time required for the completion of the projects is considered deterministic;

- The production capacity of construction modules and limitation of available funds for a recovery process have been considered as modular construction constraints and portfolio-level constraints respectively.

Socioeconomic evaluation and assessment of physical damage

These data are used in a multivariate factor analysis to identify the variables that most heavily influence on the social vulnerability of a specific community. In this study, for post-disaster recovery programs, the relative vulnerability score is used to make a distinction between affected regions in order for decision-makers to allocate reconstruction funds and resources more systematically considering diverse factors including the relative vulnerability of each region using SoVI. The proposed model in this study uses the FEMA's Hazus Hurricane-MH 4.2 Model, which "is a nationally applicable standardized methodology that contains models for estimating potential losses from earthquakes, floods, and hurricanes." (FEMA 2015).

Interdependency of facilities and regions

Affected regions and damaged facilities including homes and infrastructure are highly interdependent. For example, failure of a single major bridge will result in significant traffic flow disruptions over a vast region and cause difficulties for commuting, emergency response, evacuation, and economic recovery (Chang 2016). In addition, the characteristics of the affected region might affect the feasibility and suitability of the project. A successful post-disaster recovery plan must address the interdependency of the damaged facilities and affected communities to determine critical facilities for prioritizing reconstruction. To reflect the interdependency of regions and projects, this study uses an interdependency matrix containing the index for the dependency of each region to each project (I_{ij}) shown in the formula below.

Prioritizing schema

One of the major purposes of this study is to prioritize reconstruction projects with optimal socioeconomic benefits. In order to prioritize the projects within a reconstruction portfolio, a criticality function (Equation 1) has been developed based on SoVI, damage data, and an interdependency matrix of facilities and regions. The reconstruction projects can be prioritized based on their criticality.

$$C_i = \sum_{j=1}^{m} I_{ij} \sqrt{S_j D_j} \quad (1)$$

Where

C_i : Criticality of facility *i*

m : Number of affected regions

I_{ij} : Interdependency of facility *i* to region *j*

S_j : SoVI of region *j*

D_j : Loss index of region *j*

Resource utilization and scheduling

The other major objective of this model is to allocate limited reconstruction resources to competing for recovery projects to generate a recovery schedule for damaged facilities with respect to their priority with optimized socioeconomic benefits. The resource utilization model uses the iterative procedure indicated in Figure 2. This process assures that the required amount of funds in each time unit will fulfill the funding limitation constraint. It also can follow the constraint of module production capacity to avoid project disruption and consequent delays. The output of this step is the schedule schema that simultaneously optimizes the socioeconomic benefits and minimizes the reconstruction portfolio completion time with respect to resource constraints. The constraints are formulated with Equations (2) and (3):

$$\sum_{i=1}^{n} a_{ik} f_{ik} \leq F_k \quad (2)$$

$$\sum_{i=1}^{n} a_{ik} m_{ik} \leq M_k \quad (3)$$

Where

a_{ik} : Activeness of project i in time period k (if the project i is active in period k, then a_{ik} =1; otherwise a_{ik} =0)

f_{ik} : Required funding for project i in time period k

F_k : Total available funding for period k

m_{ik} : Required number of modules for project i in time period k

M_k : Module production capacity for period k

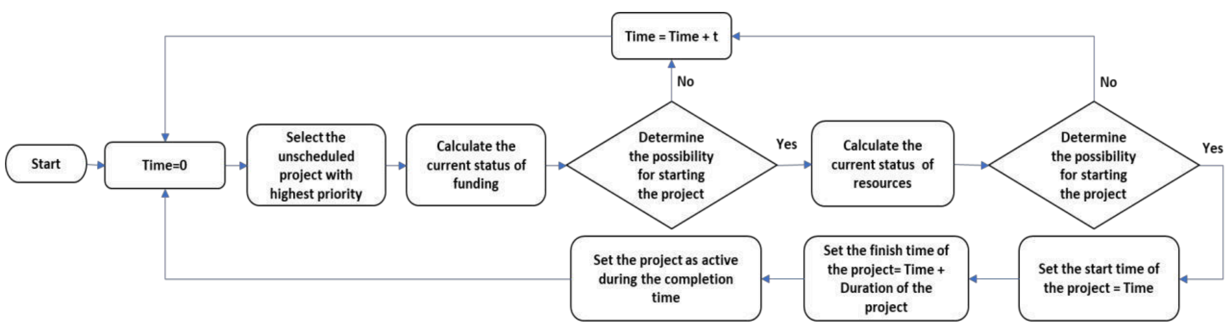

Figure 2. Resource utilization iterative algorithm.

Table 1. Post-disaster project information.

Project	Project Cost ($ million)	Completion time (weeks)	Number of Required Modules
#1	40	45	100,000
#2	58	68	140,000
#3	35	25	64,000
#4	31.5	20	78,000
#5	20.5	15	56,000
#6	39	45	80,000
#7	28.5	19	62,000

CASE STUDY AND ASSESSMENT

To demonstrate the efficiency of the proposed approach, this study developed an illustrative example using data for counties located in Louisiana (called parishes) and a simulated hurricane in this area. Figure 3 shows the location of the seven projects proposed within a post-disaster reconstruction portfolio. Table 1 provides the project cost, project duration, and a number of required modules for completion of each project overlain on wind speed map simulated using Hazus. The direct loss was used to calculate the loss index for each county. For this example, the total available funding is $3.5 million per week and module production capacity is 6,500 modules per week. For the SoVI data, previously calculated indices developed by the Hazards & Vulnerability Research Institute were used based on the American Community Survey 2012-2014 (5-year census). Figure 3 also indicates the relative SoVI scores within the nation and within the state.

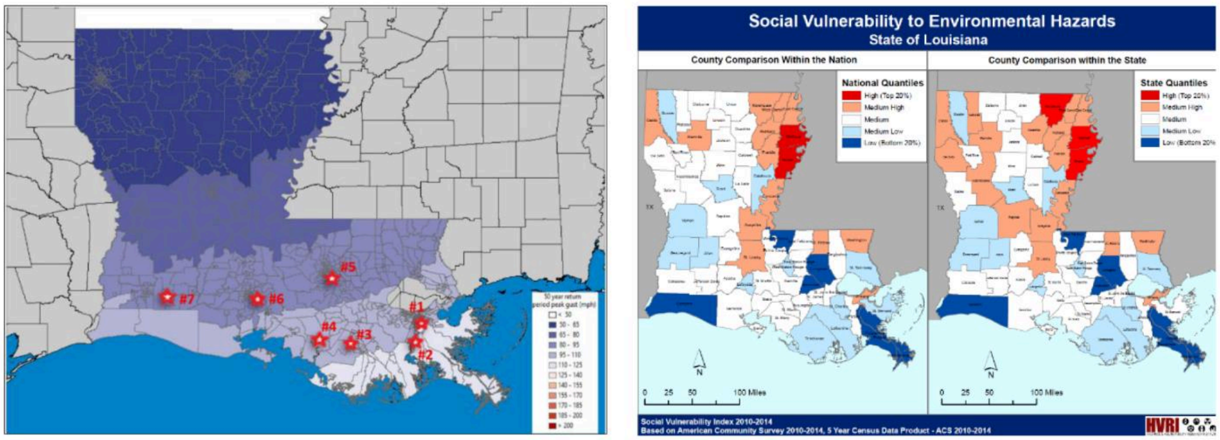

Figure 3. Post-disaster reconstruction locations overlain on Hazus-modeled wind speeds and SoVI 2010-2014 (Hazards & Vulnerability Research Institute, 2018).

Interdependency data were developed subjectively by the authors based on the location of each project. However, comprehensive studies require a defined interdependency matrix reflecting real reconstruction projects. The criticality index was calculated for each project and all projects were ranked. The project priority was found to be (in order of greatest to least criticality): 5,6,2,1,7,4,3. In the final step, given the calculated project priority and resource limitations (Table 1), the model allocated resources to the projects and the projects were scheduled to start at the earliest start time to assure that the overall completion time of the portfolio is minimized. Figure 4 indicates the optimal reconstruction portfolio plan for this illustrative example. All of the required projects can be done 108 weeks with the order of key projects to mitigate the negative social and economic impacts by the disaster considering the weekly available funds and maximum resources in the region.

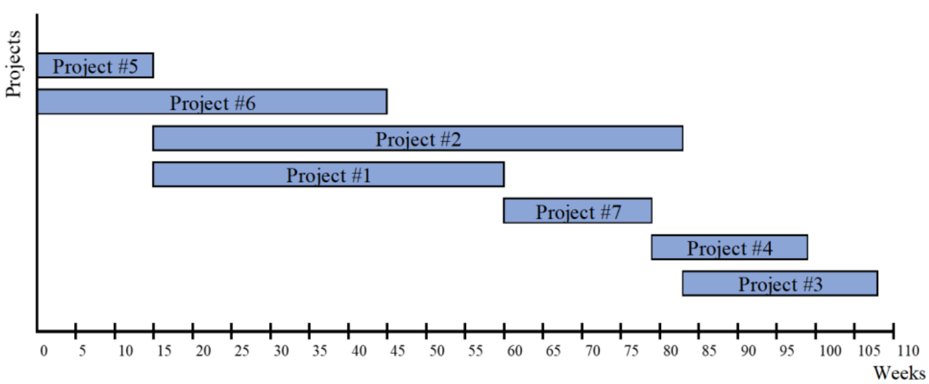

Figure 4. Optimum schedule for example reconstruction projects.

CONCLUSION

For prioritizing projects and optimizing reconstruction plans a model was developed to address both economic and social impacts of disasters. This model allowed to efficiently allocate the limited available resources to the portfolio of post-disaster reconstruction projects on the basis of project priority. The prioritizing process of the model was designed to achieve the maximum social benefits of the post-disaster reconstruction strategy while considering the severity of the economic loss to the facilities in an affected community. The illustrative example indicated promising results that the proposed method could be utilized as a decision-making tool with low computation effort to quickly and efficiently respond to the demands of the recovery process. This study is in the preliminary stage to develop a comprehensive post-disaster recovery model. Therefore, several simplifications have been made to test the proposed method, such as considering few resource constraints, focusing on the portfolio level and neglecting the single project level for resource utilization, and generalizing modules for all projects.

REFERENCES

Karlaftis, M. G., Kepaptsoglou, K. L., & Lambropoulos, S. (2007). Fund allocation for transportation network recovery following natural disasters. Journal of Urban Planning and Development, 133(1), 82-89.

Pielke Jr, R. A., Gratz, J., Landsea, C. W., Collins, D., Saunders, M. A., & Musulin, R. (2008). Normalized hurricane damage in the United States: 1900–2005. Natural Hazards Review, 9(1), 29-42.

FEMA. (2005), Planning for Post Disaster Recovery and Reconstruction, Washington D.C., FEMA (Federal Emergency Management Agency).

Federal Emergency Management Agency (FEMA). (2015). Hazus online download quick reference guide. Washington, D.C.: Federal Emergency Management Agency (FEMA).

Goodyear, R. (2014). Housing in greater Christchurch after the earthquakes: Trends in housing from the Census of Population and Dwellings 1991–2013. Statistics New Zealand.

Rowley, K. (2008). “Gulf Gov reports The role of community rebuilding plans in the hurricane recovery.” Nelson A. Rockefeller Institute of Government and Public Affairs Research Council of Louisiana, (http://www.rockinst.org/disaster_recovery/).

Chang, S. E., & Nojima, N. (2001). Measuring post-disaster transportation system performance: the 1995 Kobe earthquake in comparative perspective. Transportation Research Part A: Policy and Practice, 35(6), 475-494.

Leu, S. S., & Yang, C. H. (1999). GA-based multicriteria optimal model for construction scheduling. Journal of construction engineering and management, 125(6), 420-427.

Senouci, A. B., & Eldin, N. N. (2004). Use of genetic algorithms in resource scheduling of construction projects. Journal of Construction Engineering and Management, 130(6), 869-877.

East, E. W., & Liu, L. Y. (2006). Multiproject planning and resource controls for facility management. Journal of construction engineering and management, 132(12), 1294-1305.

Zhang, H., Li, H., & Tam, C. M. (2006). Heuristic scheduling of resource-constrained, multiple-mode and repetitive projects. Construction management and economics, 24(2), 159-169.

El-Anwar, O., Ye, J., & Orabi, W. (2015). Innovative linear formulation for transportation reconstruction planning. Journal of Computing in Civil Engineering, 30(3), 04015048.

El-Anwar, O., El-Rayes, K., & Elnashai, A. S. (2009). Maximizing the sustainability of integrated housing recovery efforts. Journal of Construction Engineering and Management, 136(7), 794-802.

Pradhan, A. R., Laefer, D. F., & Rasdorf, W. J. (2007). Infrastructure management information system framework requirements for disasters. Journal of computing in civil engineering, 21(2), 90-101.

Shaw, R. (2006). Indian Ocean tsunami and aftermath: need for environment-disaster synergy in the reconstruction process. Disaster Prevention and Management: An International Journal, 15(1), 5-20.

Freeman, P. K. (2004). Allocation of post-disaster reconstruction financing to housing. Building Research & Information, 32(5), 427-437.

HAZUS-MH [Computer software]. Federal Emergency Management Agency, Washington, DC.

Burton, C. G. (2010). Social vulnerability and hurricane impact modeling. Natural Hazards Review, 11(2), 58-68.

Watson Jr, C. C., & Johnson, M. E. (2004). Hurricane loss estimation models: Opportunities for improving the state of the art. Bulletin of the American Meteorological Society, 85(11), 1713-1726.

Shirley, W. L., Boruff, B. J., & Cutter, S. L. (2012). Social vulnerability to environmental hazards. In Hazards Vulnerability and Environmental Justice (pp. 143-160). Routledge.

Cutter, S. L., Boruff, B. J., and Shirley, L. W. (2003). "Social vulnerability to environmental hazards." Soc. Sci. Q., 84(2), 242–261.

Chang, S. E. (2016). Socioeconomic impacts of infrastructure disruptions. Oxford Research Encyclopedia of Natural Hazard Science.

Peacock, W. G., Van Zandt, S., Zhang, Y., & Highfield, W. E. (2014). Inequities in long-term housing recovery after disasters. Journal of the American Planning Association, 80(4), 356-371.

Information Requirements for Virtual Environments to Study Human-Building Interactions during Active Shooter Incidents

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ABSTRACT

Active shooter incidents present an increasing American homeland security threat to public safety and human life. Several municipal law enforcement agencies have released building design guidelines intended to offer increased resilience and resistance to potential attacks. However, these design recommendations mainly focus on terrorist attacks, prioritizing the enhancement of building security, whereas their impact on safety during active shooter incidents, and corresponding human-building interactions (HBIs) that influence the outcomes (response performance), remain unclear. To respond to this research gap, virtual reality, with its ability to manipulate environmental variables and scenarios while providing safe non-invasive environments, could be a promising method to conduct human-subject studies in the context of active shooter incidents. In this paper, we identify the requirements for developing virtual environments that represent active shooter incidents in buildings to study HBIs and their impacts on the response performance. Key components constituting virtual environments were considered and presented. These include: (1) what types of buildings should be modeled in virtual environments; (2) how to select protective building design recommendations for active shooter incidents and model them in virtual environments; (3) what types of adversary and crowd behavior should be modeled; and (4) what types of interactions among participants, buildings, adversaries, and crowds should be included in virtual environments. Findings on the above key components were summarized to provide recommendations for future research directions.

INTRODUCTION

Numerous active shooter incidents, especially in the U.S., have repeatedly reminded us of the significant threat that these incidents pose to public safety. According to the Federal Bureau of Investigation, between 2000 and 2017, active shooter incidents resulted in 779 fatalities and 1,418 injuries in the U.S., of which around 30% of fatalities and 50% of injuries happened in 2016 and 2017 only (U.S. Department of Justice and Federal Bureau of Investigation 2017). Some of the most recent active shooter incidents in 2018, such as the Stoneman Douglas High School shooting, Santa Fe High School shooting and Thousand Oaks bar shooting, further evidenced the urgent necessity of taking appropriate measures to mitigate the potential negative impacts of these tragic incidents. To improve public safety and building security, one approach is to design protective measures to be implemented in buildings in order to improve preparedness and resilience in response to active shooter incidents. Along this line, several reference manuals, including *Primer to Design Safe School Projects in Case of Terrorist Attacks* (FEMA 2003a) and *Primer for Design of Commercial Buildings to Mitigate Terrorist Attacks* (FEMA 2003b) by the Federal Emergency Management Agency (FEMA), have been published to provide building design recommendations. While these guidelines can provide valuable insights in reducing the impact of active shooter incidents, many of their proposed recommendations (e.g., limiting the number of building entries, staggering interior doors) are focused on physical security and protecting buildings from adversaries and the methods (e.g., explosives) attackers use. Moreover, these guidelines are primarily focused on terror attacks, which may not have the same characteristics as active shooter incidents. Moreover, how these recommended building design attributes influence occupant responses when active shooter incidents actually occur in buildings, to the best of our knowledge, have not been explored by prior studies.

Human behavior and building attributes are intercorrelated and human-building interactions (HBIs) collectively determine the outcome of building emergencies (Li et al. 2017). Many past building emergency incidents have demonstrated that inappropriate building design could result in disastrous outcomes (e.g., stampedes) during building emergencies (e.g., the Station Nightclub fire of 2003) (Grosshandler et al. 2005). Building occupant responses influenced by building design (e.g., herding towards the same exit while ignoring other available ones) could significantly endanger individuals and decrease building performance during emergencies as well (Aguirre et al. 2011). Therefore, to evaluate building attributes that are aimed at mitigating the threat of active shooter incidents, it is necessary to incorporate human behavior into consideration and investigate HBIs during active shooter incidents.

Many research methods, such as emergency drills, controlled laboratory experiments, post-event surveys and interviews, and modeling and simulation, have been used to study HBIs during emergencies to avoid exposing people to life-threatening situations. However, these methods bear several intrinsic limitations, such as scarcity and incompleteness of available behavioral data, failure to represent complex human behavior, and lack of ability to represent realistic building emergency situations (Zou et al. 2017). Virtual Reality (VR) technology, a real or simulated environment in which the perceiver experiences telepresence (Steuer 1992), has become a promising research tool in this area. VR has been used to evaluate the effects of various building attributes in emergencies, such as signage and corridor configurations (Vilar et al. 2014), elevators and stairs (Andrée et al. 2016). Compared with other methods, explorations with VR can provide safe and more realistic emergency scenarios and has the ability to control various environmental variables (Zou et al. 2017). Yet, VR applications to study HBIs in active shooter incidents, to the best of our knowledge, are fairly rare.

Yet, there are several questions that need to be answered before implementing VR-based investigations on HBIs during active shooter incidents. One of the first steps is to identify what information has to be represented in VR environments and how these information requirements should be visualized in order to provide a realistic environment and high ecological validity. Therefore, the objective of this paper is to present and discuss the information requirements for developing the crucial elements of a virtual environment for the sake of investigating HBIs during active shooter incidents.

UNDERSTANDING HBIS DURING ACTIVE SHOOTER INCIDENTS USING VR

Several elements, namely building attributes, building types and layouts, shooting scenarios, and human interactions with the environment are considered to constitute the core of a virtual environment for studying HBIs during active shooter incidents. The reasons for the importance of these elements and their information requirements are presented in the following subsections.

Building attributes

To study HBIs during active shooter incidents, building attributes (e.g., signs, exits, stairs) are indispensable components as they are directly related to human behavior during emergencies (Kobes et al. 2010). However, a practical question is yet to be answered: how to select building attributes that are aimed at mitigating the threat of attacks and evaluate their effectiveness in terms of safety and security using virtual environments? To tackle this issue, the first step could be a review of the published guidelines to identify the most widely proposed protective measures. However, not all of the measures are related to HBIs or relevant to active shooter incidents or could be represented in virtual environments, thus further considerations are needed for the selection process. Table 1 categorizes the objectives of these measures along with corresponding examples. For example, the measure ‘Avoid exposed structural elements’ does not have direct interactions with human behavior; another measure ‘Avoid using glass along primary egress routes or stairwells’ are primarily to protect buildings from bombs and explosions (FEMA 2003b), but this recommended building attribute may also have side effect such as decreasing the level of visual access, which could inhibit people’s wayfinding performance during emergencies (Kobes et al. 2010).

To this end, the authors reviewed several major guidelines and categorized the proposed protective measures, along with the frequency of these measures being proposed and whether they influence human behavior as well as whether they could be represented in VR, as shown in Table 2.

Table 1. Objectives and examples of protective measures against attacks on buildings

Objective of the Measure	Examples of Protective Measures
To reduce the probability of attacks	Install active vehicle crash barriers; Limit the number of doors used for normal entry/egress; Eliminate hiding places.
To minimize the influence of attacks on buildings	Install blast-resistant doors and windows; Avoid exposed structural elements; Avoid using glass along primary egress routes or stairwells.
To protect occupants and facilitate sheltering and evacuation behavior	Create shelter-in-place rooms or areas; Ensure that exterior doors into inhabited areas open outward.
To improve emergency management	Install a backup control center; Install an electronic security alarm system; Install a CCTV surveillance system.

Building types and layouts

Apart from building attributes, building types and layouts are also essential when developing virtual environments. First, unlike natural hazards (e.g., earthquakes), active shooter incidents are target dependent, hence buildings in the same area can have different risk levels. Second, human behavior depends on the type of buildings (e.g., residential vs. office buildings) (Proulx and Pineau 1996) and building layouts (e.g., spatial connectivity) (Tan et al. 2015). Selection of building types could be based on records of past active shooter incidents. For example, among the active shooter incidents in the U.S. from 2000 to 2017, 42% happened in commercial environments and 20.8% happened in educational environments, followed by open space (14%) and governmental areas (10%) (U.S. Department of Justice and Federal Bureau of Investigation 2017). With respect to the selection of building layout, there are two approaches that have been proposed by prior studies (Chittaro and Ranon 2009). The first one is to define the building layout based on an existing building. The major advantage of this approach is that it provides the opportunity to assess whether occupants follow the suggested responses in the emergency management plans and evaluate how people's familiarity with the building impacts their behavior (Lovreglio et al. 2017). Another approach is to use a hypothetical building. This approach is time-efficient since it does not require collecting any data on an existing building (Chittaro and Ranon 2009).

Nevertheless, to effectively investigate HBIs during active shooter incidents and generalize the research findings, an alternative approach needs to be developed due to the reasons elaborated here. First, functions of building attributes are dependent on the building layout. The effect of some building attributes (e.g., door size) can vary during emergencies as the complexity of building layout changes (Ha and Lykotrafitis 2012). Second, people's behavior during building emergencies is contingent upon the type, function and configuration of buildings (Kobes et al. 2010). For example, during the November 2015 Paris attack, a video recorded in a café showed that people who hid behind the bar were successful in not being found by the attacker (Li et al. 2017). Another example is office buildings, for which the two common layouts are open spaces and private offices. These layouts influence human behavior during active shooter incidents. For example, private offices could provide more cover and concealment opportunities for the occupants, whereas compared with open spaces, private office layout allows less social interactions (e.g., helping and competing behavior), which may influence people's responses during active shooter incidents (Li et al. 2017).

Therefore, to generalize research findings on HBIs during active shooter incidents, selected building layouts for the development of virtual environments should be representative. While for certain types of buildings (e.g., schools), the building layout can be geographically different by nature, the selection of building layout should still capture the characteristics of a building type in a certain region. To achieve this purpose, practitioners in related areas and industry standards could be referred to.

Shooting scenarios

Apart from building attributes, the shooting scenario is also a key component when developing virtual environments, as people's behavior can vary greatly in different attack scenarios. Compared with other emergencies (e.g., fires, earthquakes), active shooter incidents have several distinct characteristics. First, human adversaries are present in active shooter incidents. These adversaries are usually targeted at taking lives, which is very different from natural hazards (e.g., fires) and other types of terrorist attacks due to different weapons (e.g., firearms vs. bombs) the adversaries use. Moreover, adversaries can strategically respond to people's behavior and protective measures, while natural hazards (e.g., fires and earthquakes) follow certain intrinsic rules of evolution. Among 160 active shooter incidents in the U.S. between 2000 and 2013, all but two involved single shooters and most of them are males. In at least nine incidents, the shooter first shot and killed a family member(s) in a residence before moving to a more public location to continue shooting. In 40% of the incidents, shooters committed suicide, mostly at the scene of crime (Blair and Schweit 2013). Second, while building fires can last for hours and earthquakes have three seismic stages (Lovreglio et al.

2017), the duration of active shooter incidents is usually short: 69.8% of incidents ended in 5 minutes or less, of which the majority ended before police arrived (Blair and Schweit 2013). Third, crowd behavior during active shooter incidents are different from other emergencies. For example, in building fires, people usually evacuate the building quickly to escape from the fire and recommended actions during earthquakes are 'drop, cover, hold' (Lovreglio et al. 2017). Quite the contrary, in active shooter incidents, people are suggested to take 'run, hide, fight' actions.

Table 2. Summary of protective measures proposed by major guidelines.

Protective measures	FEMA-426	FEMA-427	FEMA-428	FEMA-452	Does it influence human behavior?	Can it be represented in VR?
Install barrier	2		2	2	Y	Y
Make doors open outward	1		1	1	Y	M
Limit the number of doors for normal access	1	1	1	1	Y	Y
Stagger interior doors and offset interior and exterior doors	1		1	1	Y	Y
Use blast-resistant doors	1		1	1	N	N
Install a backup control center	1		1	1	N	N
Protect HVAC systems	7	13	9	7	N	N
Install security lighting, illuminate building access points	2		2	2	Y	Y
Control access	3	5	3	3	Y	Y
Protect utility systems	2		2	2	N	N
Install public address/alarm	3	1	2	2	Y	Y
Eliminate hiding places	1		1	1	Y	Y
Install CCTV camera	1		1	1	N	N
Install call button	1		1	1	Y	M
Reinforce foyer walks structurally	1		1	1	N	N
Isolate unsecured areas from secured areas	4	6	4	4	Y	Y
Avoid exposed structural elements	2		2	2	N	N
Locate stairs remotely. Do not discharge stairs into lobbies, parking, or loading areas	1		1	1	Y	Y
Use shelter rooms	1	1	1	1	Y	Y
Protect walls	3	1	4	3	N	N
Minimize interior glazing near high-risk areas.	1	1	3	2	M	Y
Protect fire system	1		1	1	N	N
Limit nonstructural elements such as false ceilings and metal blinds on the interior.	1	3	1	1	N	N
Limit column spacing		1			Y	Y

(Numbers in the table represent the frequency of measures being proposed in the guidelines; Y: Yes; N: No; M: Maybe)