Can School Design Save Lives:
An Agent-Based Model Evaluating the Effects of Architecture on School Shootings

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Abstract:

School shootings, which have been a major societal concern for the past several decades, have drawn much interest regarding possible policies to prevent their occurrence and potential actions to reduce their destruction. This paper considers the role of school design as a mitigating factor. Due to a lack of any pre-existing data, this study uses stochastic modeling and simulations as a replacement for the data generating process. The model, which is a joint agent-based model and discrete-event simulation (ABM/DES model), serves to recreate a single-shooter indiscriminate shooting scenario including various aspects of shooter and victim behavior. Repeated application of the simulation model to various floor plans produced a completely simulated dataset for quantitative evaluation. The results show that additional exits, curved hallways, and obstacles can greatly and significantly reduce estimated casualty rates, whereas wider exits and wider hallways can insignificantly increase estimated casualty rates.

Contents:

Introduction:

May 18, 2018. 7:40 AM. 17-year-old Dimitrios Pagourtzis walked into Santa Fe High School in Santa Fe, Texas and began shooting. Armed with both a shotgun and handgun, he rampaged through the art complex, indiscriminately shooting students. Innocent students quickly fled the scene, and those who could not manage to escape instead barricaded themselves in classrooms and buried themselves in the backs of closets. Although the attack had been carefully premeditated, the plans of the shooter and the motivation behind the assault were completely unknown to the students and teachers who were fighting for their lives.[1]

Ten individuals lost their lives that day, and ten more were injured. Yet, to say that the impact of the shooting was limited to those 20 individuals is far from the truth. While much of the devastation of a school shooting is felt and lived by the children and teachers, the impact extends to first responders and medical personnel, friends and families, the school district and neighbors, and individuals all across the nation. Severe trauma and mental-health ramifications linger far past the shooting and can even claim more lives.[2] Each shooting and each casualty starts a chain-reaction that extends far past what the numbers may indicate.

The Santa Fe Shooting was the 53rd of 59 indiscriminate (or rampage) school shootings between 1971 and 2019 and was the fourth deadliest school shooting in American history. This begs the question: why not begin with an anecdote of any of the three deadliest shootings?[3] Why not focus on the attacks at Sandy Hook Elementary School, Marjory Stoneman Douglas High

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[1] Dakin Andone and Keith Allen, "Alleged Shooter at Texas High School Spared People He Liked, Court Document Says," CNN, Cable News Network, May 19, 2018. https://www.cnn.com/2018/05/18/us/texas-school-shooting/index.html.

[2] Patricia Mazzei and Miriam Jordan, "'You Can't Put It Behind You': School Shootings Leave Long Trail of Trauma," The New York Times, The New York Times, March 28, 2019. https://www.nytimes.com/2019/03/28/us/parkland-shooting-suicides-newtown-mental-health.html.

[3] "CHDS," K-12 School Shooting Database, Accessed March 13, 2020, https://www.chds.us/ssdb/.

School, or Columbine High School, which killed 28, 17 and 15 students, respectively?[4] While the sheer amount of viable anecdotes is cause for alarm itself, the shooting at Santa Fe High School is unique, not just in the course of events, but in the aftermath as well.

Similar to many mass shootings, the Santa Fe Shooting was met with commentary on gun control and an analysis of what went wrong. Yet, unlike many other shootings, it brought about an unusual and unique conversation topic: doors. Only hours after the attack, Texas Lt. Governor Dan Patrick stated, "we may have to look at the design of our schools moving forward… And what I mean by that is there are too many entrances and too many exits to our more than 8,000 campuses in Texas."[5] The thought seems intriguing and novel. Could it be that less doors are the answer to saving children's lives? Does school design hold the answers to America's school shooting problem?

Unfortunately, as school shootings are difficult to prevent, it is imperative to consider and assess mitigation measures designed to save lives once an event occurs.[6] This paper explores the "doors" question and takes it one step further: how does a school's architecture impact the number of estimated casualties during a school shooting with respect to five axes of variation (number of exits, width of exits, curved hallways, width of hallways, and hallway obstacles).

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[4] Ibid.

[5] Jacob Shamsian, "People Are Calling out a Top Texas Official for Saying Shootings Could Be Stopped If Schools Had Fewer Doors," Insider, Insider, May 18, 2018, https://www.insider.com/santa-fe-shooting-texas-dan-patrick-doors-stop-school-shootings-2018-5.

[6] Kristina Libby, "Why Tech Will Never Be Able to Predict the Next Mass Shooting," Popular Mechanics, October 18, 2019, https://www.popularmechanics.com/technology/security/a28621846/can-tech-detect-mass-shootings/.

Literature Review:

There has been a substantial amount of research conducted on school shootings. There are two main subsets of literature regarding school shootings, which this paper labels event prevention and event mitigation.

Event Prevention:

Event prevention, which corresponds to efforts designed to prevent school shootings from occurring in the first place, often seeks to find patterns in school shooter profiles. While many studies have identified that school shooters are likely students or former students of the school and that they are typically adolescents, much research is still carried out in order to identify other risk factors, causes, and triggers that lead individuals to carry out these acts.[7] Several studies point to links between school shootings and a combination of depression, paranoia, desperation, and mental-health concerns. A specific study using non-randomly chosen, adolescent mass murderers found that depression and historical anti-social behavior were predominantly present among the sample.[8] However, while many, if not all school shooters may possess these traits, these studies fail to show that these characteristics are sufficient conditions for a student becoming an assailant. Many students deal with depression, alienation, desperation, etc. and do not turn into school shooters.

A study conducted by the Federal Bureau of Investigation (FBI) dives deeper into linking threats to actual violent exhibitions. The FBI identified a four-pronged threat assessment

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[7] Rhitu Chatterjee, "School Shooters: What's Their Path To Violence?" NPR, NPR, February 10, 2019, https://www.npr.org/sections/health-shots/2019/02/10/690372199/school-shooters-whats-their-path-to-violence.
[8] J. Reid Meloy, Anthony G. Hempel, Kris Mohandie, Andrew A. Shiva, and B. Thomas Gray, "Offender and Offense Characteristics of a Nonrandom Sample of Adolescent Mass Murderers," *Journal of the American Academy of Child & Adolescent Psychiatry* 40, no. 6 (2001), https://doi.org/10.1097/00004583-200106000-00018.

protocol for determining the likelihood that a threat will turn into something greater. These prongs include the personality of the student, family dynamics, school dynamics and the student's role in those dynamics, and social dynamics.[9] The study advocates for the use of these prongs (which were designed with the intention of identifying the optimal school-shooter profile) when a threat is made to determine the possibility of an actual attack. Often times, identified risk factors are used to better inform violence reduction efforts. Many institutions, such as the Children's Hospital of Philadelphia Research Institute, point to a reduction in overall day-to-day aggression, isolation and mental-health gaps as potential methods to reduce the likelihood of a school shooting. Despite the large amount of attention devoted to event prevention research, identifying clear and definite policies to address these findings remains a difficult task, and school shootings have continued to occur.

Event Mitigation:

In contrast to event prevention research on this subject, event mitigation research has been less developed, yet it still presents tremendous benefits to violence reduction efforts. The main difference between the two subsets of research is that event prevention focuses on preventing a school shooting from occurring while event mitigation focuses on reducing the number of casualties given that a school shooting will occur.

This paper fills a void at the intersection of three currently existing realms of event mitigation literature: school shooting models, evacuation models considering building design, and untested and unstudied hypotheses regarding the impact of school design on shootings.

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[9] Mary Ellen O'Toole, "The School Shooter: A Threat Assessment Perspective," *PsycEXTRA Dataset*, 2000, https://doi.org/10.1037/e319532004-001.

Previous Models to Study School Shootings:

Existing literature in this realm often use agent-based models (ABMs), which are stochastic simulation models where individual actors are provided with set behavioral patterns and rules.[10] This allows for the evaluation of group-wide phenomena and patterns. Many studies using these techniques have tested the efficacy of certain propositions intended to reduce casualties specifically with respect to school shootings.

Hayes and Hayes (2014) used an ABM to examine the potential effectiveness of Senator Dianne Feinstein's (D-Calif.) assault weapons and high-capacity magazines bill.[11] The paper defines specific actions for individual actors (shooter, victim) based on reasonable assumptions of behavioral patterns, and it tested the simulation on indoor and outdoor variations. By modifying the constraints and assumptions of the model, the authors were able to conclude that the assault weapons ban would not have a significant effect on the number of casualties. This paper did not allow for victims to hide or fight, did not allow the shooter to move, and only ran 200 trials. It also calibrated the model to a specific shooting instance which decreases the generality of the findings.

Stewart (2014) studied civilian response strategy for active-violence situations. Stewart uses an ABM and "focuses on three parameters: law enforcement response time, civilian response strategy, and cognitive delay of the civilians" in an effort to understand how these three parameters impact the number of anticipated casualties.[12] Stewart found that law enforcement response time had a substantial effect on the number of casualties. This paper did not feature

[10] "Agent-Based Modeling," Population Health Models. Columbia University Mailman School of Public Health, Accessed May 1, 2020, https://www.mailman.columbia.edu/research/population-health-methods/agent-based-modeling.
[11] Roy Hayes and Reginald Lee Hayes, "Agent Based Simulation of Mass Shootings: Determining How to Limit the Scale of a Tragedy," *SSRN Electronic Journal*, March 31, 2014, https://doi.org/10.2139/ssrn.2239171.
[12] Alexandria Stewart, "Active Shooter Simulations: An Agent-Based Model of Civilian Response Strategy," 2017, https://doi.org/10.31274/etd-180810-5235.

much variation in the shooter's path, reduced the decision of a victim to hide to random, probabilistic assignment, and did not allow victims to fight.

Anklam, et al. (2014) examined the influence of resource officers and/or concealed carry individuals. The paper, which also used an ABM, found that there were "statistically significant fewer casualties in scenarios where on scene armed responders such as resource officers and concealed carry personnel were present."[13] This model restricted shooter movement, only allowed for victim evacuation, did not address cognitive delay, and only executed 200 trials.

Briggs and Kennedy (2016) used an ABM to study the effect of several individuals attempting to fight the gunman on the number of casualties. The paper found that "even with a miniscule probability of overcoming a shooter, fighters may save lives but put themselves at increased risk."[14] This model assumes an open landscape and as such, does not include the possibility of hiding.

Lee and Ostrowski (2018) used an ABM to propose a model for analyzing active shooter incidents. The study found that "immediate evacuation of civilians, early detection of the shooter, and the rapid deployment of first responders are contributing factors in decreasing casualty rate for civilians and law enforcement personnel during an active shooter incident."[15] Similar to Briggs and Kennedy (2016), this model assumes an open landscape. This paper also does not include the possibility of hiding or fighting.

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[13] Charles Anklam III Phd, Ms Adam Kirby, Ms Filipo Sharevski, and J. Eric Dietz Phd Pe. "Mitigating Active Shooter Impact: Analysis for Policy Options Based on Agent/Computer-Based Modeling," *Journal of Emergency Management* 13, no. 3 (April 2015): 201, https://doi.org/10.5055/jem.2015.0234.
[14] Thomas W Briggs and William G. Kennedy, "Active Shooter: An Agent-Based Model of Unarmed Resistance," *2016 Winter Simulation Conference (WSC)*, December 2016. https://doi.org/10.1109/wsc.2016.7822381.
[15] Jae Yong Lee, J. Eric Dietz, and Kayla Ostrowski, "Agent-Based Modeling For Casualty Rate Assessment Of Large Event Active Shooter Incidents," *2018 Winter Simulation Conference (WSC)*, 2018, https://doi.org/10.1109/wsc.2018.8632535.

No agent-based-model or quantitative study was discovered that analyzed the impact of a school's layout on the number of estimated casualties. Additionally, none of these publications used a victim behavior model that considered factors other than random assignment and simple evacuation.[16] The model used by this paper builds off of several of the aforementioned limitations of these publications including the number of trials, victim behavior, shooter variation, and of course, architecture manipulation.

Previous Analysis Regarding the Impact of Building Design on Evacuation Dynamics:

There have been several attempts to model evacuation dynamics using ABMs in the past that address the impact of building design on population dynamics. While this is not the same as evaluating the impact of building design on mass shootings as the presence of a shooter will drastically impact victim behavior during the simulation, it is closely related.

Ha (2010) examines the impact of complex architectural design on evacuation time and efficiency. The study particularly analyzes "the room door size, the size of the main exit, the desired speed and the friction coefficient."[17] The paper analyzes the effects of different structures that vary by the number of rooms and stories. The study found that while some of the aforementioned factors influenced congestion at exits, and in turn, evacuation times, different building designs produced different results. For example, in the one-room case, larger exits resulted in faster evacuation speeds whereas in the two-room and hallway case, smaller exits resulted in faster evacuation speeds. This study also examined the effect of obstacles (such as a cylindrical column in front of the exit) on evacuation rates. It found that in some cases, obstacles

[16] In this case, "simple evacuation" refers to either choosing a pre-selected exit or running away from the shooter.
[17] Vi Ha and George Lykotrafitis, "Agent-Based Modeling of a Multi-Room Multi-Floor Building Emergency Evacuation," *Physica A: Statistical Mechanics and Its Applications* 391, no. 8 (2012): 2740–51, https://doi.org/10.1016/j.physa.2011.12.034.

can help reduce congestion, and in turn, increase evacuation speeds, by dividing up the crowd. However, in other cases, it can actually increase congestion and reduce evacuation speeds.

Kasereka et al. (2018) similarly uses an ABM to assess evacuation dynamics during a fire. The base building structure used was chosen to resemble that of Kinshasa supermarkets. While this simulation does not necessarily test specific hypotheses regarding event mitigation, it does address the fact that more exits increased the total number of estimated survivors and decreased the overall time to the exit.[18]

Several other studies such as Helbing, Farkas and Vicsek (2000), and Sime (1995) evaluate the impact of crowd dynamics and escape panic behavior.[19,20] Both papers stress the importance of including psychological factors affecting human panic behavior into simulations and models. While Helbing, Farkas and Vicsek are more focused on identifying an optimal escape strategy given psychological constraints, Sime addresses the impact of a psychological delay that can cause temporary inaction and increase response time. In other words, Sime claims that the response time for an individual during a panic-inducing event consists of two components: time to start moving and time to move to safety.

In combination with previous school shooting ABMs, the development of evacuation ABMs as well as the introduction of algorithmic panic and crowd-dynamic psychology highlights the feasibility of analyzing the effects of building design on school shootings.

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[18] Selain Kasereka, Nathanaël Kasoro, Kyandoghere Kyamakya, Emile-Franc Doungmo Goufo, Abiola P. Chokki, and Maurice V. Yengo, "Agent-Based Modelling and Simulation for Evacuation of People from a Building in Case of Fire," *Procedia Computer Science* 130 (2018): 10–17, https://doi.org/10.1016/j.procs.2018.04.006.
[19] Dirk Helbing, Illés Farkas, and Tamás Vicsek, "Simulating Dynamical Features of Escape Panic," *Nature* 407, no. 6803 (2000): 487–90, https://doi.org/10.1038/35035023.
[20] J.d. Sime, "Crowd Psychology and Engineering," *Safety Science* 21, no. 1 (1995): 1–14, https://doi.org/10.1016/0925-7535(96)81011-3.

Previous Analysis Regarding School Design:

There has been a substantial amount of interest in the impact of school architecture on the number of casualties during a school shooting; however, as mentioned above, there were no formal studies testing any effects. Most of the focus is in the form of media attention.

In August of 2018, a few months after the Santa Fe shooting, Eric Levenson (CNN) took on this question from a journalistic perspective: how to design schools in the era of mass shootings. After speaking with designers, architects, and security experts, Levenson identified several factors that were likely to contribute to fewer casualties. These include increasing visitor visibility, creating one single entrance point, reinforced doors, and wider and more open hallways. These arguments are not empirically supported. This is not to dismiss the propositions of the article and the findings, but rather to acknowledge that as of now these arguments have been untested.[21]

Fruitport High School in Michigan is undergoing a redesign with an emphasis on protection against school shootings. Some elements of construction include curved hallways to limit shooter sight lines, and locker placement (lockers are placed in perpendicular islands in the hallways to serve as potential barricades).[22] These ideas remain untested and are met with theoretical opposition. One major complaint is that designing a school which limits a potential shooter could potentially inhibit law enforcement personnel during the apprehension of the shooter.[23] The idea of a redesign isn't novel, as Sandy Hook was redesigned after the shooting

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[21] Eric Levenson, "How to Design a School in the Era of Mass Shootings," CNN, Cable News Network, August 15, 2018, https://www.cnn.com/2018/08/15/health/school-design-era-mass-shootings-trnd/index.html.
[22] Scotty Hendricks, "Do People Think This Will Actually Work? What Are Experts Saying?" Big Think. Big Think, September 19, 2019, https://bigthink.com/politics-current-affairs/architecture-mass-shooting?rebelltitem=1#rebelltitem1.
[23] Danny Hakim, "Ex-Employee Held in Campus Attack," The New York Times, The New York Times, May 11, 2003, https://www.nytimes.com/2003/05/11/us/ex-employee-held-in-campus-attack.html.

that occurred in December 2012.[24] In fact, the new Sandy Hook school features a rain garden between the parking lot and entrance which limits entry points and allows for a clear line of sight to who is entering the school.

This question is met with much attention from architecture firms as well. HMC Architects specifically focus on five areas of school design that may play a role in casualty counts. These include one secured main entry, mass notification systems, distinct floor pattern plans indicating safe zones, automatic door locking systems, and glazing (using glass in construction). Similar to the above claims, these ideas remain empirically untested, yet seem to act in consensus with other proposals designed to reduce the estimated number of casualties.

Given the substantial amount of interest in redesigning schools in the era of school shootings, as well as the high investment required to execute a rebuild, there is a strong need for empirical testing. This paper seeks to provide that empirical analysis by creating a model that tests the effect of school design on casualty rates.

Methods and Data:

This paper does not use a currently existing dataset on school shootings to answer this question, and instead uses a simulation to generate a dataset. This is primarily because of two reasons. First, there is a lack of quality information available regarding the architecture of schools which have been the locations of school shootings. Between 1999 and 2009, there were 59 indiscriminate school shootings and many of these shootings varied drastically.[25] For many of these cases, it was not possible to obtain information regarding the floor plan of the school and

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[24] Lisa Prevost, "After School Shootings, a Push for Openness Over Barricades," The New York Times, The New York Times, October 22, 2019, https://www.nytimes.com/2019/10/22/business/school-shooting-barricades.html.
[25] Michael Roberts, "School Shootings List in Twenty Years Since Columbine: 240 and Counting," Westword. 4, August 2, 2019, https://www.westword.com/news/school-shootings-list-in-twenty-years-since-columbine-240-and-counting-11314828.

the impact that certain design features had on the shootings. That brings about the second issue: there is no available information regarding the actual schematics of many school shootings. Hypothetically, if one of these schools had curved walls, it would be nearly impossible to discern whether the curved walls had an impact on the actual events of the shooting.

As such, this paper turns towards a simulation environment to replicate the different architectural elements in question and create a shooting scenario. The general model is a combination of agent-based-modeling and discrete-event-simulation stochastic models. ABMs simulate situations by providing individual agents (actors) in the model with a set of guiding principles and rules, which is especially useful when there is no overall governing structure. Discrete-event-simulation allows for the modeling of a process, or an event-sequence, that each agent observes.[26] In the event of a shooting, there are many different sequential states for each agent that are critical to the functioning of the model. As such, these particular models are specifically helpful in the case of school shootings, because the actions of victims and of the shooter are far easier to understand than the events of a whole shooting event as a whole. The simulation can then be overlaid on generated floor plans that differ only on the above listed axes of variation.[27]

Creating the simulation model requires clearly defining the rules followed by the agents and making core assumptions about the environment. Given the absence of data, it is certainly possible that some of the assumptions may not be entirely accurate; however, introducing

[26] Michael Allen, "What Is Discrete Event Simulation, and Why Use It?" Right cot, right place, right time: improving the design and organisation of neonatal care networks – a computer simulation study, U.S. National Library of Medicine, Accessed May 16, 2020, https://www.ncbi.nlm.nih.gov/books/NBK293948/.

[27] This simulation was created using Anylogic software, which is a Java-based simulation environment with accessible libraries meant for ABM/DES models.

random variation and repetition should increase the reliability of the simulation. There are three discrete sequential stages of the simulation: pre-shooting, shooting, and post-shooting.

Stage One: Pre-Shooting Behavior:

In this stage, the victims and the shooter (who is unidentified and unannounced) behave almost exactly the same, and wander around the environment. Movement during this stage is designed to replicate movement of students in a school and incorporates group conglomeration and typical pedestrian flow. The only difference between the victims and the shooter is that the shooter travels independently and is never formally associated with groups. All students are coded to periodically wait at different locations, then walk to other locations, similar to the actual actions of students in a school. The initial population is 50 groups of sizes ranging from two to three which is consistently around 125 students.[28] Individual attributes (height, diameter, and speed) were based on probabilistic variations that match nationwide and global averages.[29,30]

Transition One: Pre-Shooting to Shooting:

The shooter transitions to this stage once each victim has entered the environment and student movement has reached a natural flow. The shooter will begin at a random location in the school. After the shooter transitions to the shooting stage and shoots the first individual (which will be later explained), victims are notified that there is a shooting and face varying levels of cognitive delay. This delay is based on a uniform distribution of values between one and five

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[28] Population size was chosen based on model calibration and the traversable area of the environment.
[29] Live Science Staff, "Four-Decade Study: Americans Taller, Fatter," LiveScience, October 27, 2004, https://www.livescience.com/49-decade-study-americans-taller-fatter.html.
[30] "100m Final: How Fast Could You Run It?" The Telegraph, Telegraph Media Group, August 4, 2012, https://www.telegraph.co.uk/sport/olympics/athletics/9450234/100m-final-how-fast-could-you-run-it.html.

seconds and is designed to replicate the effect discussed in the aforementioned literature which indicates individuals face a linear delay time during crisis events.[31]

Stage Two: Shooting:

The actions of the shooter and victims in the shooting stage can be modeled as a series of game-theoretic decisions between the shooter and each victim; however, these sequential games can be probabilistically simplified into a series of equations that allow them to be incorporated into the model.

First, as this paper only considers rampage shootings, the shooter operates indiscriminately and within the constraints of time. As such, the shooter attempts to maximize the total number of casualties as quickly as possible. If the shooter reaches within three meters of the currently targeted victim, the victim is shot and remains in that location to simulate an actual casualty.[32] With respect to each victim, the shooter has two options: target or do not target.

If there is a visible non-shot victim (non-shot victims will hereafter be referred to simply as victims), the shooter's dominant strategy is to pursue the nearest visible victim. Pursuing the non-nearest victim would decrease time-efficiency and pursuing a non-visible victim would lower the expected number of casualties, as a lack of visibility offers a lack of certainty regarding victim existence at that location. If there is no visible victim, the dominant strategy of the shooter is to keep moving around the school until they see another victim.

On the other hand, each victim chooses to maximize their payoff function, which is the probability of their survival. During the shooting, if a student arrives at a designated exit, they have "escaped" and are removed from the model. Based on the conventional wisdom and

[31] Sime "Crowd Psychology and Engineering", 1–14.
[32] Three meters was chosen as the range given model calibration and observation.

acceptance of "Run, Hide, Fight," those are the three options facing each victim.[33] Each victim re-evaluates this decision every two seconds. It is certainly possible that not every victim has internalized this strategy; however, it serves to be the best framework for the sake of the model. Because of heightened levels of adrenaline and survival instincts, it is confidently assumed that almost all victims act rationally (i.e. almost all victims attempt to maximize the probability of their survival), which supports the choice to use a game theory framework.[34] Steps are taken to account for "irrational decisions" including increased prioritization of evacuation and slight variation in victim decision-making.

If the victim is in range of the shooter, they face a high level of imminent threat, and as such, the dominant strategy is to choose to fight. Upon deciding to fight, this victim joins all other victims within range in the fight. If the fighting group succeeds in overcoming the shooter, the model terminates; however, if the fighting group does not succeed, then they are shot, and the model continues to run. Briggs and Kennedy (2016), who specifically analyzed victim retaliation, determined that 0.01 was the stable probability of overcoming the shooter.[35] Unfortunately, Briggs and Kennedy did not consider retaliation involving more than one individual nor did they incorporate the distance between the victims and shooter. This paper uses a modified binomial probability distribution for victim victory in order to account for the number of individuals within range and the distance of those individuals. Actual fighting is not simulated by the model and is instead treated as an instantaneous probabilistic event, which serves the same

[33] Rebecca Harrington, "What You Should Do in an Active-Shooter Situation - Remember 'Run Hide Fight'," Business Insider, Business Insider, April 3, 2018, https://www.businessinsider.com/what-is-run-hide-fight-what-should-you-do-if-theres-an-active-shooter-2016-11.
[34] Harvard Health Publishing, "Understanding the Stress Response," Harvard Health, Accessed May 17, 2020, https://www.health.harvard.edu/staying-healthy/understanding-the-stress-response.
[35] Briggs and Kennedy, "Active Shooter: An Agent-Based Model of Unarmed Resistance.," 3525.

purpose. Equation 1 represents the probability of victim victory when there is at least one individual within fighting range.

$$\Pr\,(Victim\ Victory)\ = \sum_{k=1}^{n}\left(\frac{n!}{(n-k)!(n!)}\right)\left(0.01\left(\frac{3}{d_k}\right)\right)^k\left(1-\left(0.01\left(\frac{3}{d_k}\right)\right)\right)^{n-k} \quad \text{(Equation 1)}$$

where

$n\ =\ number\ of\ victims\ within\ range$

$d_k\ =\ distance\ between\ shooter\ and\ victim_k\ in\ meters$

If the victim is not in range of the shooter, the dominant strategy is to either run or hide, with the specific choice of exits or hiding spot (hereafter referred to as destinations) depending on the option that maximizes their likelihood of survival. The decision to fight is clearly outweighed by the decision to run or hide, which offers a greater likelihood of survival.

Considering the situation from a game theoretic perspective, each victim will attempt to maximize the probability they will survive, which is equivalent to minimizing the probability that they are targeted by the shooter. Given the aforementioned dominant strategy of the shooter, the probability of a victim becoming the shooter's target is equal to the probability of becoming the shooter's nearest visible victim. As such, the probability of survival conditional on a destination is then transitively proportional to three factors that influence the probability of becoming the nearest visible victim to the shooter while pursuing that destination: the distance between the shooter and the destination, the distance between the victim and the destination, and the probability that the victim will survive once they arrive at the destination.

The probability of surviving while pursuing a destination is modeled by a modification of Newton's Universal Law of Gravitation. The "Gravity model," as it has been termed, is used in subfields of physics such as electricity, magnetism, and astronomy; however, it is also used in many social science fields such as natural disaster analysis and trade flows.[36,37] Each designated destination is considered to be a point of gravitational pull on the victim. As such, the victim will choose the destination that offers the greatest force and in turn, maximizes their probability of survival. Equation 2 represents the force of a destination on a victim.

$$F_{destination} = \frac{Q * d^2}{r^2} \qquad \text{(Equation 2)}$$

where

$$Q = 1 - \frac{visible\ area\ from\ destination}{total\ area\ of\ environment}$$

$$r = distance\ between\ destination\ and\ victim$$

$$d = distance\ between\ destination\ and\ shooter$$

This accounts for the increased chances of a victim encountering the shooter if the shooter is closer to the victim's destination, if the victim has a lower likelihood of survival at their destination, and if the victim must traverse a longer distance to their destination.

Q, which ranges from 0 to 1, represents the destination's "safety quality index" and is proportional to the probability of survival once the victim arrives at that destination. The safety quality index reflects the protection it offers the victim from discovery and is calculated by the proportion of visible area at the exit/hiding spot. For example, A hiding spot in a small protected corner of the building may offer more protection than a hiding spot in the middle of the main hallway, and as such will have a higher safety quality index. The safety quality index of an exit is substantially more than that of a hiding spot because it guarantees survival upon arrival.[38] If a

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[36] Thomas Chaney, "The Gravity Equation in International Trade: An Explanation," NBER, August 9, 2013, https://www.nber.org/papers/w19285.
[37] Ankai Rocard Xu, and Amèvi Rocard Kouwoaye, "How Do Natural Disasters Affect Services Trade?" *How Do Natural Disasters Affect Services Trade?* World Trade Organization Economic Research and Statistics Division, n.d.
[38] The safety quality index of each hiding spot was divided by 10 based on model calibration.

hiding spot's area of protection is visible to the shooter, then during that time, it has a safety quality index of 0. See Appendix A for further discussion on the calculation of the safety quality index.

Implementing this model, along with path-minimization and obstacle-avoidance principles, provides each agent with a set of rules to guide them during the actual shooting event.

Transition Two: Shooting to Post-Shooting:

Transition two, which transitions shooters and victims from the shooting to the post-shooting stage, effectively determines the termination of the model. There are three possible events that can trigger the end of the shooting stage: the successful escape of all remaining victims (non-casualties) in the environment, victim victory during an altercation with the shooter, and the apprehension or neutralization of the shooter by law enforcement. As such, transition two is triggered by the earliest of these events, using four minutes as successful law enforcement intervention (given that the average law enforcement response time to school shootings is three minutes, with a one-minute period for law enforcement intervention).[39] This model assumes that law enforcement will be successful in apprehending or neutralizing the shooter. Once this transition is triggered, it leads all agents to stage three (post-shooting) and subsequent model termination. Figure 1 depicts the three distinct stages along with the transition conditions. This diagram does not reflect the exact specifics of the stages; however, it serves to illustrate the natural processes. The evolution of the aforementioned stages is depicted in Appendix B using an example floor plan.

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[39] Erica Goode, "In Shift, Police Advise Taking an Active Role to Counter Mass Attacks," The New York Times, The New York Times, April 6, 2013, https://www.nytimes.com/2013/04/07/us/in-a-shift-police-advise-taking-an-active-role-to-counter-mass-attacks.html.

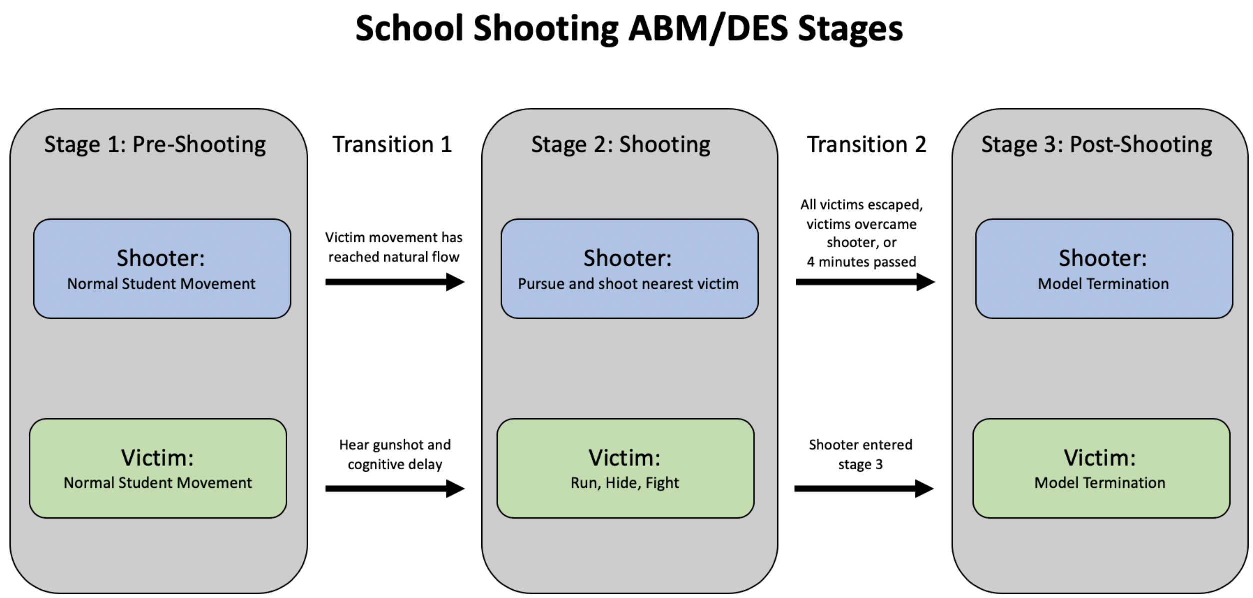


Figure 1: A flowchart explaining the three distinct stages of the ABM/DES model

Table 1 lists the tested measurements for each axis of variation. A floor plan, based loosely on the first floor of Battle Creek High School in Michigan (chosen for simplicity and availability), was created for every possible one of these combinations.[40] This resulted in a total of 144 total tested designs. Each floor plan is one level and features classrooms, a cafeteria, a main entrance area, and restrooms. Each internal door is one meter wide and does not change among variations. "Obstacles" refer to 13 cylindrical columns of one meter in diameter placed periodically in the centers of the hallways.

[40] *Floorplan of Battle Creek High School, Michigan*, n.d. https://www.pinterest.com/pin/793266921840643071/.

Hallway Type	Obstacles Present	Width of Hallways	Width of Exits	Number of Exits
Straight	Yes	2 Meters	1 Meter	1
Curved	No	4 Meters	2 Meters	2
		6 Meters	3 Meters	3
				4

Table 1: Tested measurements for each axis of variation.

The shooting model, which was not altered between floor plans, was performed 250 times on each floor plan which created a dataset of eight fields and 36,000 observations. The fields correspond to the five axes of variation, the total number of students in the model, the number of casualties, and the casualty rate. Because of the randomized, controlled experiment, there is no omitted-variable bias and a simple ordinary-least-squares regression of casualty rate on architectural features will indicate the causal impact of the design features on casualties.

While some existing publications, such as Hayes and Hayes (2014), have elected to validate their models on buildings which have featured school shootings, this paper does not. By calibrating the model to single-shooter instances on other buildings, there is a very high likelihood of overfitting. This is due to a wide variety of factors that are not able to be incorporated into this model (i.e. shooter targeting and favoritism, victim-specific behavior, luck and chance, etc.). As a result, choosing to compare this shooting model to existing shootings would not only offer little towards verification, but could inhibit the generality of the model. Instead, this paper follows the example of several other publications on the topic, including Briggs and Kennedy (2016), which chooses to internally validate the model through sequential stage checks that confirm proper performance.

Analysis and Results:

The dataset, which consisted of 36,000 simulations, featured 4,482,207 total students (average of 124.506 students per simulation; standard deviation of 3.425), and 966,149 total casualties (average of 26.837 casualties per simulation; standard deviation of 13.562). This translates to an average casualty rate of 21.555%. The highest average casualty rate was 33.053% (an average of 41.828 casualties) and was obtained by the floor plan with one, one-meter-wide exit, straight two-meter-wide hallways, with no obstacles. The lowest average casualty rate was 8.683% (an average of 10.944 casualties) and was obtained by the floor plan with four, three-meter-wide exits, curved two-meter-wide hallways with obstacles.

Figure 2 is a series of box plots that illustrate the distribution of casualty rates for each tested factor. Within each factor, each average (mean) is statistically different from the other averages at less than a 1% level, except for two cases. First, the averages for the tested values of the widths of the exits are all statistically indistinguishable. Second, the averages for a four-meter-wide hallway and six-meter-wide hallway are significantly different only at a 10% level.

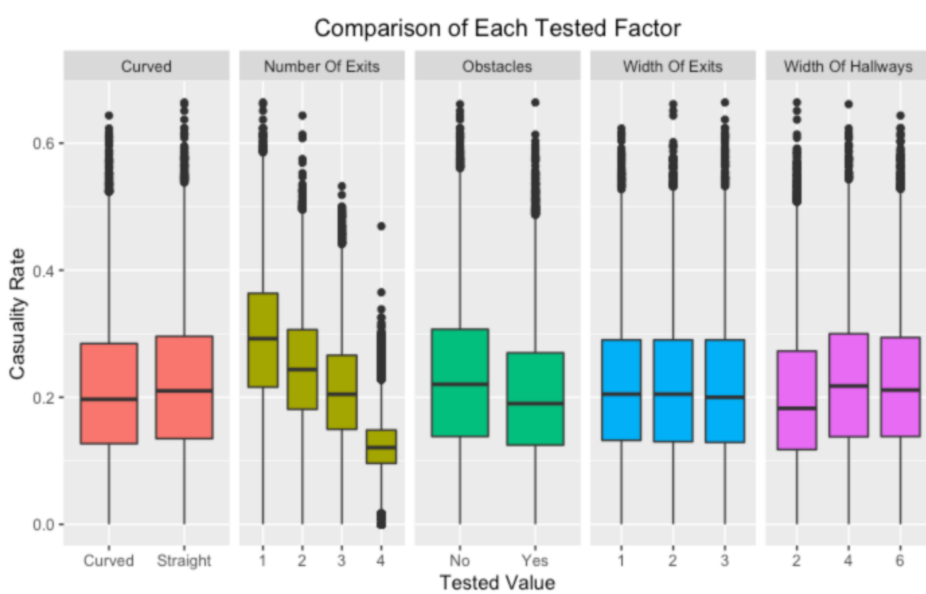


Figure 2: Box Plots for Each Tested Factor

This paper relies on two linear regressions for analysis. One regression featured interaction terms and one did not. The specific interpretation of each coefficient along with statistical significance can be found in Appendix C; however, the main points will be summarized below. For the sake of discussion, any architectural feature that reduced casualty rates will be called a mitigating factor and any feature that increased casualty rates will be called a risk factor.

Without interaction terms, coefficients represent the average impact of each factor, and serve to be the key findings when understanding each factor in isolation. While average effects are accurate and *do* indicate causation because of the controlled nature experiment, the interaction terms appropriately qualify those effects.[41] The key findings are summarized below. For specific quantitative results and detailed interpretations, see Appendix C.

Number of Exits:

Adding exits are the most impactful mitigating factor on average (5.234% reduction per exit). This is likely because adding an exit to a school provides another evacuation option for victims which improves their chances of survival. Adding an exit has the greatest impact when no other mitigating factors are present. This could be attributed to the effects of other mitigating factors, such as limiting visibility or slowing shooter movement which could reduce the strength of evacuating relative to other options. In other words, when no mitigating factors are present, evacuation is a more successful strategy which is reflected in the increased impact of adding an exit.

[41] Higher order interaction terms were not introduced due to the lack of interpretability

Width of Exits:

Wider exits, on average, are an insignificant risk factor (0.049% increase per additional meter of width) but accounting for interactions brings significance at the 10% level. Wider exits are most likely a risk factor because they increase victim exposure. In schools with larger exits, evacuating victims have a greater probability of becoming visible to the shooter as they are spreading out across the exit. Widening exits have a reduced impact in curved hallways (significant at the 10% level). This could likely be a result of the reduced emphasis on evacuation in schools with curved hallways, similar to the effect discussed with respect to the number of exits.

Obstacles:

Obstacles also have a strong impact as a mitigating factor (2.790% reduction with obstacles) and are most impactful in buildings with smaller, curved hallways, and fewer exits. This is most likely attributed to restrictions placed on the shooter. While the presence of obstacles can slow down victim movement and evacuation speeds, it appears that the limitations placed on the shooter outweigh the limitations placed on the victim. These limitations are on the shooter’s visibility, shooting lines, and movement patterns. Curved hallways likely increase the impact of obstacles because they compound the issues regarding restricted visibility and target lines. Smaller hallways likely increase the impact of obstacles because obstacles are able to block more of the pathway and visible area, which is illustrated in Figure 3.

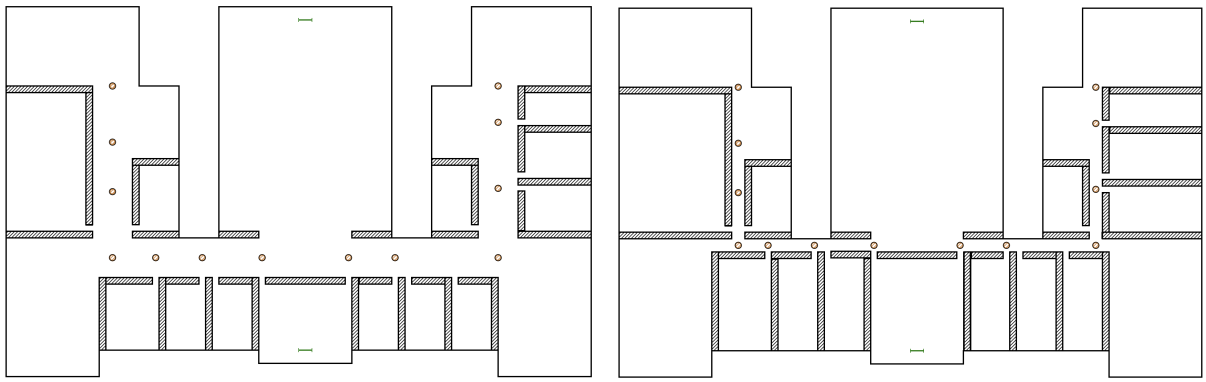


Figure 3: Two floor plans, both with two, two-meter wide exits, straight hallways, and obstacles. The floor plan on the left has six-meter-wide hallways whereas the floor plan on the right has two-meter-wide hallways.

Width of the Hallway:

Wider hallways are a significant risk factor on average (0.579% increase per additional meter of width) yet accounting for interaction presents high insignificance. The interaction with obstacles, which was previously addressed, is likely the reason for the disappearance of statistical significance and is depicted in Figure 3. In fact, obstacles had the largest impact by far when placed in two-meter-wide hallways, which explains why wider hallways are a risk factor on average. This is graphically illustrated in Figure 4. It is important to note that when placing a pillar of one meter in diameter in the middle of a two-meter-wide hallway, anything larger than 0.5 meters would not be able to navigate through that hallway. While this is relevant to consider, it does not change the findings or reliability of the model. There were two other significant interactions with the width of the hallway. First, as previously mentioned, additional exits reduce the impact of widening hallways. Second, curved hallways also increase the impact of widening hallways; however, that effect is best interpreted from the opposite perspective.

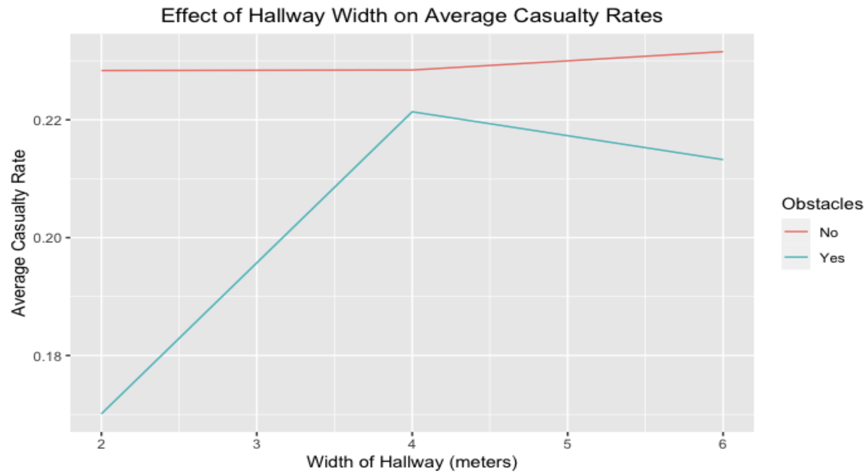


Figure 4: Graph depicting the effect of hallway width on average casualty rates.

Curved Hallways:

Curved hallways are also a large and significant mitigating factor on average (0.966% reduction with curved hallways) likely due to reducing shooter visibility. There are significant interactions with each of the other factors, several of which were previously mentioned. The final interaction, which was previously referenced, shows that curved hallways are more effective when the hallways are smaller. This is likely because the curvature of the hallway, which remained constant, is more pronounced in smaller hallways which leads to less visibility from the shooter's perspective. Figure 5 offers a visual representation of this effect.

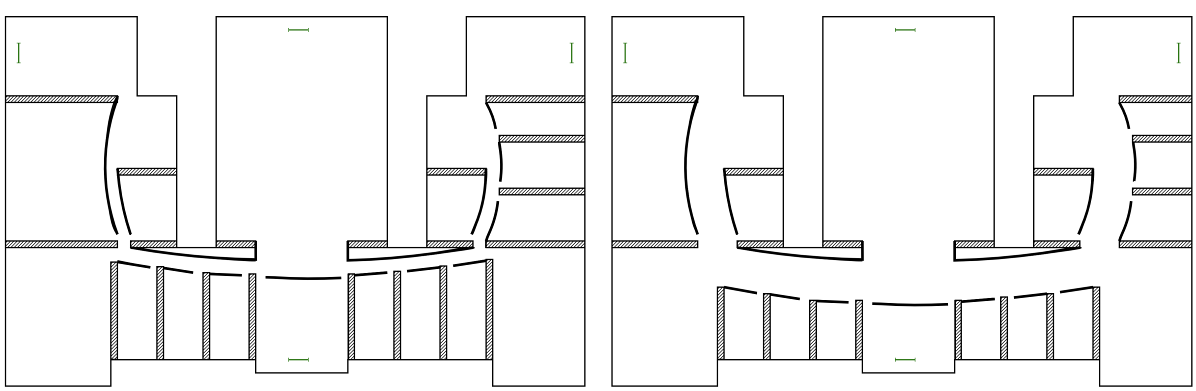


Figure 5: Two floor plans, both with four, three-meter wide exits, curved hallways, and obstacles. The left floor plan has a two-meter-wide hallway whereas the right floor plan has a six-meter-wide hallway.

Conclusion and Discussion:

This paper found that school design can significantly impact the number of casualties during school shootings. Through repeated simulation analysis, it was discovered that additional exits, obstacles, and curved hallways are significant and impactful mitigating factors. Wider exits are a questionable and low impact risk factor, and wider hallways can also be a slight risk factor when combined with other architectural features. These results offer evidence against several of the proposed design features discussed in the literature review; however, the results also reveal two broader themes that transcend the specific findings regarding the tested features of this paper. First, increasing evacuation options can, and likely will, reduce the number of casualties. Second, restricting shooter movement, visibility, and target lines can, and likely will, reduce the number of casualties. Designing schools based on these themes, regardless of whether schools use the specific design ideas addressed in this paper, should decrease casualty rates in the event of a shooting. With that being said, there must be a balance between designing schools for student safety, pragmatism, and cost. One example of this is the aforementioned case of the two-meter-wide hallways with one-meter pillars. While this example could save many lives during a shooting, it restricts hallway access to any items or students larger than 0.5 meters that may need to move through the hallway. The inclusion of non-safety features in this discussion is not meant to qualify the findings of this paper, but rather, to illustrate the complexity of school design as a broader issue. Safety during shootings is merely one aspect that should be considered during the design process.

As is the case with many research papers, there are several limitations to these findings. These limitations do not reduce the validity of these findings, but rather remain important to note when evaluating this study and offer important launching points for future research.

The first notable limitation is model termination, specifically the decision to not involve law enforcement. This paper uses an average response time to replicate law enforcement action, yet by accounting for law enforcement arrival, one may be able to draw enhanced conclusions. As was mentioned in the literature review, there is a possibility that law enforcement could also be affected by visibility restrictions and other methods to impair the shooter. These concerns remain valid, and while total confidence remains in this paper's findings, addressing this limitation in a future study could prove to be more insightful.

Another limitation is model construction regarding initial pedestrian density and movement. Although many steps were taken to match initial pedestrian density to true student behavior, obtaining an actual dataset on initial density metrics for a school could also aid in the accuracy of the findings. The largest issue with this limitation is the almost complete lack of data; however, if such data were to be obtained, this model can and should be improved.

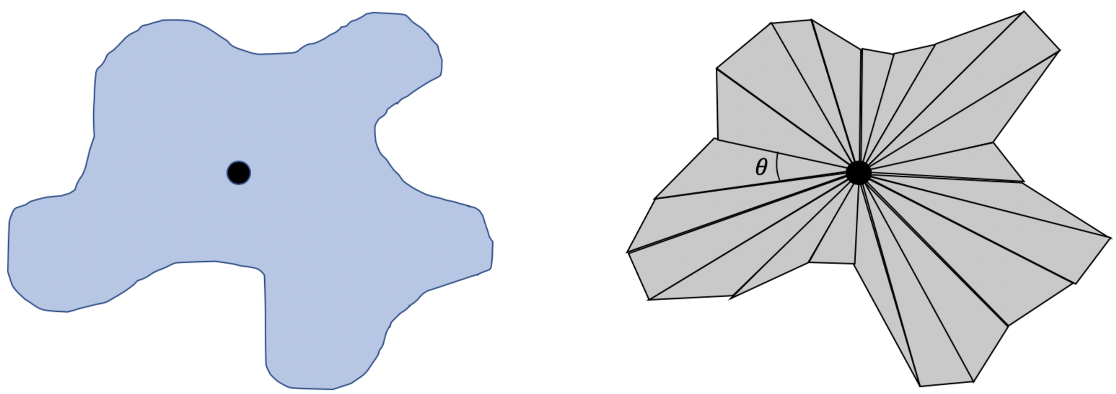
The largest limitation is the lack of robustness measures with the simulation model. It is quite possible that the dynamics of actual school shootings are different from the dynamics of the model; however, the accuracy of the model is currently impossible to gauge. While many steps were taken to maximize accuracy, the lack of data prohibits any stronger analysis or verification. As such, while this limitation is important to note, there do not appear to be any stronger modeling options.

The largest advantage of this study is the generalizability of the model. In fact, because this model is floor-plan agnostic, one could apply this model to any building and perform a threat assessment analysis. This model could also identify design vulnerabilities and possible areas within a specific building that could face the most damage during a shooting. Furthermore, with alterations, this model could be used to better inform law enforcement response strategy for different building designs. The list of possible adaptations and applications of this model is nearly endless.

As is the case with many tragic events, saving the greatest number of lives is of utmost importance. Although preventing these attacks from occurring would certainly present the best option, event mitigation research better informs life-saving policies given that an attack has occurred. Mitigating strategies, which can range from teaching students “Run Hide Fight” to redesigning schools, can save lives; however, risk factors, such as the ones explored in this paper, can further endanger students. As such, it is critical that schools and policymakers fully understand the impacts of their recommendations, policies, and actions. This is the case for Texas Lt. Governor Dan Patrick, who in the aftermath of the San Antonio Shooting suggested designing schools with fewer doors. It is certainly possible fewer doors may prevent a shooter from entering; however, that’s a matter of building security rather than building design. This paper, which directly addressed the impact of exits during a shooting, found that fewer doors would *not* save lives; however, it also offers something far greater: a critical evaluation of other design choices that *can* save lives.

Appendix A: Visible Area Approximation

The below graphic is a demonstration of the methodology employed by this paper to determine the area of visibility from a hiding spot (considered to be a point on the x-y plane). While this example is imprecise, it illustrates the technique quite well.



Visible Area (Exact) Visible Area (Approximated)

Consider the area on the left to be the actual visible area from a hiding spot (marked in black) where the borders represent obstacles or walls. Calculating the area of that shape is difficult, and it is not crucial for the purposes of the model to obtain the exact measurements. The area of the shape on the right, which is constructed by several different triangles whose outer vertices fall on the edges of the actual shape, is far easier to calculate.

The estimator used by this paper essentially constructs several triangles, each with a central angle, $\theta = \frac{\pi}{18}$, and calculates their total sum. By doing so, it is able to approximate the visible area from a hiding spot at a far lower computational and mathematical cost. While the approximation improves with a smaller choice of θ, computational power increases as well. As such, using $\theta = \frac{\pi}{18}$ balances computation and accuracy. This process is explained by the following equations, where x_i denotes the i[th] edge in an ordered list of the edges of all the triangles. App. Equation 2 shows that the chosen estimator for visible area is consistent.

$$\widehat{visible\ area} = \frac{1}{2}\sum_{i=1}^{2\pi/\theta} x_i * x_{(i+1)mod(2\pi/\theta)} * sin(\theta) \qquad \text{(App. Equation 1)}$$

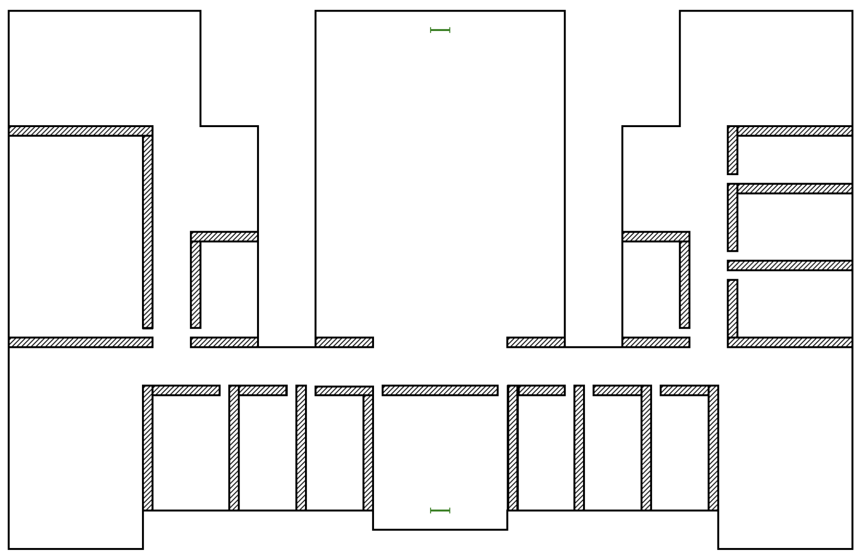
$$visible\ area = \lim_{\theta \to 0} \frac{1}{2}\sum_{i=1}^{2\pi/\theta} x_i * x_{(i+1)mod(2\pi/\theta)} * sin(\theta) \qquad \text{(App. Equation 2)}$$

Appendix B: Illustration of Model Stages

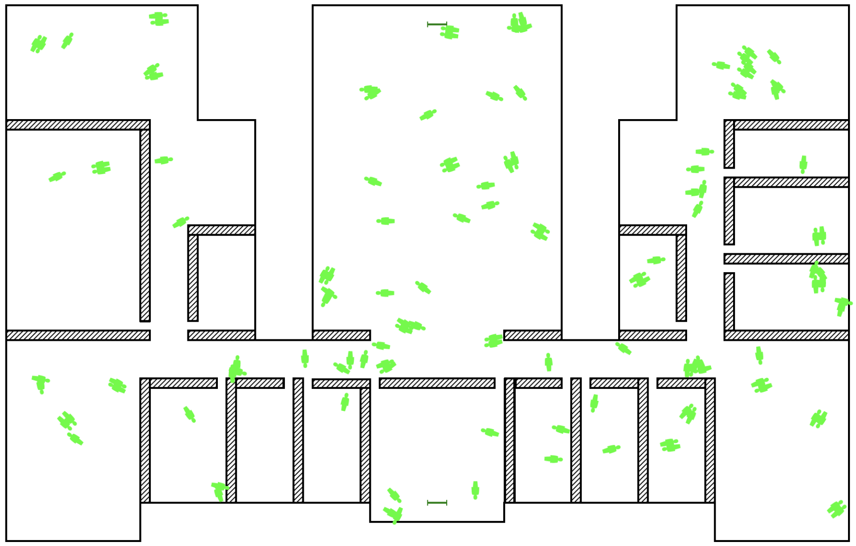
Using still images to reflect the progression of a simulated shooting can help illustrate the stages of the ABM/DES model. In this example, the school has two two-meter-wide exits, no obstacles, and straight four-meter-wide hallways.

Stage 1: Pre-Shooting

This floor plan shows the layout of the unpopulated school. The green lines mark the exits.

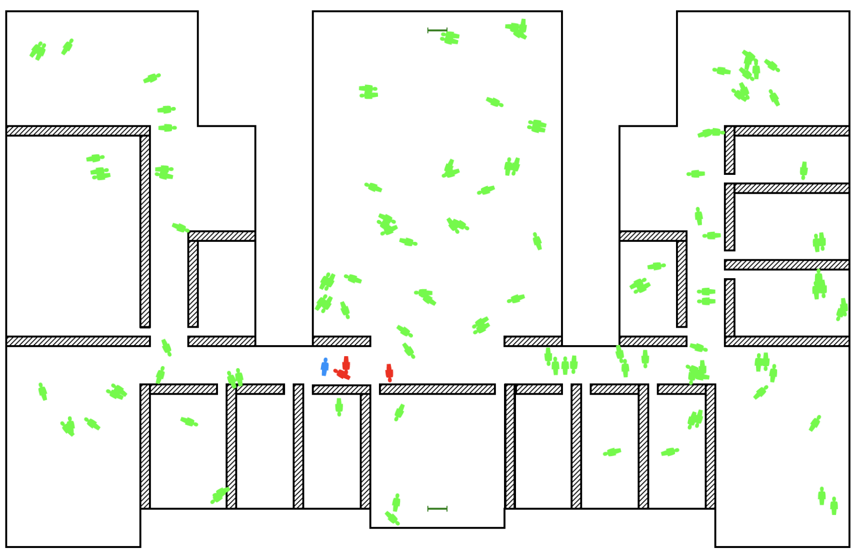


Once the school is fully populated by students, students are able to aggregate and disperse, which represents actual student behavior. The shooter is also present in the situation seen below but is indistinguishable from the victims.

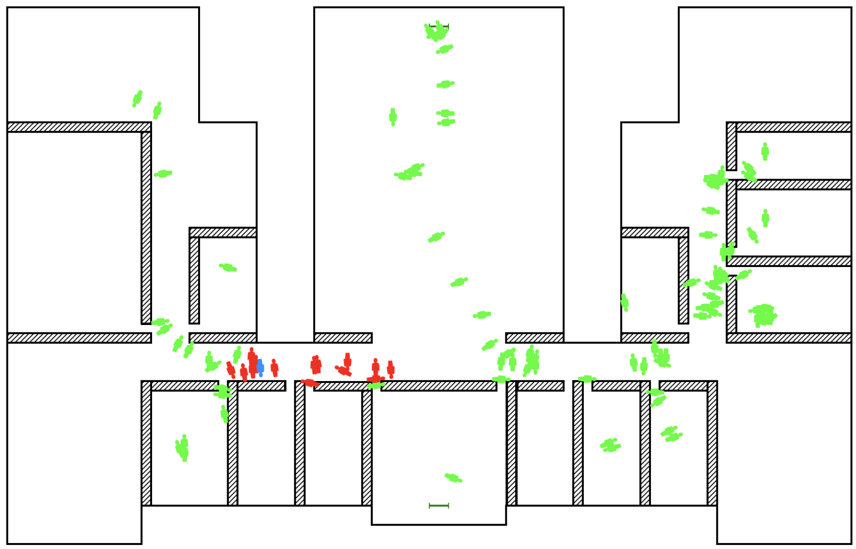


Stage 2: Shooting

Once the shooting has begun, the shooter (marked in blue) begins to target students indiscriminately. The students marked in red are casualties. As this is almost immediately after the first shot was fired, students face varying levels cognitive delay. As such, many have not registered that there is a shooting and altered their behavior.

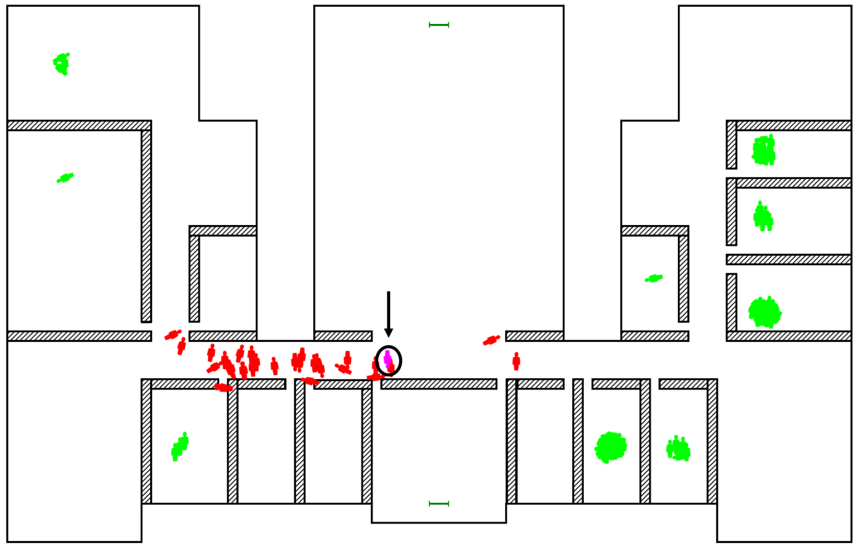


Once the shooting has begun to unravel, the number of casualties has increased. Victims are taking different steps to ensure survival based on which option (run, hide, or fight) presents them the greatest chance of survival.



Stage 3: Post-Shooting

The shooting has terminated due to the time limit (i.e. law enforcement apprehension). The shooter is pink and marked for clarity. Victims who escaped are removed and victims who hid remain.



Appendix C: Regression Output.[42]

Results

	Dependent variable:	
	Casualty Rate	
	(1)	(2)
Number Of Exits	-0.052***	-0.053***
	(0.0004)	(0.002)
Width Of Exits	-0.0005	0.004*
	(0.001)	(0.002)
Obstacles	-0.028***	-0.085***
	(0.001)	(0.004)
Width Of Hallway	0.006***	0.0003
	(0.0003)	(0.001)
Curved Hallway	-0.010***	-0.041***
	(0.001)	(0.004)
Number Of Exits * Width Of Exits		-0.001
		(0.001)
Number of Exits * Obstacles		0.010***
		(0.001)
Width Of Exits * Obstacles		-0.001
		(0.001)
Width Of Hallway * Number Of Exits		-0.001***
		(0.0003)
Width Of Hallway * Obstacles		0.010***
		(0.001)
Width Of Hallway * Width of Exits		-0.0002
		(0.0004)
Curved Hallway * Number of Exits		0.004***
		(0.001)
Curved Hallway * Width of Exits		-0.002*
		(0.001)
Curved Hallway * Width of Hallway		0.008***
		(0.001)
Curved Hallway * Obstacles		-0.015***
		(0.002)
Constant	0.343***	0.372***
	(0.002)	(0.006)
Observations	36,000	36,000
R^2	0.317	0.332
Adjusted R^2	0.317	0.332
Note:		*p<0.1; **p<0.05; ***p<0.01

[42] Hlavac, Marek (2018). stargazer: Well-Formatted Regression and Summary Statistics Tables. R package version 5.2.2. https://CRAN.R-project.org/package=stargazer

Interpretation of Regression Results (With Interaction Terms). Bolded values represent significant results at the 10% level

Coefficient	Estimate	Interpretation
(Intercept)	**0.37244**	**The casualty rate when all other variables are 0 is 37.244%.**
Number of Exits	**-0.05261**	**Adding an exit reduces the casualty rate by 5.261% (when the exits and hallways are 0 meters wide, there are no obstacles, and the hallways are straight)**
Width of Exits	**0.003662**	**Widening the exit(s) by 1 meter increases the casualty rate by 3.662% (when there are 0 exits, hallways are 0 meters wide, there are no obstacles, and the hallways are straight)**
Obstacles	**-0.08526**	**Adding obstacles reduces the casualty rate by 8.526% (when there are 0 exits, the exits and hallways are 0 meters wide, and the hallways are straight)**
Width of Hallway	0.00028	Widening the hallways by 1 meter increases the casualty rate by 0.028% (when there are no exits, the exits are 0 meters wide, there are no obstacles, and the hallways are straight)
Curved	**-0.04128**	**Curving the hallways reduces the casualty rate by 4.128% (when there are no exits, the exits and hallways are 0 meters wide, and there are no obstacles).**
Number of Exits * Width of Exits	-0.00083	Widening the exit(s) by 1 meter reduces the impact of adding an exit by 0.083%. Equivalently, adding an exit reduces the impact of widening the exit by 1 meter by 0.083%.
Number of Exits * Obstacles	**0.01044**	**Adding obstacles reduces the impact of adding an exit by 1.044%. Equivalently, adding an exit reduces the impact of adding obstacles by 1.044%.**
Width of Exits * Obstacles	-0.00055	Adding obstacles reduces the impact of widening the exit by 1 meter by 0.0547% Equivalently, widening the exit(s) by 1 meter increases the impact of adding obstacles by 0.055%.
Number of Exits * Width of Hallway	**-0.00133**	**Widening the hallways by 1 meter increases the impact of adding an exit by 0.133%. Equivalently, adding an exit reduces the impact of widening the hallways by 1 meter by 0.133%**
Obstacles * Width of Hallway	**0.00999**	**Widening the hallways by 1 meter reduces the impact of adding obstacles by 0.999%. Equivalently, adding obstacles increases the impact of widening the hallways by 1 meter by 0.999%**
Width of Exits * Width of Hallway	-0.00018	Widening the hallways by 1 meter reduces the impact of widening the exit(s) by 1 meter by 0.018%. Equivalently, widening the exit(s) by 1 meter reduces the impact of widening the hallways by 1 meter by 0.018%
Number of Exits * Curved	**0.00402**	**Curving the hallways reduces the impact of adding an exit by 0.402%. Equivalently, adding an exit reduces the impact of curving the hallways by 0.402%.**
Width of Exits * Curved	**-0.00220**	**Curving the hallways reduces the impact of widening the exit(s) by 1 meter by 0.220%. Equivalently, widening the exit(s) by 1 meter increases the impact of curving the hallways by 0.220%**
Width of Hallway * Curved	**0.00840**	**Curving the hallways increases the impact of widening the hallways by 1 meter by 0.840%. Equivalently, widening the hallways by 1 meter reduces the impact of curving the hallways by 0.840%**
Obstacles * Curved	**-0.01522**	**Curving the hallways increases the impact of adding obstacles by 1.522%. Equivalently, adding obstacles increases the impact of curving the hallways by 1.522%.**

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