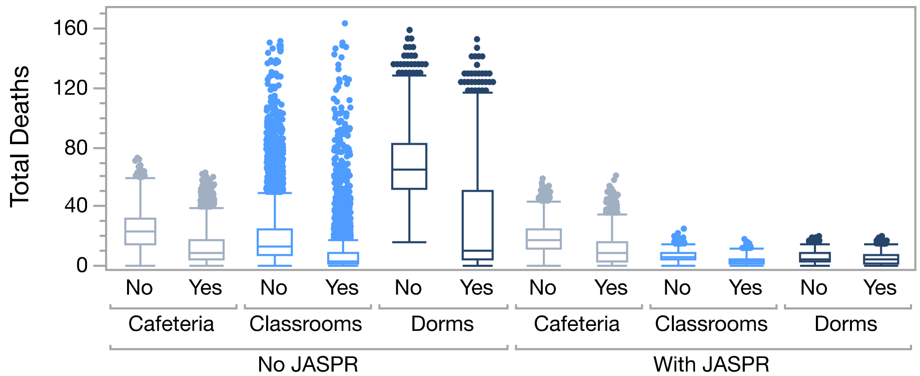

Figure 8: Boxplots of *Total Deaths* versus *JASPR Presence*, *Shooter Ingress*, and *Shooter Suicide*.

The six boxplots on the left represent *Total Deaths* without an active shooter defeat system, and the six on the right represent *Total Deaths* with an active shooter defeat system (*JASPR Presence*). Both sets of six are separated again by *Shooter Ingress*, and then a third time to indicate whether or not the active shooter suicided during the simulation run. From this display, we can conclude that (1) the presence of JASPR is effective at reducing *Total Deaths* overall, but that (2) the magnitude of the impact depends on the shooter's ingress location and whether or not the shooter suicides.

Figure 9 shows cumulative deaths over time, to illustrate how this time series is affected by the same three categorical factors. The horizontal axis represents time in minutes. The horizontal grouping boxes indicate the levels of *Shooter Suicide* and *Shooter Ingress* location, while the vertical grouping boxes indicate the levels of the *JASPR Presence* factor. Clearly, runs in which the shooter does not suicide are generally associated with higher death counts, but there is also quite a lot of variability, due to the levels of other factors not shown changing, as well as stochastic variability across the replications.

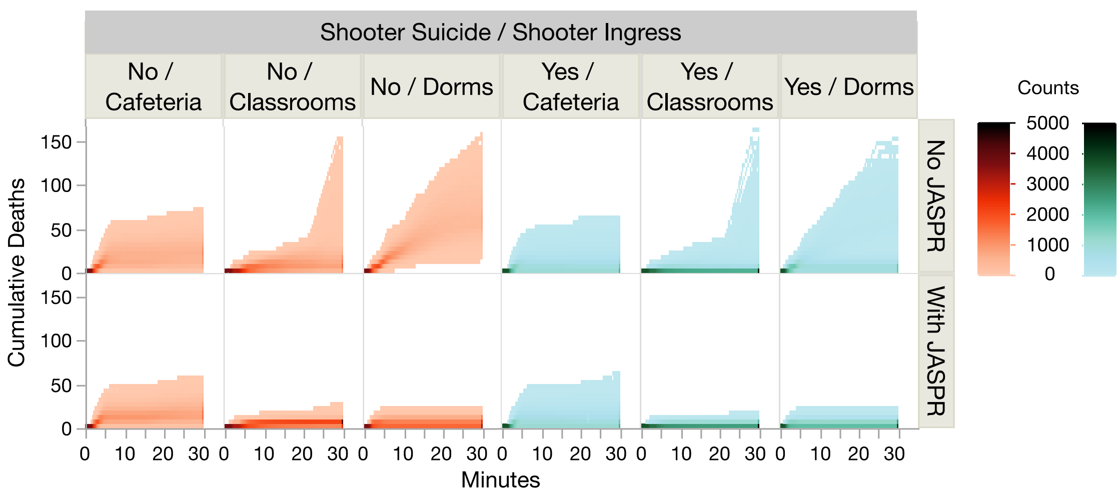

Figure 9: Cumulative deaths over time versus *Shooter Ingress*, *JASPR Presence*, and *Shooter Suicide*.

Figure 9 shows that when JASPR is present, the majority of the deaths occur during the first five to seven minutes, and the largest loss of life is associated with ingress through the cafeteria. The patterns for ingress through the classrooms and dorms are strikingly different when JASPR is not present. Roughly 16-20% of the runs associated with classroom ingress result in a second wave of deaths beginning at about 21 minutes. For shooter ingress through the dorms, the death toll tends to rise more steadily over time and deaths occur in all runs where the shooter does not suicide.

5 DISCUSSION

5.1 The Active Shooter Defeat System was Effective Overall

Our analysis suggests that an active shooter defeat system such as JASPR may be extremely effective at reducing the total number of fatalities. A claim that it may be the single most important controllable variable for determining total fatalities in a real-world scenario, at least insofar as the model reflects the circumstances and physical layout of the USMAPS building at West Point, NY, seems reasonable at this point. The presence or absence of such a system is the single most significant term in the fitted regression model. Further, the display in Figure 8 conveys that an active shooter defeat system can reduce fatalities in most of the modeled cases.

5.2 Active Shooter Entrance Location and Active Shooter Suicide Mattered

Though employing an active shooter defeat system reduced casualties in most circumstances, the shooter's choice of entry location and decision to suicide or not significantly impacted how many simulated lives were saved. In our simulation runs, the defeat system had the least impact when the active shooter entered via the cafeteria area. This is due in part to the availability of several exits, either out of the building or into another section of the building. Additionally, because most bystanders in the cafeteria have a line-of-sight to the shooter when the shooting begins, their delays in understanding an active shooting is in progress is minimized. This reduction in cognitive delay would reasonably extend throughout the remainder of the building as people flee and simultaneously communicate with each other across parts of the building through both word-of-mouth and electronically. Finally, because of the large number of bystanders in a relatively open room, key JASPR components such as the automated door locks would be of little benefit, and a number of targets are available to the shooter immediately.

Conversely, the defeat system is far more effective when the shooter enters sections of the building where there are multiple rooms in the same section (meaning more walls and doors and fewer exits), few people per room, and opportunities for automatic door locks to impede the shooter. Without an active shooter defeat system, the active shooter is presented with small, but repeated, sets of targets incapable of alerting the rest of the building with any comparative speed as they are menaced at close range by the shooter from dorm room to dorm room. The defeat system mitigates this by quickly alerting all bystanders and first responders, while effectively containing the spread of the violence.

As to why the dorm scenario was generally associated with higher fatalities than the classroom scenario when a defeat system was not employed, we offer several insights. In the classroom setting, a large number of people understand what is happening very quickly. With usually two exits for every classroom, one leading to the corridor and one to an adjoining classroom, the potential exists for many to escape quickly. Further, if an individual is able to rapidly lock a door manually or otherwise harden or conceal people inside, many lives are potentially spared. In the dorm rooms, even though there are fewer people per room, this works to the shooter's advantage since bystanders in adjacent rooms may take longer to become aware of the shooter's presence and alert others; meanwhile these bystanders have fewer exit opportunities, as compared with the classrooms.

Finally, and not surprisingly, the active shooter's decision to suicide nearly always reduces fatalities regardless of the presence of the active shooter defeat system or the shooter's selection of entrance location. Therefore, the defeat system has less potential for benefit in scenarios that are destined to end quickly.

5.3 Constraints, Limitations, and Future Research

As all models have limitations and require assumptions, further study is warranted and, as mentioned previously, these outcomes should not be extrapolated beyond the model's assumptions or experimental domain. Our experimentation allowed only the complete presence or absence of JASPR, and we recommend further study into which components, and which combinations of components, may be more or less effective. We also recommend further investigation into the timing of the automated door locks and the potential for bystanders to be trapped on the wrong side of a door. Additionally, our response of interest was fatalities, not the larger set of all casualties (injury or death). Further study to include all casualties would certainly be relevant for medical first responders. Expanding the physical scope of the simulation from one building to several buildings, or to more urbanized locations where an active shooter defeat system might potentially reduce fatalities even further, also seems fully warranted.

Another limitation of our study is that we do not attempt to model any effects that the JASPR system may have on the shooter's behavior, either positive or negative. For example, an active shooter intending to suicide does so at a random time that is not affected by the presence or absence of the JASPR system, or by the arrival of first responders. Additionally, the mere presence of a system like JASPR might serve either to modify an active shooter's target location of choice or deter them altogether.

5.4 Closing Thoughts

This study was performed for the U.S. Department of Defense to support their efforts to create safer communities. If appropriately and ethically deployed, smart sensors and devices offer opportunities to improve safety in urban environments where people live, work, and intermingle. Given the breadth and depth of factors for potential future study, we recommend making further use of simulations—combined with data farming—as a means to efficiently and effectively achieve valuable insights. It also provides an explainable modeling and analysis structure that may help to frame the larger policy and cost discussions among senior leaders. Ultimately, such research may help reduce the scale of such horrific events—and, at least in some cases, prevent them.

ACKNOWLEDGMENTS

Department of Defense Distribution Statement: Approved for public release; distribution is unlimited. The views and opinions of the authors do not necessarily state or reflect those of the Naval Postgraduate School, the Navy, or the U.S. Government. The authors would like to thank the JASPR team leadership for funding this research.

REFERENCES

Abreu, O., A. Cuesta, A. Balboa, and D. Alvear. 2019. "On the Use of Stochastic Simulations to Explore the Impact of Human Parameters on Mass Public Shooting Attacks". *Safety Science*, 120:941-949. https://doi.org/10.1016/j.ssci.2019.08.038, accessed 15th April 2020.

Anklam, C., A. Kirby, F. Sharevski, and J. Dietz. 2014. "Mitigating Active Shooter Impact: Analysis for Policy Options Based on Agent/Computer Based Modeling". *Journal of Emergency Management*, 13(3). https://doi.org/10.5055/jem.2015.0234, accessed 15th April, 2020.

Army Technology. 2021. "Colt M4 Carbine". Projects. https://www.army-technology.com/projects/colt-m4-carbine-assault-rifle-us/, accessed 20th March.

Beaudwin, J., R. Domondon, B. Scott, B. Shah, K. Shah, C. Sikes, and C. Tchatcho. 2018. *A Systems Engineering Approach to School System Enhancements for Countering Active Shooters in U.S. K-12 Schools*. Master's thesis, Department of Operations Research, Naval Postgraduate School, Monterey, California.

Blair, J. and K. Schweit. 2014. "A Study of Active Shooter Incidents in the United States Between 2000—2013". Texas State University and Federal Bureau of Investigation, U.S. Department of Justice. Washington, D.C. https://www.fbi.gov/file-repository/active-shooter-study-2000-2013-1.pdf/view, accessed 15th April 2020.

Briggs, T. and W. Kennedy. 2016. "Active Shooter: An Agent-Based Model of Unarmed Resistance". In *Proceedings of the 2016 Winter Simulation Conference*, edited by T. M. K. Roeder, P.I. Frazier, R. Szechtman, E. Zhou, T. Huschka, and S. E. Chick. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Ergenbright, C. and S. Hubbard. 2012. *Defeating the Active Shooter: Applying Facility Upgrades in Order to Mitigate the Effects of Active Shooters in High Occupancy Facilities*. Master's thesis, Department of Defense Analysis, Naval Postgraduate School, Monterey, California.

Gunn, S., P. Luh, X. Lu, and B. Hotaling. 2017. "Optimizing Guidance for an Active Shooter Event". In *IEEE International Conference on Robots and Automation*, May 29th–June 3rd, Singapore, 4299-4304. https://doi:10.1109/ICRA.2017.7989495, accessed 15th April 2020.

Global Security. 2021. "M4 Carbine". Specifications. https://www.globalsecurity.org/military/systems/ground/m4-specs.htm, accessed 31st March, 2021.

Hayes, R. and R. Hayes. 2014. "Agent-Based Simulation of Mass Shootings: Determining How to Limit the Scale of a Tragedy". *Journal of Artificial Societies and Social Simulation*, 17 (2) 5. http://jasss.soc.surrey.ac.uk/17/2/5.html, accessed 15th April 2020.

Henscheid, Z., D. Middleton, and E. Bitinas. 2006. "Pythagoras: An Agent-Based Simulation Environment". *Scythe: Proceedings and Bulletin of the International Data Farming Community*, Issue 1, Workshop 13. https://calhoun.nps.edu/handle/10945/35599, accessed 15th April 2020.

Lee, J., K. Ostrowski , and E. Dietz. 2020. "Agent-Based Modeling for Casualty Rate Assessment of Large Event Active Shooter Incidents". In *Proceedings of the 2018 Winter Simulation Conference*, edited by M. Rabe, A. A. Juan, N. Mustafee, A. Skoogh, S. Jain, and B. Johansson. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

Lovejoy, C. 2020. *Joint Active Shooter Protection and Response (JASPR) Scenario Modeling and Analysis in Support of Force Protection*. Master's thesis, Department of Operations Research, Naval Postgraduate School, Monterey, California.

MacCalman, A., H. Vieira, and T. Lucas. 2017. "Second Order Nearly Orthogonal Latin Hypercubes for Exploring Complex Stochastic Simulations". *Journal of Simulation*, 11(2):137–150.

Lucas, T.W., W. Kelton, P. Sanchez, S. Sanchez, and B. Anderson. 2015. "Changing the Paradigm: Simulation, Often the Method of First Resort ". *Naval Research Logistics*, 12(4):293–303.

Sanchez, S. M. and P. J. Sanchez. 2017. "Better big data via data farming experiments". Chapter 9 in *Advances in Modeling and Simulation—Seminal Research from 50 Years of Winter Simulation Conferences*, eds. A. Tolk, J. Fowler, G. Shao, and E. Yücesan, 159–179. Cham, Switzerland: Springer International Publishing.

SAS Institute Inc. 2020. JMP® Version 15 Cary, NC, USA.

Sporrer, A. 2020. *Analytic Models for Active Shooter Incidents*. Master's thesis, Department of Operations Research, Naval Postgraduate School, Monterey, California.

Stewart, A. 2017. *Active Shooter Simulations: An Agent-Based Model of Civilian Response Strategy*. Master's thesis, Department of Industrial and Manufacturing Systems Engineering, Iowa State University, Ames, Iowa. https://lib.dr.iastate.edu/etd/15621/, accessed 15th April 2020.

Towers, S., A. Gomez-Lievano, M. Khan, A. Mubayi, and C. Castillo-Chavez. 2015. "Contagion in Mass Killings and School Shootings". *PLoS ONE,* 10(7). https://doi.org/10.1371/journal.pone.0117259, accessed 15th April 2020.

United States Army. 2016. "Rifle and Carbine." [TC 3-22.9], Army Publishing Directorate.

Xi, J. and W. Kin. 2019. "Simulation of Knife and Gun Attacks on University Campus Using Agent-Based Modeling and GIS". In *Proceedings of the 2019 Winter Simulation Conference,* edited by N. Mustafee, K.-H.G. Bae, S. Lazarova-Molnar, M. Rabe, C. Szabo, P. Haas, and Y.-J. Son. Piscataway, New Jersey: Institute of Electrical and Electronics Engineers, Inc.

AUTHOR BIOGRAPHIES

CHARLES V. LOVEJOY is a Major in the United States Army. He received his B.A. in Economics from the University of Maryland, College Park, M.S. in Leadership Studies from the University of Texas at El Paso and M.S. in Operations Research from the Naval Postgraduate School. His email address is charles.lovejoy.mil@mail.mil.

MARY L. MCDONALD is a Faculty Associate for Research in the Naval Postgraduate School's Simulation Experiments & Efficient Designs Center for Data Farming. She received her B.A. in Mathematics from Northwestern University and M.S. in Applied Mathematics from the Naval Postgraduate School. She has lectured for courses in probability and statistics and combat modeling and has over 20 years of experience in military simulation modeling and analysis. Her email and web addresses are mlmcdona@nps.edu and http://faculty.nps.edu/mlmcdona/.

THOMAS W. LUCAS is a Professor of Operations Research at the Naval Postgraduate School (NPS) in Monterey, California. His primary research interests are simulation, warfare analysis, computational design of experiments, and robust Bayesian statistics. Professor Lucas is a co-director of NPS's Simulation Experiments & Efficient Designs (SEED) Center for Data Farming–see https://harvest.nps.edu/. His email address is twlucas@nps.edu. His website is http://faculty.nps.edu/twlucas/.

SUSAN M. SANCHEZ is a Distinguished Professor of Operations Research at the Naval Postgraduate School, where she is a co-director of the Simulation Experiments & Efficient Designs (SEED) Center for Data Farming. She has a B.S. in Industrial & Operations Engineering from the University of Michigan, and a Ph.D. in Operations Research from Cornell. She has been an active member of the simulation community for many years, and has been recognized as a Titan of Simulation and an INFORMS Fellow. Her web page is http://faculty.nps.edu/smsanche/ and her email is ssanchez@nps.edu.