
Testing the Validity of 2D CAD and 3D Navigable Imagery for Emergency Preparedness



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16. Abstract A series of simulated pre-incident emergency response planning exercises were conducted with 81 firefighters across Eastern North Carolina to explore perceptions of how various formats of building design visualizations affect pre-incident emergency response planning. In total, 81 firefighters were provided with one of three visualization formats of three existing commercial facilities including: (2) two-dimensional computer aided design drawings (CAD), (3) three-dimensional navigable imagery, and (3) a combination of the two. Participants were randomly assigned to a singular visualization format using a randomized design. Participants were asked to explore the structure using the visualization provided to build an understanding of the layout and internal configuration of the facility. ANOVA tests suggest that the format of visualization did have a significant effect on firefighters' perceptions of conceptualization of navigational aspects of buildings, perceptions of conceptualization of building layout and configuration, and perceptions of conceptualization of division connectivity. Results suggest the provision of a combination of 2D CAD and navigable imagery improve conceptualization of building navigation, layout and configuration, and division connectivity. Additionally, the result suggest that all formats are easy to use, are interactive, and participants were comfortable using the formats. Participant feedback to open-ended questions regarding benefits of the visualizations, suggestions for improvements, and uses for pre-incident planning and emergency response activities are presented. The results of this study advance the theoretical knowledge in firefighter safety and pre-incident planning and assists researchers, firefighters, emergency management professionals, and NCDOT professionals in developing effective visualizations to facilitate increased target and high hazard building knowledge and pre-incident planning. The practical implication is that the format of visualization may enable firefighters to train remotely on building navigation and potentially improve the effectiveness of rescue activities and patient and firefighter survivability in potential NCDOT emergency events.			
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EXECUTIVE SUMMARY

Emergencies have the potential to be serious events that can happen at any time and require responsive action to protect life or property (FEMA, 2020). Firefighters and other emergency agencies are routinely dispatched by 911 call centers to events like structure fires, active shooter incidents, building collapses, flash flooding, and cardiac arrests and medical calls. During dispatch, the call center dispatch provides the responding units with the emergency type, building location, and call details to emergency responders. Often, 911 call centers house information in their Computer Aided Dispatch (CAD) systems that can be communicated to first responders prior to arrival. This information may include building, occupant, and/or hazard information. With today's vehicle cab technology and cellular internet connection, pre-incident plans including two-dimensional Computer Aided Design (2D CAD) and web-based links with 3D navigable imagery could be shared with first responders to provide them with various floor plans of the facility so they can make critical entry, travel, and tactical decisions. These decisions can greatly affect firefighter and patient survival when time for search and rescue operations is limited due to decreased oxygen, fire gasses, and other health and safety hazards.

At present, there is an interest in building coordinated pre-incident emergency response plans to enhance life safety and property conservation within the fire-service industry. Standard EAP's are essential for emergency preparedness and business continuity during emergency events. Businesses have begun to coordinate these EAP's with first responders who cover their representative businesses in their response district. Emergency responders create pre-incident emergency response plans to cover these standard occupancy and high and target hazard businesses in their districts. Although these plans may be in place, a potential improvement to these plans would be to incorporate two-dimensional computer aided design (2D CAD) drawings and three-dimensional design information (i.e., 3D navigable imagery) so firefighters and emergency responders may become aware of the interior configuration and layout of the building. As a result, firefighter and patient survival rates may be improved when time for search and rescue operations is limited. To date, no research has examined firefighters' perceptions of incorporating 2D CAD and 3D navigable imagery for developing pre-incident emergency response plans. Additionally, no prior research has examined if the provision of this information will decrease search and rescue time during emergency events. The research questions "*What is the feasibility and practicality of employing 2D CAD and 3D navigable imagery as visual interfaces to improve pre-incident planning?*" and "*What are the characteristics and limitations of the visual interfaces that enhance and limit pre-incident plan development?*" are thereby presented. Examining these research questions and associated hypotheses will uncover the potential for 2D CAD and 3D navigable imagery to be used by professional fire departments

to better prepare their firefighters to perform emergency response activities at NCDOT workplaces and beyond.

To test this, 81 firefighters were provided with one of three visualization formats of three existing commercial facilities including: (2) two-dimensional computer aided design drawings (CAD), (3) three-dimensional navigable imagery, and (3) a combination of the two. Participants were randomly assigned to a singular visualization format using a randomized design. Participants were asked to explore the structure using the visualization provided to build an understanding of the layout and internal configuration of the facility. In all conditions, participants were instructed to respond to a series of statements relating to individual formats of design visualizations using a 7-point Likert scale varying from “Strongly Disagree” to “Strongly Agree.” The average of the participant responses within each visualization format was computed across all three commercial facilities for hypothesis testing. The corresponding null hypotheses are listed below:

Ho1: The format of design information does not affect navigational understanding.

Ho2: The format of design information does not affect understanding of building layout and configuration.

Ho3: The format of design information does not affect understanding of floor connectivity.

Ho4: The format of design information does not affect the formats ease of use.

Ho5: The format of design information does not affect the interactivity of the information.

Ho6: The format of design information does not affect the formats comfort of use.

Ho7: The format of design information does not affect pre-incident response planning.

Analysis of Variance (i.e., ANOVA) analysis suggests a significant difference in the mean of participant Likert scales for hypotheses Ho1 – Ho6 with all p -values ($p < 0.05$). Hypothesis Ho7 p -value was ($p > 0.05$) therefore there is not sufficient to reject the null hypothesis. These results indicate that the provision of 3D navigable imagery and the combination of 3D navigable imagery and 2D CAD are superior to 2D CAD alone as imagery which is used as visual interfaces to improve pre-incident planning. However, in each of the hypotheses it is noted that the mean Likert scales are all above 5 indicating the participants agree to some extent that all formats are useful in practice regarding the questions they were asked about the visualization format. For example, The ANOVA results for hypothesis Ho1: “*The format of design information does not affect navigational understanding.*” suggested a significant difference between the

formats across building locations. The mean response for the 2D CAD Image visualization format was 5.6296 and the mean response for the Matterport visualization format was 6.1481. Lastly the mean response for the Combination (2D CAD and Matterport) was 6.3333 ($p < 0.05$). There is sufficient statistical significance to reject the null hypothesis and conclude that the 3D and combination formats are superior for helping firefighters gain an understanding of how to navigate throughout the building. However, it was found that all three formats are useful for this purpose as participants mean values were above 5 in all three format categories indicating agreement that all formats are useful for gaining an understanding of how to navigate throughout the studies buildings. Table 1 below shows mean Likert values, p -values, and hypothesis rejections for each hypothesis listed above.

Table 1: Mean Likert Values, p-Values, and Hypothesis Rejection Decisions

Hypothesis	Format	Mean Likert Value	P Value	Rejection Decision
Ho1	2D CAD	5.6296	0.0318	Reject Null
	3D Navigable Imagery	6.1481		
	Combination	6.3333		
Ho2	2D CAD	5.8148	0.0422	Reject Null
	3D Navigable Imagery	6.4074		
	Combination	6.3333		
Ho3	2D CAD	5.4444	0.0044	Reject Null
	3D Navigable Imagery	6.3704		
	Combination	6.1481		
Ho4	2D CAD	5.1851	0.0002	Reject Null
	3D Navigable Imagery	6.4074		
	Combination	6.1481		

Ho5	2D CAD	5.4814	0.0029	Reject Null
	3D Navigable Imagery	6.4444		
	Combination	6.3703		
Ho6	2D CAD	5.1481	0.0005	Reject Null
	3D Navigable Imagery	6.1481		
	Combination	6.2222		
Ho7	2D CAD	5.8518	0.0674	Fail to Reject Null
	3D Navigable Imagery	6.5555		
	Combination	6.3703		

In the study, participants were also asked to respond to four separate open-ended questions regarding the format of visualization they were provided during the research trials. The questions were related to positive aspects of the visualization format, potential improvements, and use in pre-incident planning and emergency response activities. Each of the questions received clear and thoughtful feedback. Overall, firefighters thought the 2D CAD drawings had accurate labelling, relevant scaled dimensions, and could be used in a team setting for pre-planning for evaluating fire tactics for a variety of information. Participants provided feedback on improvements including reducing nonessential information, including multiple layers to make it easier to find information by categories, and had excellent ideas for including items such as alarm panned, exterior fire department connections, and entry and exit locations. For the 3D navigable imagery, the firefighters appreciated the ability to remotely visit a building to get an idea of the layout, occupant load, fire load, and special hazards they might face on a real structure fire. They suggested improving the 3D visuals by making all areas of the building accessible in the online space and including exterior walkarounds of the building. In terms of pre-planning, firefighters plan to use both systems to conduct remote site visits and build fire tactics into the pre-plan. During active emergencies, firefighters would like access to the 2D CAD and 3D navigable imagery through Matterport at the command post on PC and iPad/tablet. The shift Captains also requested that the 2D CAD files be delivered in pdf format to the respective departments so they can be uploaded into the Active 911 and First Due first responder systems. Similarly, the departments

also would like access to the Matterport systems. The implementation recommendations are listed in the recommendations and implementation section of this report.

This is the first research to implement the use of a mixture of 2D CAD and 3D navigable imagery in a controlled quasi-experimental study to evaluate the feasibility and practicality of these formats of information on pre-incident planning. The results of this study advance the theoretical knowledge in firefighter safety and pre-incident planning and assists researchers, firefighters, emergency management professionals, and NCDOT professionals in developing effective visualizations to facilitate increased target and high hazard building knowledge and pre-incident planning. The primary contribution to the body of knowledge is that firefighters perceived that both the 3D navigable imagery and the combination of 2D CAD and 3D improved the conceptualization of the navigational aspects of buildings, an understanding of the layout and interior configuration of the buildings, and division/floor connectivity (all $p < 0.05$). For the fire service industry, the current work implies that that the provision of 2D CAD, 3D navigable imagery, and a combination of the two may all have their unique place in pre-incident emergency response planning and during active emergency response activities. Overall, these results suggest the provision of 2D CAD and 3D navigable imagery should increase firefighters' knowledge of the structure and may lead to improved search and rescue times.

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Chapter 1. Introduction

1.1 Background

Emergencies can happen at any time. The most effective way to handle crises is to prepare in advance by creating pre-incident emergency response plans. These written procedures detail the appropriate responses to various types of emergencies. These plans are an essential component of an organization's safety program. Creating emergency response plans and training employees on how to follow them can greatly reduce employee injuries, property damage, and can ensure the safety of visitors in the event of an emergency. The benefits of these plans are further increased when plans are completed in partnership with local emergency response organizations and fire department personnel.

The Occupational Safety and Health Administration (OSHA) outlines general minimum requirements for developing emergency action plans (EAP) for internal operations during an emergency. OSHA's minimum requirement for EAP's include procedures for reporting a fire or other emergency, emergency and delayed evacuation, accountability, medical care, and emergency contact procedures (OSHA, 2002). Additionally, OSHA 1910.120 covers EAP's for hazardous materials incidents that includes outside agency interaction as part of the minimum requirements of the plan (OSHA, 2019). However, OSHA does not require that building floor plans and high target hazards within buildings and facilities be communicated to local emergency management officials and fire departments for standard use facilities. On the other hand, the National Fire Protection Agency (NFPA) outlines guidance as to what information should be contained in EAP's. This includes a site and building floor plans.

During events like structure fires, active shooter incidents, building collapses, flash flooding, and cardiac arrests and medical calls; firefighters and other emergency responders respond to 911 center dispatches and are provided a call scope and other important information. Often, 911 centers house information in their Computer Aided Dispatch (CAD) systems that can be communicated to first responders prior to arrival. This information may include building, occupant, and/or hazard information. With today's vehicle cab technology and cellular internet connection, pre-incident plans including two-dimensional Computer Aided Design (2D CAD) and web-based links with 3D navigable imagery could be shared with first responders to provide them with various floor plans of the facility so they can make critical entry and travel decisions. These decisions can greatly affect firefighter and patient survival when time for search and rescue operations is limited due to decreased oxygen, fire gasses, and other health and safety hazards. Therefore, it is hypothesized that more robust site and floor plans provided across a variety of information formats will result in an increased understanding of facility layout and interior configuration for firefighters. One promising method to improve the quality of a pre-incident plan is to provide a mixture of two- and three-dimensional design information that can be employed by fire department personnel for

pre-incident planning and during live emergencies. To date, no research has examined the effects that the format of design information may have on firefighter's abilities to efficiently develop pre-incident plans or the effects that the format of design information may have on firefighter's abilities to understand the layout and interior configuration of a facility. Research examining these effects will help NCDOT to provide safe work environments for employees and contractors.

1.2 Research Objective and Scope

The objectives for this proposed study will be met in two distinct phases. Phase 1 will consist of site selection and 3D imagery capture. Phase 2 will consist of quasi-experimental data collection trials using the 2D CAD, 3D navigable imagery, and a mixture of the two. The sections below describe the literature review and research methods in detail. This is the first research to implement the use of a mixture of 2D CAD and 3D navigable imagery in a controlled quasi-experimental study to evaluate the feasibility and practicality of these formats of information on pre-incident planning. This project is relevant to NCDOT's commitment of providing a safe workplace by uncovering the potential for 2D CAD and 3D imagery to be used by fire departments to better prepare their firefighters to perform emergency response activities at NCDOT workplaces. This will open the lines of communication for NCDOT to further expand its opportunity to collaborate with representative emergency responders to create working emergency response guidelines for target facilities.

1.3 Research Approach

In total, 81 firefighters were provided with one of three visualization formats of three existing commercial facilities including: (2) two-dimensional computer aided design drawings (CAD), (3) three-dimensional navigable imagery, and (3) a combination of the two. Participants were randomly assigned to a singular visualization format using a randomized design. Participants were asked to explore the structure using the visualization provided to build an understanding of the layout and internal configuration of the facility.

1.4 Report Organization

This report is organized in a manner to communicate the results of the research objective. Organization includes the results of literature review, research objectives and point of departure, research methods, findings and conclusions, discussions, limitations, and conclusions sections. References and appendices are provided.

Chapter 2. Results of Literature Review

2.1 Overview

To accomplish the projects objectives, a literature review was conducted of peer-reviewed journals and conference proceedings from the following search databases: Google Scholar, ECU Laupus Library Data Base, IEEE Explore, Science Direct, and PubMed. Key search phrases included “Firefighting, firefighter safety, emergency response, emergency planning, pre-incident planning, way-finding performance.” The sections below connect firefighter safety and emergency response planning in the context of wayfinding performance and facility navigation and conceptualization during emergency response events.

Additionally, the literature review describes the use of visualization technologies in the context of emergency preparedness, define the context in which this study has been conducted; and provide necessary background to establish the authors’ epistemological positioning for each of the variables under investigation.

2.2 Firefighter Safety and Fatality Statistics

[Firefighting is dangerous work. Fire fighters face many occupational hazards including physical stresses, transportation risks, and a multitude of training and fire ground hazards. Responding to structural fires poses hazards to fire fighters from structural collapse; becoming lost or disoriented and unable to escape before running out of air; and hazards from cuts, burns, abrasions, chemical exposures, and more. Compared to international firefighter injury rates, U.S. firefighters have previously had significantly higher injury rates than most other modern countries (Burges et al, 2014). There are many dangerous aspects of firefighting activities related to firefighter operations inside structure fires. The United States National Fire Protection Association (NFPA) reports that 101 firefighters were killed between 2009 through 2018 while operating inside of structures at active fire scenes. In this span, 34 of the 101 deaths were the result of smoke inhalation or running out of air. Specifically, of the 34 firefighters who died of smoke inhalation or ran out of air, the major causes of injury included structural collapses (10 deaths); becoming lost inside the structure and running out of air (10 deaths); and caught by the progress of the fire, backdraft, or flashover (9 deaths) (FEMA, 2022). In 2020, there were 62 reported non-COVID 19 on-duty firefighter deaths. Of the 62 firefighters who died while on duty in 2020, 27 represented volunteer fire departments, 23 firefighters were career firefighters, 8 were state and federal contractors, and 2 were military members. Of the 62 on-duty deaths, 20 firefighters died on active fireground scenes. A total of 9 of these died at residential and non-residential structure fires (Fahy and Petrillo, 2021). These alarming statistics suggest the need for an increase in the capability for fire departments, and other emergency response organizations, to develop emergency response plans for successful fireground operations to increase firefighter survivability. One area to potentially build upon emergency responders’ capability to

efficiently plan for emergency incidents is simulation exercises and trainings. Specifically, improving firefighter's abilities to identify correct travel routes inside structures during active fire events may help to decrease the probability of firefighters becoming disoriented or lost inside of a structure and running out of air while attempting to escape or awaiting crew member assistance.

2.3 Emergency Response Plans

Emergencies can happen at any time. Emergencies are incidents, whether natural, technological, or human-caused, that require responsive action to protect life or property (FEMA, 2020). When these incidents occur, it is imperative that emergency response plans are in place to reduce the effect of the incident on life and property. The most effective way to handle crises is to prepare in advance by creating pre-incident emergency response plans. As quoted by Perry and Lindell, (2003) emergency preparedness refers to “a state of readiness to respond to environmental threats.” In the context of structure fires, an effective emergency response plan would outline the threats and opportunities and the associated contingencies of on-site fireground operations to ensure successful firefighting operations. The most effective way to handle crises is to prepare in advance by creating pre-incident emergency response plans. These written procedures detail the appropriate responses to various types of emergencies. These plans are an essential component of an organization's safety program. Creating emergency response plans and training employees on how to follow them can greatly reduce employee injuries, property damage, and can ensure the safety of visitors in the event of an emergency. The benefits of these plans are further increased when plans are completed in partnership with local emergency response organizations and fire department personnel.

The United States Occupational Safety and Health Administration (OSHA) outlines general minimum requirements for developing Emergency Action Plans (EAP) for internal operations during an emergency. OSHA's minimum requirement for EAP's include procedures for reporting a fire or other emergency, emergency and delayed evacuation, accountability, medical care, and emergency contact procedures (OSHA, 2002). However, OSHA does not require that building floor plans and high target hazards within buildings and facilities be communicated to local emergency management officials and fire departments for standard use facilities. On the other hand, the National Fire Protection Agency (NFPA) outlines guidance as to what information should be contained in EAP's. This includes a site and building floor plans. Photographs are also used.

During events like structure fires, firefighters and other emergency responders respond to 911 center dispatches and are provided a call scope and other important information. Often, 911 centers house information in their Computer Aided Dispatch (CAD) systems that can be communicated to first responders prior to arrival. This information may include building, occupant, and/or hazard information.

With today's vehicle cab technology and cellular internet connection, pre-incident plans including two-dimensional Computer Aided Design (2D CAD) and web-based links with 3D navigable imagery and first-person game-based digital environments could be shared with first responders and their support staff to provide floor plan information of the facility so interior firefighters can make critical wayfinding decisions. These interior travel decisions have the potential to increase firefighter and patient survival when time for search and rescue operations is limited due to decreased air, increasing fire gasses, and other health and safety hazards.

2.4 Firefighter Wayfinding Performance

Wayfinding is defined as “the process of determining and following a path or route between an origin and destination” (Golledge, 1999, p.6). Wayfinding is an essential part of everyday human life and is critical for firefighters' interior fire attack and search and rescue operations. According to research by Wiener et al. (2009), wayfinding belongs to the most complex cognitive operations as the wayfinder must monitor both external and internal cues while manipulating formal representations of spatial information to effectively travel an identified route. Research has been conducted to improve pedestrian wayfinding performance using various techniques including sketch-map assessments (Rovine and Weisman, 1989), map design (Soh and Smith-Jackson, 2004), color mapping effects (Jansen-Osmann and Wiedenbauer 2004), signage placement and assessment (O'Neil, 1992; Vilar et al., 2014), and simulation tools (O'Neil, 1992; Tang et al., 2009; Joo et al., 2013; and Vilar et al., 2014).

In the fire service, research has identified the navigation strategies that firefighters use during search and rescue operations. Cope et al. (2019) interviewed 12 firefighters from 3 regions of the US to understand the navigation strategies during interior search and rescue missions. Specifically, they performed semi-structured interviews with firefighters, asking them to explain how they navigate indoor environments during rescue searches. The results suggest four distinct groups of strategies were consistent among the firefighters. These included: (1) building a mental pathway (i.e., right-hand rule, staying connected to the fire hose, etc.), (2) improving their visibility (i.e., using flashlights or thermal camera), (3) using cognitive strategies (i.e., landmarks and structure assessment), and (4) using directional aids (i.e., directed search, etc.) (Cope et al., 2019). In terms of cognitive strategies, firefighters create mental representations of interior spaces based on external information. Firefighters must process spatial information quickly as their first exposure to the internal layout of a building is usually during search and rescue operations on active firegrounds (Cope et al., 2019).

Research has been conducted to improve firefighter wayfinding performance. For example, research has examined the effectiveness of virtual reality applications for administering spatial navigation training to firefighters (Bliss et al., 1997). Bliss et al. (1997) conducted an experiment where 30 firefighters were

randomly assigned to 3 experimental groups of 10 participants each including a virtual reality group, a 2D drawing group, and a control group. Treatment group participants were provided the design of an actual as-built facility and trained on its spatial configuration. Once trained, firefighters completed simulated search and rescue tasks. The results of the experiment show that the treatment group participants outperformed the control group participants in terms of errors made in the search and rescue task. These results suggest the provision of design information in 2D drawings or virtual reality formats may help firefighters reduce the time spent inside structures by increasing building familiarity and decreasing wayfinding time. However, the results show that there was no significance difference between the effectiveness of virtual reality and 2D drawing formats on wayfinding performance (Bliss et al., 1997). Additionally, research by Hsiao et al., 2016 presented a discussion on the characteristics of firefighter wayfinding under low visibility conditions by having 55 firefighters participate in controlled search and rescue activities at a training facility. In their experiment, 55 firefighters wore full firefighter turnout gear and performed search and rescue activities while equipped with a radio frequency identification tag to track firefighter location and derive search and rescue operation task times by individual rooms. The results suggest low visibility environments decrease space familiarity suggesting that an adaptation period for both physical and psychological states might be required for search and rescue operations when multiple rooms are involved. Additionally, the results show that highly complex room structures resulted high rates of wayfinding confusion and led to errors that increased task completion time (Hsiao et al., 2016). For this reason, it is suggested that designing a more effective wayfinding strategy is crucial for firefighter and patient survivability in active structure fire incidents.

2.5 Three-Dimensional Modelling and 3D Photogrammetry Based Technologies

In recent years, researchers have made significant improvements in the tools available to model buildings and facilities using 3D technologies (Hardison and Hallowell, 2019). Current 3D modeling tools offer pre-defined objects that facilitate the development, routing, and connection of building systems in 3D, and provide conflict detection mechanisms that help to automatically identify physical interferences between components (Staub-French, 2007). Many construction industry research efforts have discussed the potential of these tools to significantly improve design coordination and project execution. Typically, construction design information may range from two-dimensional computer aided drawings (CAD) to three-dimensional building information models (BIM) (Goodrum et al., 2016). Recently game engine software has become more accessible to non-commercial developers, opening the door to exploration of gaming engines as platforms for simulation (McGrath and Hill, 2004 and Politowski et al., 2021).

In addition to these technologies, three-dimensional photogrammetry has shown promise as serving a critical role in emergency response planning. Photogrammetry is defined as “*the art, science, and*

technology of obtaining reliable information about physical objects and the environment through processes of recording, measuring, and interpreting photographic images and patterns of recorded radiant electromagnetic energy and other phenomena” (DeWitt and Wolf, 2000). Three-dimensional photogrammetry, on the other hand, is a technique used to create three-dimensional models from a series of interconnected two-dimensional photographs which involves taking multiple images of an object from various angles and then using specialized software to analyze these images, identify overlapping patterns, and stitch them together to form a cohesive 3D representation. This is typically done in third party proprietary software that comes at an expense for the user. The core principle behind photogrammetry is that by comparing the differences in perspective between the photographs, the software can calculate depth and spatial relationships, ultimately reconstructing the object’s geometry into a precise model which can be explored based on the number of reference positions the imagery was captured from (Awange et al., 2013).

Currently, several platforms are available to capture 3D spaces with photogrammetry and create navigable virtual 3D spaces for users to explore. For example, The Matterport Pro 2 system is a web-based platform that allows users to create 3D digital twins of any given space by capturing 3D scans using a 3D camera. A digital twin, or Matterport Space, is a visually immersive, accurate, and interactive 3D model of a real-world space (Matterport, 2023). These expansive design and visualization technologies provide open platforms for research in the domain of first responder and occupational safety as they present novel and unique approaches to visualizing design intent and as-built spaces. In sum, alarming firefighter fatality statistics, the need for improved emergency response plans, previous research in firefighter wayfinding performance, and technological advancements in BIM and 3D photogrammetry (hereinafter referred to a 3D navigable imagery) provided the inspiration for this research.

Chapter 3. Research Objectives and Point of Departure

The objectives for this proposed study will be met in two distinct phases. Phase 1 will consist of site selection and 3D imagery capture. Phase 2 will consist of quasi-experimental data collection trials using the 2D CAD, 3D navigable imagery, and a mixture of the two. The sections below describe the literature review and research methods in detail. The following null research hypotheses will be tested in this proposed study.

Ho1: The format of design information does not affect navigational understanding.

Ho2: The format of design information does not affect understanding of building layout and configuration.

Ho3: The format of design information does not affect understanding of floor connectivity.

Ho4: The format of design information does not affect the formats ease of use.

Ho5: The format of design information does not affect the interactivity of the information.

Ho6: The format of design information does not affect the formats comfort of use.

Ho7: The format of design information does not affect pre-incident response planning.

This is the first research to implement the use of a mixture of 2D CAD and 3D navigable imagery in a controlled quasi-experimental study to evaluate the feasibility and practicality of these formats of information on pre-incident planning. This project is relevant to NCDOT's commitment of providing a safe workplace by uncovering the potential for 2D CAD and 3D imagery to be used by fire departments to better prepare their firefighters to perform emergency response activities at NCDOT workplaces. This will open the lines of communication for NCDOT to further expand its opportunity to collaborate with representative emergency responders to create working emergency response guidelines for target facilities.

Chapter 4. Research Methods

The research activities and methodology for this proposed study will occur in two distinct phases. Phase 1 will consist of site selection and 3D imagery capture. Phase 2 will consist of quasi-experimental data collection trials using the 2D CAD and 3D Matterport navigable images as design information. The research steps within each of these phases is outlined in the sections below.

4.1 Phase 1: Site Selection and 3D Matterport Imagery Capture

At the beginning of the award, the PI consulted with NCDOT staff to identify three target site that were to be employed in the study. Care was taken to ensure the selected facility fits the scope of the project by being large enough to necessitate emergency response planning by local emergency responders and two-dimensional computer aided design (2D CAD) drawings exist for the as-built facility. Facilities without 2D CAD documents were excluded from the list as 2D CAD is required as a format of design information that will be used for hypothesis testing. The PI, along with NCDOT staff agreed on the following locations to be used for testing. They are listed below:

1. NCDOT Resident Engineers Office. Location: 1629 US 258 South, Kinston, NC 28504
2. NCDOT Division 2 Engineers Office. Location: 2815 Rouse Road Extension, Kinston, NC 28504
3. NCDOT Century Center. Location: 1000 Birch Ridge Dr., Raleigh, NC 27610

These locations were selected as they were considered large enough to necessitate emergency response planning by local emergency responders and a form of two-dimensional computer aided design (2D CAD) drawings exist for these as-built facilities. Additionally, the facilities were approximately 200,000 square foot in size or less and the PI has demonstrated capability to capture buildings of this size with the Matterport software. One the sites were identified, digital.pdf copies of the 2D CAD documents were collected by the PI with the assistance of the NCDOT research team and opportunities to capture 3D Matterport imagery was scheduled at the target facility. Scheduling was primarily completed by the PI for the Kinston, NC offices and the Century Center (Building A) was scheduled by NCDOT staff. These facilities were also selected as there was a commitment from the City of Kinston Fire Department, North Lenoir Fire Department, and Southwood Fire Department to assist with data collection in these areas. Additionally, the City of Raleigh Fire Department in Raleigh, NC agreed to assist with data collection since the Century Center was in their response district. This increases the ecological validity of the research results by having firefighters participate in the research by viewing design deliverables of facilities in their immediate response districts. Table 2 below shows the facility name and the primary and mutual aid responders. A Google Streetview image of each facility is shown in the images below.

Table 2: Location and Fire Department Responders

Facility Name	First Dispatch Organization	Mutual Aid Dispatch Organization
NCDOT Resident Engineers Office	North Lenoir VFD	City of Kinston FD
NCDOT Division 2 Engineers Office	Southwood VFD	City of Kinston FD
NCDOT Century Center	City of Raleigh FD	Wake County Emergency Mgt. as Directed by Incident Commander



Figure 1: NCDOT Resident Engineers Office, Kinston, NC.



Figure 2: NCDOT Resident Engineers Office, Kinston, NC.



Figure 3: NCDOT Century Center (Building A), Raleigh NC.

4.2 Quasi Experimental Testing

To study the effects of format of design information on emergency response planning, a counterbalanced and blocked research design, inspired by traditional Latin square designs, was developed. A Latin square is an experimental design that controls for the negative effects of multiple variable interactions by blocking the treatment and independent variables. Within Latin square designs, the number of levels of independent variables must equal the number of levels of the treatment factor. This creates an orthogonal ($n \times n$) matrix to cross the treatment factors with the independent variables to assess the variability in the data of an independent variable for a single population group (Edwards, 1951 and McNemar, 1951).

An adapted 3x3 Latin square design (see Table 3) has been developed to cross the 3 treatment factors (i.e., design information format) with the 3 independent variables (i.e., facility ID). This resulted in a counterbalanced 2-factor blocked design; factors including design information format and facility ID. The design information formats include 2D CAD, 3D Imagery, and a combination of the two.

Table 3: Experimental Research Design

Quasi-Experimental Research Design		Information Format		
		2D CAD	3D Imagery	Combination
Facility ID	NCDOT Resident Engineers Office, Kinston NC	N = 9	N = 9	N = 9
	NCDOT Division 2 Engineers Office, Kinston NC	N = 9	N = 9	N = 9
	NCDOT Century Center (Bldg. A), Raleigh NC	N = 9	N = 9	N = 9
Total Participants by Column		N = 27	N = 27	N = 27

As can be seen in table 3 above, 9 participants were assigned to a single cell in the matrix within a set of experimental arrangements that balance the order of research trial and control for confounding errors. This provided a total of N=27 participants within each row and column to examine the effects of the treatment and independent variables. Benefits of this experimental design are that it: (1) allows for the removal of any learning curve as participants will only be placed into one cell within the matrix; (2) allows the assessment of variability of means within the independent variable; and (3) ensures that the variability in performance is truly attributable to the format of design information (Edwards, 1951 and McNemar,1951).

The first objective for building the necessary design information files for testing was to acquire the 2D CAD files for each of the target facilities. This was initiated by gathering the necessary NCDOT contacts from the research team. The NCDOT Resident Engineers Office in Kinston NC included a full set of 2D CAD drawings including the civil, architectural, structural, plumbing, and electrical plans dated 2006. Next, the NCDOT Division 2 Engineers office in Kinston, NC included a revisions 2D CAD file including architectural, mechanical, and electrical drawings dated 2018 as this building was repurposed at that time. Finally, the NCDOT Century Center in Raleigh, NC included a 2D CAD drawing of an architectural floor plan, visitor and conference room map, and color-coded unit area map of building A and B. These files have been delivered as products of this research along with the final research report.

Another objective of the research was to compile a set of three-dimensional 360-degree navigable imagery of the target facilities using the Matterport Pro2 system made by Matterport, Inc. The Matterport Pro 2 system is a web-based platform that allows users to create 3D digital twins of any given space by capturing 3D scans using a 3D camera. A digital twin, or Matterport Space, is a visually immersive, accurate, and interactive 3D model of a real-world space (Matterport, 2023). To collect imagery, the PI team accessed the facilities over days when limited pedestrians were inside the buildings. Care was taken

to ensure that each image captured was in the required proximity to the next image capture to ensure research participants had the capability to jump from one position to another in the Matterport Space. All images of the Kinston, NC facilities were captured in one single online space. The Century Center building was captured in three separate spaces at different elevations within the facility which were separated by interior hallway stairs. All images were taken at an eye height of approximately 72 inches. Imagery was captured to ensure the entirety of building spaces and building systems were included in the Matterport Space. Once the imagery was collected, the files were uploaded and rendered through Matterport’s web-based system and stored on a NCDOT Matterport cloud account. Then, a shared web link allowed access to each building division and Matterport space during research trials using internet access. The links to these Matterport spaces are currently listed in a NCDOT Matterport account.

A total of 81 firefighters from the Pine Knoll Shores FD, Atlantic Beach FD, City of Kinston, NC FD and Raleigh FD participated in this study. Firefighters were chosen as the target population since they are the agencies that will respond to fire and life safety emergencies requiring search and rescue activities to save the lives of NCDOT employees and citizens in the target facilities. Professional firefighters were allowed to participate if they hold the Firefighter certification through the North Carolina Office of the State Fire Marshal. This Firefighter certification complies with the NFPA 1001, 2019 Standard for Firefighter Professional Qualifications and will ensure a homogenous and qualified population to answer the research questions. This will also ensure the results are externally generalizable to a larger population within the fire service. An ANOVA sample size calculation ($\alpha = 0.05$) yielded an $N = 27$ required for each treatment group (i.e., design information format). The selection and order of the research trials will be assigned using the adapted research design. Table 4 below presents the participant demographic characteristics.

Table 4: Participant Demographic Characteristics

Demographic Characteristic	Count	Mean	Median	Minimal Value	Maximum Value
Age	-	35.06	32	19	61
Years of Driving Experience	-	12.67	10	1	41
Gender (Female/Male)	4 / 77	-	-	-	-

Data were collected at fire stations across Pine Knoll Shores FD (PKS FD), Atlantic Beach FD (AB FD), Kinston FD (KFD), and Raleigh FD (RFD). These include PKS FD, AB FD, KFD Station #1, and RFD stations #1, #9, #10, #11, #12, #14, #16, and # 26. Once a participant was randomly assigned to one of the experimental conditions, participants were briefed about the research process. Randomization was set by creating a randomized and mutually exclusive list of 81 numbers from 1 to 81. For example, the first

research participant was randomly assigned research booklet #37 which included the Matterport imagery as the format of design information for the NCDOT Division 2 Engineers Office building on Rouse Road in Kinston, NC. The second research participant was randomly assigned research booklet #37 which included the Combination as the format of design information for the NCDOT Century Center building in Raleigh, NC. Each participant was then provided a copy of the research instructions which read “*You are being asked to review design information of office style facility to better understand the internal layout and configuration of the building. You will be presented with design information and asked to review the design information until you are comfortable with the layout and configuration of the building. You will then be asked to respond to the following questions.*” Once the researcher verified the participant understood the directions, the participant was provided with the appropriate visualization format and was allowed an unrestricted time to navigate the visualization. All visualizations were delivered to the research participant using a Dell G7 laptop with a 17” monitor. The 2D CAD files were provided in digital .pdf format. The 3D navigable Imagery was provided through the Matterport cloud link with secure internet access. In all conditions, participants were instructed on the navigation of the visualization prior to beginning the research tasks. Participants time was not restricted in any of the conditions. Participants were instructed to verbally indicate when they were finished with the visualization. No part of the experimental process was time restricted. Participants were asked to respond to the following statements using a 7-point Likert scale varying from “Strongly Disagree” to “Strongly Agree.” An excerpt of the participant survey is shown in Figure 4 below.

Q1: The design information visualizes navigational aspects of the building.

Q2: The design information helped me understand the building layout and interior configuration of the facility.

Q3: The design information helped me understand the connectivity of the various divisions of the facility.

Q4: This design information is easy to use.

Q5: The design information is interactive.

Q6: I was comfortable during the practical experience with the design information.

Q7: The design information could be used to facilitate pre incident planning.

Question 1: Do you agree or disagree with the following statement? (Circle One)						
Statement: "The design information visualizes navigational aspects of the building"						
Strongly Disagree	Disagree	Somewhat Disagree	Neither Disagree nor Agree	Somewhat Agree	Agree	Strongly Agree
(1)	(2)	(3)	(4)	(5)	(6)	(7)

Figure 4: Survey Excerpt (Question 1)

Question 1 specifically addresses research hypothesis Ho1 as the question relates to the potential *conceptualization of navigational aspects of buildings*. Question 2 addresses research hypothesis Ho2 as the question relates to the potential *conceptualization of building layout and configuration*. Additionally, Question 3 addresses research hypothesis Ho3 as the question relates to the potential *conceptualization of division connectivity*. Lastly, questions 4-7 were included in the survey for exploratory analysis.

In addition to this, participants were also asked a series of open-ended questions about the design information. This information was used explore firefighter opinions of the design information formats and identify methods to implement them on the fire ground and during training operations. The questions are listed in order below and are discussed in further detail in the results and conclusions section.

Q8: What specifically about the design information was useful for you to understand the layout and interior configuration of the building?

Q9: How do you think the design information can be improved to help you better understand the layout and interior configuration of the building?

Q10: How do you think the design information can be best used for pre-incident planning?

Q11: How do you think the design information can be best used during an active response?

The aggregate of participant responses was combined across all facility identifiers (Resident Engineers Office, Division 2 Engineers Office, and Century Center) within each design information format (2D CAD, 3D Visualization, and combination) for each study question. This was done as the variability of participant responses within each design information format is the primary variable under investigation. It is important to note that the variability of participant responses across facility identifier within each format of design information was not investigated as part of this research as this variable was seen to lack relevant importance. The research team and PI chose not to investigate variability in responses across facilities within a single design information format as the broader results should be generalizable across all three target facilities. Additionally, all responses for the open-ended questions were compiled for each question within each format of design information and later transcribed by the PI into Microsoft Word.

Chapter 5. Findings and Conclusions

5.1 Results

A total of 81 firefighters participated in this research. Of the 81 participants, 10 participants were from Atlantic Beach FD, 15 were from the City of Kinston NC FD, 15 were from Pine Knoll Shores FD, and 41 were from Raleigh NC FD. The average age of the research participants was 35 years old with a range of 19 years to 61 years old. The average length of active firefighting experience of the research participants was 12.67 years with a range of 1 years to 41 years of firefighting experience. The participants came from a wide range of organizational ranks including Chief (n = 1), Assistant Chief (n = 1), Battalion Chief (n = 5), Division Chief (n = 2), Fire Inspector (n = 3), Captain (n = 20), Engineer (i.e., industry term for apparatus driver and pump operator) (n = 5), Lieutenant (n = 7), and Firefighter (n = 37). Table 5 below shows a breakdown of participant demographics by department.

Table 5: Participants Demographics by Department

Department	Age	Experience	Rank
Atlantic Beach FD (ABDF)	n = 10 $\mu = 34$ Range Low = 19 Range High = 36	$\mu = 11.5$ Range Low = 1 Range High = 41	Chief = 0 Assistant Chief = 1 Battalion Chief = 0 Division Chief = 0 Fire Inspector = 2 Captain = 1 Engineer = 1 Lieutenant = 0 Firefighter = 5
City of Kinston FD (KFD)	n = 15 $\mu = 33.6$ Range Low = 19 Range High = 53	$\mu = 14.63$ Range Low = 4.5 Range High = 30	Chief = 0 Assistant Chief = 0 Battalion Chief = 2 Division Chief = 0 Fire Inspector = 0

			Captain = 7 Engineer = 1 Lieutenant = 2 Firefighter = 3
Pine Knoll Shores FD (PKSFD)	n = 15 $\mu = 32.6$ Range Low = 20 Range High = 61	$\mu = 9.76$ Range Low = 2 Range High = 32	Chief = 1 Assistant Chief = 0 Battalion Chief = 0 Division Chief = 0 Fire Inspector = 1 Captain = 3 Engineer = 0 Lieutenant = 0 Firefighter = 10
Raleigh FD (RFD)	n = 41 $\mu = 36.75$ Range Low = 19 Range High = 61	$\mu = 13.31$ Range Low = 1 Range High = 37	Chief = 0 Assistant Chief = 0 Battalion Chief = 3 Division Chief = 2 Fire Inspector = 0 Captain = 9 Engineer = 3 Lieutenant = 5 Firefighter = 19
Total	n = 81 $\mu = 35.06$ Range Low = 19 Range High = 61	$\mu = 12.67$ Range Low = 1 Range High = 41	Chief = 1 Assistant Chief = 1 Battalion Chief = 5 Division Chief = 2

			Fire Inspector = 3
			Captain = 20
			Engineer = 5
			Lieutenant = 7
			Firefighter = 37

Data analysis was conducted between each visualization condition group using analysis of variance (ANOVA). The ANOVA statistical test determines whether there is a difference between means of independent variables (Dielman 2005; Fellows and Liu 2008). This test estimates statistically significant differences between the mean values using an F value while measuring the variability of the dependent variable that is explained by the independent variable (Dielman 2005; and Fellows and Liu 2008). This parametric test was selected as the Likert scale data is, in this case, treated as interval data with equal spacing between scale values across the four visualization format categories. This is further addressed in the study limitations. Each research hypothesis and exploratory analysis is discussed in the sections below.

5.2 Examining the Effect of Visualization Format on Navigation Conceptualization

The first hypothesis Ho1: “*The format of design information does not affect navigational understanding.*” was tested using ANOVA analysis in R statistical package. Within R, the format of visualization was set as a factor for ANOVA analysis. The data for Question 1 were found to be normally distributed for all conditions ($p > 0.05$). Table 6 below provides the sample size, sample mean scale rating, F, and p values of ANOVA analysis of Likert scale data by experimental condition across all participants.

Table 6: Visualization Format ANOVA Results Across all Study Participants for Question 1

Visualization Format	Sample Size	Mean Likert Response	F	p
2D CAD	27	5.6296	3.606	0.0318*
Matterport Imagery	27	6.1481		
Combination	27	6.3333		

Note: F = variance of the group mean; p = significance.

Asterisk (*) = Statistically significant difference beyond 95% confidence.

Overall, there was a significant difference in the mean of the 7-point Likert responses for Question 1. The mean response for the 2D CAD Image visualization format was 5.6296 and the mean response for the Matterport visualization format was 6.1481. Lastly the mean response for the Combination (2D CAD and Matterport) was 6.3333. The ANOVA analysis suggests that there is sufficient statistical significance to reject the null hypothesis H_0 for the treatment group ($F(2,78) = 3.606, p < 0.05$). Therefore, the results suggest the format of visualization does affect firefighters' perceptions of potential conceptualization of navigational aspects of buildings. A boxplot of Likert scale data for each visualization format is shown in Figure 5 below. A bar chart of mean survey data is also shown in Figure 6 below.

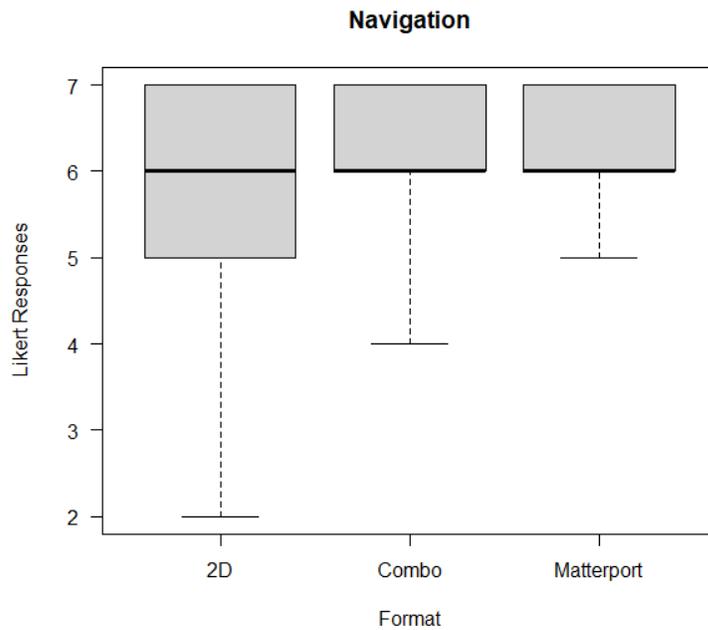


Figure 5: Likert Data for Visualization Format Across all Study Participants for Question 1

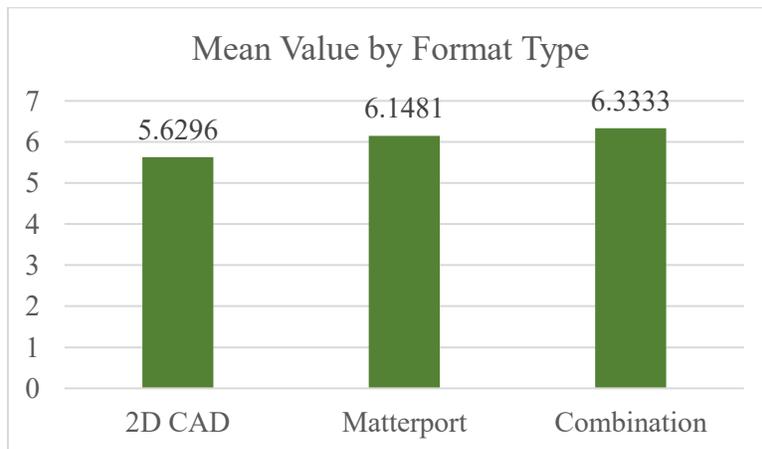


Figure 6: Mean Likert Value of Responses for Question #1 by Visualization Format

5.3 Examining the Effect of Visualization Format on Building Layout and Interior Configuration Conceptualization

The second hypothesis Ho2: “*The format of design information does not affect understanding of building layout and configuration.*” was tested using ANOVA analysis in R statistical package. Within R, the format of visualization was set as a factor for ANOVA analysis. The data for Question 2 were found to be normally distributed for all conditions ($p > 0.05$). Table 7 below provides the sample size, sample mean scale rating, F, and p values of ANOVA analysis of Likert scale data by experimental condition across all participants.

Table 7: Visualization Format ANOVA Results Across all Study Participants for Question 2

Visualization Format	Sample Size	Mean Likert Response	F	p
2D CAD	27	5.8148	3.297	0.0422*
Matterport Imagery	27	6.4074		
Combination	27	6.3333		

Note: F = variance of the group mean; p = significance.

Asterisk (*) = Statistically significant difference beyond 95% confidence.

Overall, there was a significant difference in the mean of the 7-point Likert responses for Question 2. The mean response for the 2D CAD Image visualization format was 5.8148 and the mean response for the Matterport visualization format was 6.4074. Lastly the mean response for the Combination (2D CAD and Matterport) was 6.3333. The ANOVA analysis suggests that there is sufficient statistical significance to reject the null hypothesis Ho2 for the treatment group ($F(2,78) = 3.297, p < 0.05$). Therefore, the results suggest the format of visualization does affect firefighters’ perceptions of potential conceptualization of building layout and internal configuration. A boxplot of Likert scale data for each visualization format is shown in Figure 7 below. A bar chart of mean survey data is also shown in Figure 8 below.

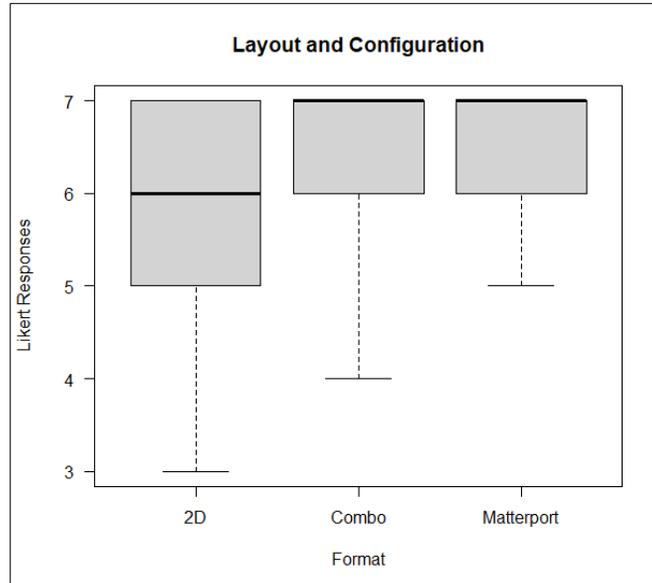


Figure 7: Likert Data for Visualization Format Across all Study Participants for Question 2

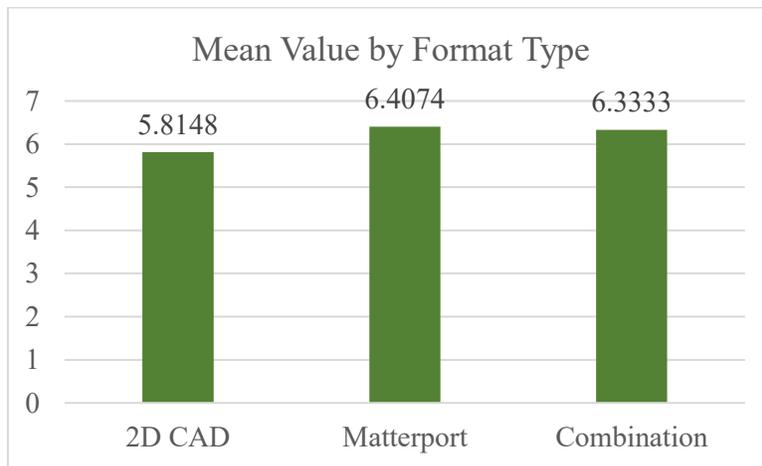


Figure 8: Mean Likert Value of Responses for Question #2 by Visualization Format

5.4 Examining the Effect of Visualization Format on Floor Connectivity

The third hypothesis Ho3: “*The format of design information does not affect understanding of floor connectivity.*” was tested using ANOVA analysis in R statistical package. Within R, the format of visualization was set as a factor for ANOVA analysis. The data for Question 3 were found to be normally distributed for all conditions ($p > 0.05$). Table 8 below provides the sample size, sample mean scale rating, F, and p values of ANOVA analysis of Likert scale data by experimental condition across all participants.

Table 8: Visualization Format ANOVA Results Across all Study Participants for Question 3

Visualization Format	Sample Size	Mean Likert Response	F	p
2D CAD	27	5.4444	5.832	0.0044*
Matterport Imagery	27	6.3704		
Combination	27	6.1481		

Note: F = variance of the group mean; p = significance.

Asterisk (*) = Statistically significant difference beyond 95% confidence.

Overall, there was a significant difference in the mean of the 7-point Likert responses for Question 3. The mean response for the 2D CAD Image visualization format was 5.4444 and the mean response for the Matterport visualization format was 6.3704. Lastly the mean response for the Combination (2D CAD and Matterport) was 6.1481. The ANOVA analysis suggests that there is sufficient statistical significance to reject the null hypothesis Ho3 for the treatment group ($F(2,78) = 5.832, p < 0.05$). Therefore, the results suggest the format of visualization does affect firefighters' perceptions of potential conceptualization of a buildings division (i.e., floor) connectivity. A boxplot of Likert scale data for each visualization format is shown in Figure 9 below. A bar chart of mean survey data is also shown in Figure 10 below.

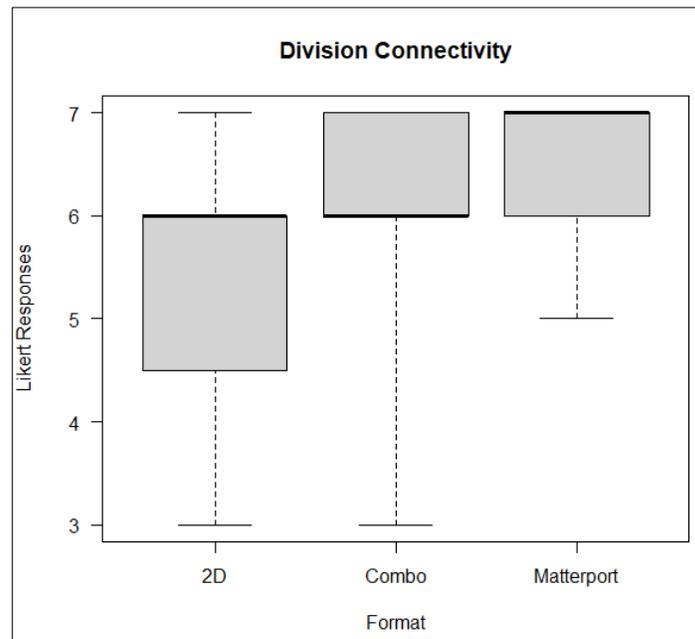


Figure 9: Likert Data for Visualization Format Across all Study Participants for Question 3

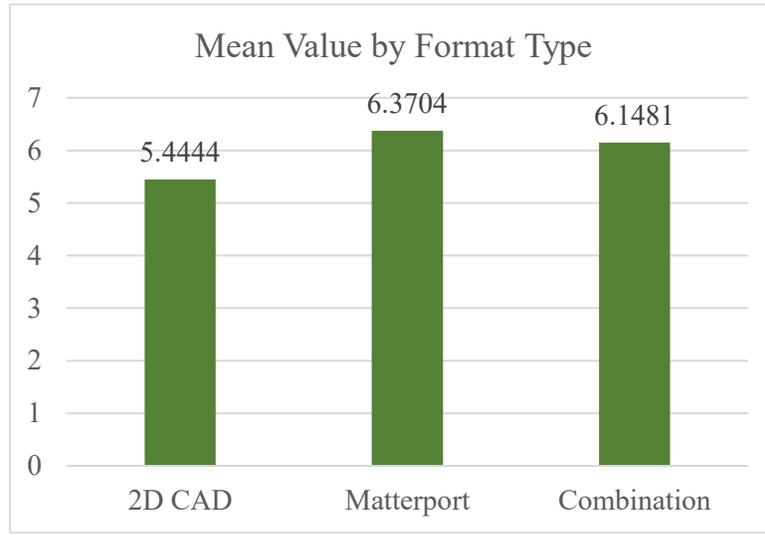


Figure 10: Mean Likert Value of Responses for Question #3 by Visualization Format

5.5 Examining the Effect of Visualization Format on Ease of Use

The fourth hypothesis Ho4: “*The format of design information does not affect the formats ease of use.*” was tested using ANOVA analysis in R statistical package. Within R, the format of visualization was set as a factor for ANOVA analysis. The data for Question 4 were found to be normally distributed for all conditions ($p > 0.05$). Table 9 below provides the sample size, sample mean scale rating, F, and p values of ANOVA analysis of Likert scale data by experimental condition across all participants.

Table 9: Visualization Format ANOVA Results Across all Study Participants for Question 4

Visualization Format	Sample Size	Mean Likert Response	F	p
2D CAD	27	5.1851	9.098	0.0002*
Matterport Imagery	27	6.4074		
Combination	27	6.1481		

Note: F = variance of the group mean; p = significance.

Asterisk (*) = Statistically significant difference beyond 95% confidence.

Overall, there was a significant difference in the mean of the 7-point Likert responses for Question 4. The mean response for the 2D CAD Image visualization format was 5.1851 and the mean response for the

Matterport visualization format was 6.4074. Lastly the mean response for the Combination (2D CAD and Matterport) was 6.1481. The ANOVA analysis suggests that there is sufficient statistical significance to reject the null hypothesis H_0 for the treatment group ($F(2,78) = 9.098, p < 0.05$). Therefore, the results suggest the format of visualization does affect firefighters' perceptions of the formats ease of use. A boxplot of Likert scale data for each visualization format is shown in Figure 11 below. A bar chart of mean survey data is also shown in Figure 12 below.

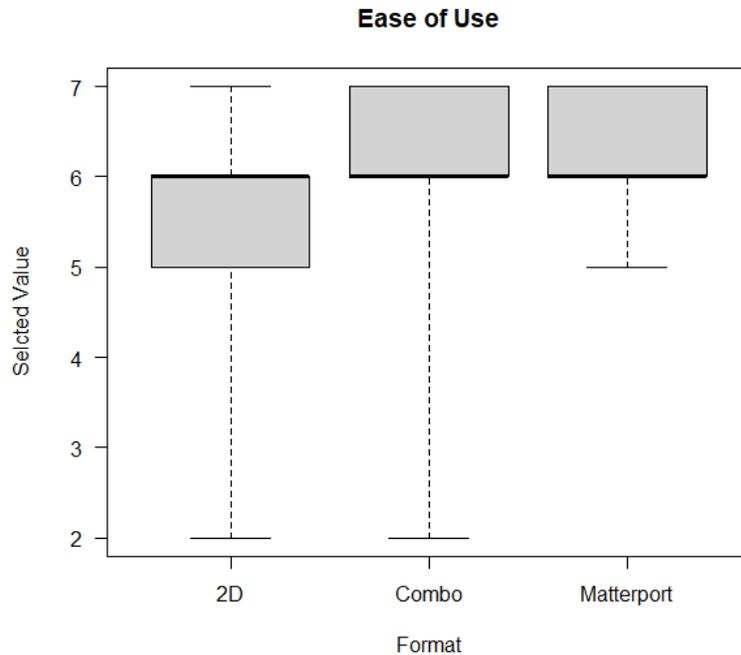


Figure 11: Likert Data for Visualization Format Across all Study Participants for Question 4

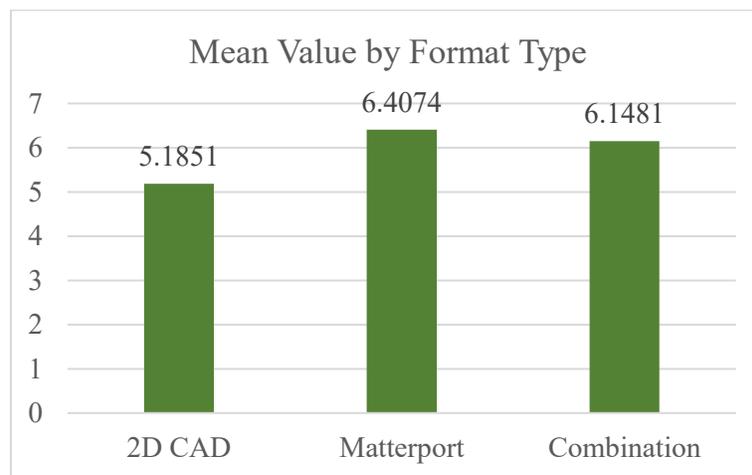


Figure 12: Mean Likert Value of Responses for Question #4 by Visualization Format

5.6 Examining the Effect of Visualization Format on Information Interactivity

The fifth hypothesis Ho5: “*The format of design information does not affect the interactivity of the information.*” was tested using ANOVA analysis in R statistical package. Within R, the format of visualization was set as a factor for ANOVA analysis. The data for Question 5 were found to be normally distributed for all conditions ($p > 0.05$). Table 10 below provides the sample size, sample mean scale rating, F, and p values of ANOVA analysis of Likert scale data by experimental condition across all participants.

Table 10: Visualization Format ANOVA Results Across all Study Participants for Question 5

Visualization Format	Sample Size	Mean Likert Response	F	p
2D CAD	27	5.4814	6.319	0.0029*
Matterport Imagery	27	6.4444		
Combination	27	6.3703		

Note: F = variance of the group mean; p = significance.

Asterisk (*) = Statistically significant difference beyond 95% confidence.

Overall, there was a significant difference in the mean of the 7-point Likert responses for Question 5. The mean response for the 2D CAD Image visualization format was 5.4814 and the mean response for the Matterport visualization format was 6.4444. Lastly the mean response for the Combination (2D CAD and Matterport) was 6.3703. The ANOVA analysis suggests that there is sufficient statistical significance to reject the null hypothesis Ho5 for the treatment group ($F(2,78) = 6.319, p < 0.05$). Therefore, the results suggest the format of visualization does affect firefighters’ perceptions of the formats interactivity. A boxplot of Likert scale data for each visualization format is shown in Figure 13 below. A bar chart of mean survey data is also shown in Figure 14 below.

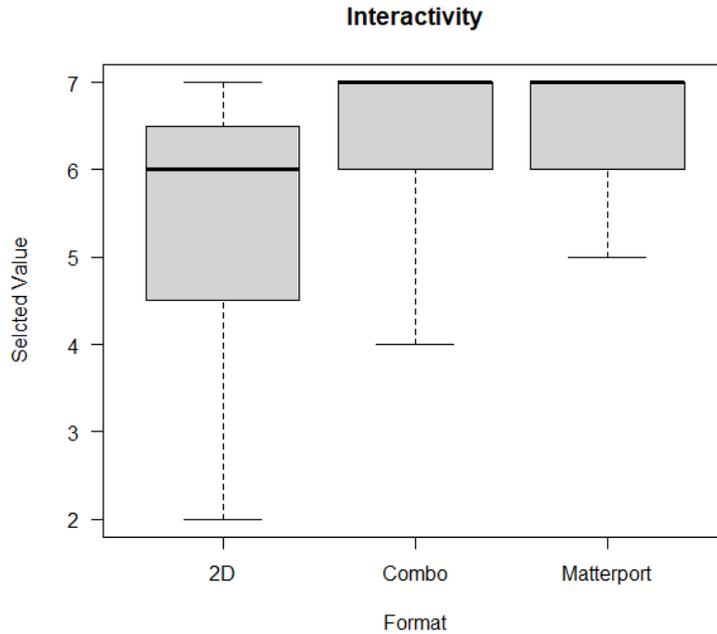


Figure 13: Likert Data for Visualization Format Across all Study Participants for Question 5

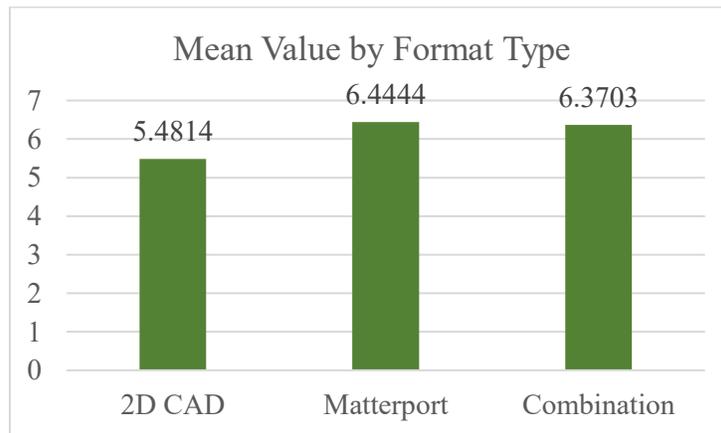


Figure 14: Mean Likert Value of Responses for Question #5 by Visualization Format

5.7 Examining the Effect of Visualization Format on Comfort of Use

The sixth hypothesis Ho6: “*The format of design information does not affect the formats comfort of use.*” was tested using ANOVA analysis in R statistical package. Within R, the format of visualization was set as a factor for ANOVA analysis. The data for Question 6 were found to be normally distributed for all conditions ($p > 0.05$). Table 11 below provides the sample size, sample mean scale rating, F, and p values of ANOVA analysis of Likert scale data by experimental condition across all participants.

Table 11: Visualization Format ANOVA Results Across all Study Participants for Question 6

Visualization Format	Sample Size	Mean Likert Response	<i>F</i>	<i>p</i>
2D CAD	27	5.1481	8.469	0.0005*
Matterport Imagery	27	6.1481		
Combination	27	6.2222		

Note: *F* = variance of the group mean; *p* = significance.

Asterisk (*) = Statistically significant difference beyond 95% confidence.

Overall, there was a significant difference in the mean of the 7-point Likert responses for Question 6. The mean response for the 2D CAD Image visualization format was 5.1481 and the mean response for the Matterport visualization format was 6.1481. Lastly the mean response for the Combination (2D CAD and Matterport) was 6.2222. The ANOVA analysis suggests that there is sufficient statistical significance to reject the null hypothesis H_{06} for the treatment group ($F(2,78) = 8.469, p < 0.05$). Therefore, the results suggest the format of visualization does affect firefighters' perceptions of the formats comfort of use. A boxplot of Likert scale data for each visualization format is shown in Figure 15 below. A bar chart of mean survey data is also shown in Figure 16 below.

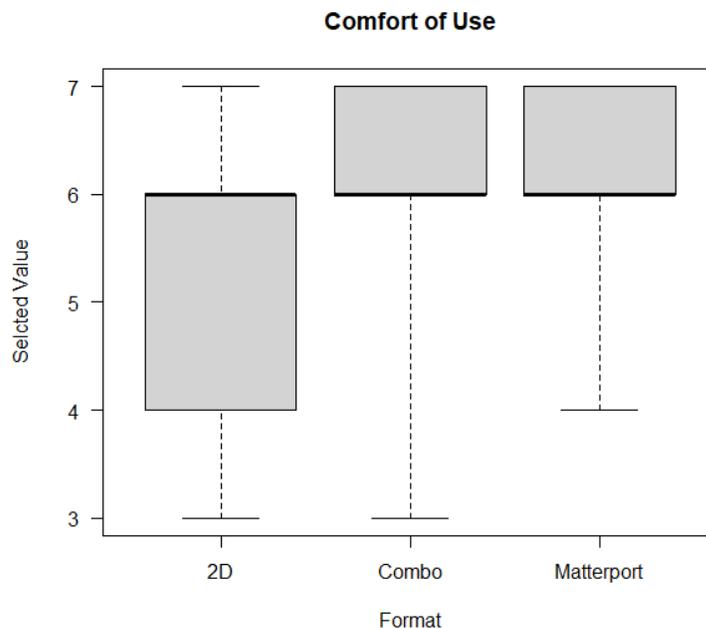


Figure 15: Likert Data for Visualization Format Across all Study Participants for Question 6

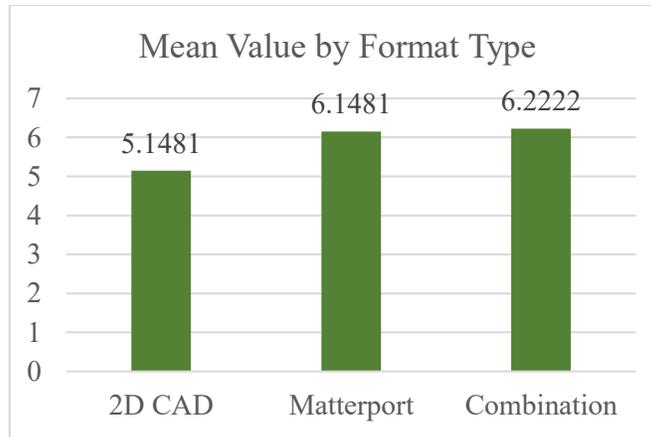


Figure 16: Mean Likert Value of Responses for Question #6 by Visualization Format

5.8 Examining the Effect of Visualization Format on Pre-Incident Planning

The seventh hypothesis Ho7: “*The format of design information does not affect pre-incident response planning.*” was tested using ANOVA analysis in R statistical package. Within R, the format of visualization was set as a factor for ANOVA analysis. The data for Question 7 were found to be normally distributed for all conditions ($p > 0.05$). Table 12 below provides the sample size, sample mean scale rating, F, and p values of ANOVA analysis of Likert scale data by experimental condition across all participants.

Table 12: Visualization Format ANOVA Results Across all Study Participants for Question 7

Visualization Format	Sample Size	Mean Likert Response	F	p
2D CAD	27	5.8518	2.792	0.0674
Matterport Imagery	27	6.5555		
Combination	27	6.3703		

Note: F = variance of the group mean; p = significance.

Asterisk (*) = Statistically significant difference beyond 95% confidence.

Overall, there was a not significant difference in the mean of the 7-point Likert responses for Question 7. The mean response for the 2D CAD Image visualization format was 5.8518 and the mean response for the Matterport visualization format was 6.5555. Lastly the mean response for the Combination (2D CAD and Matterport) was 6.3703. The ANOVA analysis suggests that there is not sufficient statistical significance to reject the null hypothesis Ho7 for the treatment group ($F(2,78) = 2.792, p > 0.05$). Therefore, the

results suggest the format of visualization does not affect firefighters' perceptions of the usefulness of the format for pre-incident planning. A boxplot of Likert scale data for each visualization format is shown in Figure 17 below. A bar chart of mean survey data is also shown in Figure 18 below. The results of this section are discussed in the discussion section below.

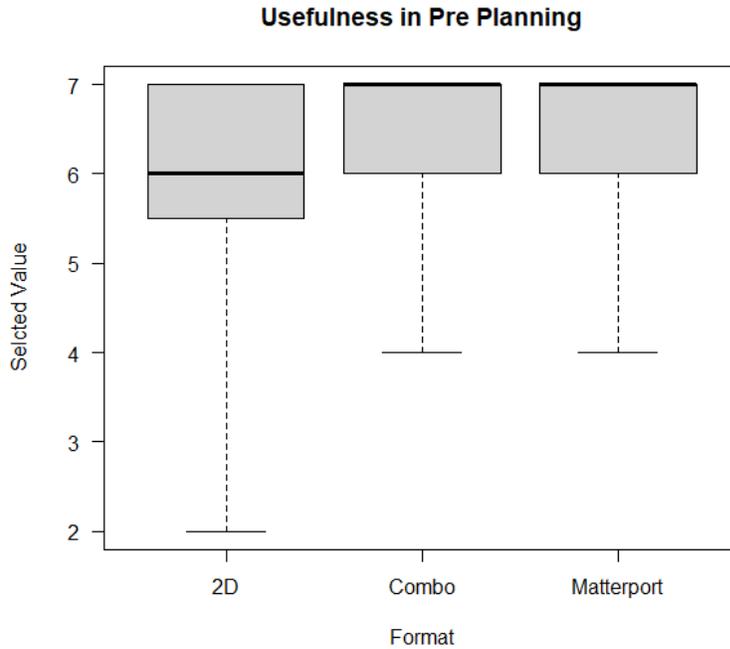


Figure 17: Likert Data for Visualization Format Across all Study Participants for Question 7

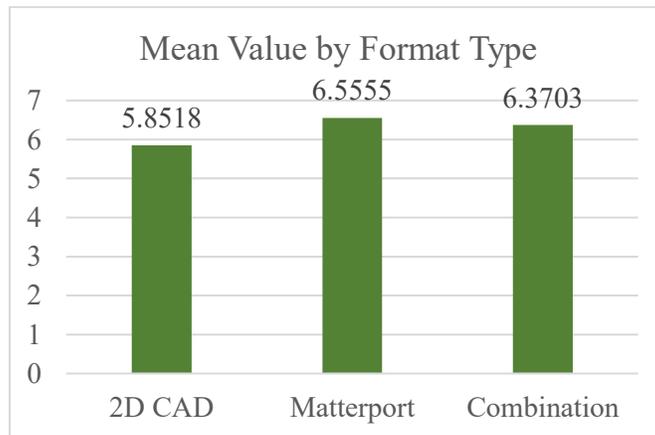


Figure 18: Mean Likert Value of Responses for Question #7 by Visualization Format

Chapter 6. Discussion

This investigation explores the effects of real-world building design visualizations on firefighters' perceptions of their usefulness in understanding building characteristics and implementation for pre incident planning and emergency response activities. This is the first research to implement the use of a mixture of 2D CAD and 3D navigable imagery in a controlled quasi-experimental study to evaluate the feasibility and practicality of these formats of information on pre-incident planning. The research questions “*What is the feasibility and practicality of employing 2D CAD and 3D navigable imagery as visual interfaces to improve pre-incident planning?*” and “*What are the characteristics and limitations of the visual interfaces that enhance and limit pre-incident plan development?*” are explored by using a mixture of quantitative and qualitative analysis techniques. Examining these research questions and associated hypotheses has uncover potential uses for 2D CAD and 3D navigable imagery to be used by professional fire departments to better prepare their firefighters to perform emergency response activities at NCDOT facilities.

6.1 Quantitative Analysis Discussion

Analysis of Variance (i.e., ANOVA) statistical results found that there is a statistically significant difference in the mean of the Likert responses across the visualization formats for firefighters' perception on formats usefulness in understanding how to navigate throughout the building. From the ANOVA results in Table 6 above, the mean value of the 2D CAD format is ($\mu = 5.6296$), Matterport is ($\mu = 6.1481$), and the combination of the two is ($\mu = 6.3333$) with a ($p = 0.0318$). These results suggest the Matterport and Combination visualization formats provide the most utility to gaining and understanding of the navigational aspects of buildings as these values are higher. However, the researcher sees importance in all three formats as the mean values of the Likert data indicate that firefighters somewhat agree (i.e., #5 Likert Selection Point) to strongly agree (#7 Likert Data Selection Point) that all formats are useful in understanding how to navigate through the building. Although there is sufficient statistical significance to reject null hypothesis *H01: The format of design information does not affect navigational understanding* and conclude that the Matterport and combination formats are superior, it is suggested to continue to develop 2D CAD documentation as it is seen as useful.

Likewise, ANOVA statistical results found that there is a statistically significant difference in the mean of the Likert responses across the visualization formats for firefighters' perception on formats usefulness in understanding building layout and configuration. From the ANOVA results in Table 7 above, the mean value of the 2D CAD format is ($\mu = 5.8148$), Matterport is ($\mu = 6.4074$), and the combination of the two is ($\mu = 6.3333$) with a ($p = 0.0422$). These results suggest the Matterport and Combination visualization formats provide the most utility to gaining and understanding of building layout and configuration as

these values are higher. However, the researcher sees importance in all three formats as the mean values of the Likert data indicate that firefighters agree that all formats are useful in understanding building layout and configuration. Although there is sufficient statistical significance to reject null hypothesis *Ho2: The format of design information does not affect understanding of building layout and configuration* and conclude that the Matterport and combination formats are superior, it is suggested to continue to develop 2D CAD documentation as it is also seen as useful.

ANOVA statistical results also found that there is a statistically significant difference in the mean of the Likert responses across all facilities and within each visualization format for firefighters' perception on formats usefulness in understanding of floor connectivity. From the ANOVA results in Table 8 above, the mean value of the 2D CAD format is ($\mu = 5.4444$), Matterport is ($\mu = 6.3704$), and the combination of the two is ($\mu = 6.1481$) with a ($p = 0.0044$). These results suggest the Matterport and Combination visualization formats provide the most utility to gaining and understanding of floor connectivity as these values are higher. This is seen as important in buildings with multiple divisions or floors. However, the researcher again sees importance in all three formats as the mean values of the Likert data indicate that firefighters agree that all formats are useful in understanding floor connectivity. Although there is sufficient statistical significance to reject null hypothesis *Ho3: The format of design information does not affect understanding of floor connectivity* and conclude that the Matterport and combination formats are superior, it is suggested to continue to develop 2D CAD documentation.

ANOVA analysis was used to investigate firefighters perceptions on the formats level of ease of use (*Ho4*), interactivity (*Ho5*), comfort (*Ho6*), and usefulness in pre-incident planning (*Ho7*). With regard to the formats ease of use (*Ho4*), there was a statistically significant difference among the three formats with 2D CAD ($\mu = 5.1851$), Matterport ($\mu = 6.4074$), and the combination ($\mu = 6.1481$) with a $p = 0.0002$ suggesting the 2D CAD format is the least favorable. However, firefighters agreed again that all three formats were easy to use. Therefore, the researcher suggests developing all three formats for use. Additionally, ANOVA analysis suggests firefighters agreed that all three formats were interactive (*Ho5*) as mean Likert data for the 2D CAD is ($\mu = 5.4814$), Matterport is ($\mu = 6.4444$), and the combination is ($\mu = 6.3703$) with a $p = 0.0029$. This suggests the firefighters thought all formats were interactive suggesting adoption in the industry. In terms of the formats comfort of use (*Ho6*), firefighters generally agreed that all formats were comfortable to use in the field. The mean Likert data for the "Comfort" variable for 2D CAD is ($\mu = 5.181$), Matterport is ($\mu = 6.1481$), and the combination format is ($\mu = 6.2222$) with a $p = 0.0005$. These results suggest that all three formats are easy and comfortable to use and are interactivity. This is important as these factors will greatly contribute to field adoption during high-stress emergency events.

Lastly - and in contrast to the results above - ANOVA results suggest there is no statistically significance difference in the mean of the Likert responses across all facilities and within each visualization format for firefighters' perception on formats usefulness in pre-incident planning. From the ANOVA results in Table 12 above, the mean value of the 2D CAD format is ($\mu = 5.8518$), Matterport is ($\mu = 6.5555$), and the combination of the two is ($\mu = 6.3703$) with a ($p = 0.0674$). These results suggest that no format is superior to another. Therefore, the researcher must fail to reject null hypothesis Ho7: The format of design information does not affect pre-incident response planning and conclude that no individual format is superior in this regard. However, firefighters agreed with the mean Likert selections that all three formats are useful in pre-incident planning. Since firefighters agreed that all formats are useful, it is suggested that NCDOT continue to develop 2D CAD and Matterport systems as shown in the implementation section of the report. A qualitative analysis of open-ended questions is addressed below.

6.2 Qualitative Analysis Discussion

Research participants were asked to read each question and write their responses on paper using a pencil provided by the PI. Participants were asked to write legibly so the responses could be later transcribed into excel by the researcher. Participants had an unrestricted time to write in their responses to each of the for questions and could answer the questions in any order that they chose. The PI transcribed the data into the tables shown below and compiled a series of themes for each of the visualization formats across all building locations. The PI transcribed a place holder text of "No response from participant" where the participant failed to answer the question. A breakdown of the participant responses across the visualization format categories by question is provided below. The sections below present a breakdown of responses across all and within each format category. Other hemes are present and not identified in narrative format. The remaining themes are shown in the tables below. A full summary of responses can be seen in Appendix B. The questions asked are as follows:

Q8: What specifically about the design information was useful for you to understand the layout and interior configuration of the building?

Q9: How do you think the design information can be improved to help you better understand the layout and interior configuration of the building?

Q10: How do you think the design information can be best used for pre-incident planning?

Q11: How do you think the design information can be best used during an active response?

The responses for question #8: *What specifically about the design information was useful for you to understand the layout and interior configuration of the building?* received a variety of responses. Across all formats of visualizations, 17 participants stated that the visualization was helpful in helping the

understand where everything was at, 14 stated that it helps them understand building layout, 11 stated that the formats helped them understand where they needed to go. Additionally, 9 stated the formats provided good visuals and 7 stated the Matterport software provided remote access experiences and 6 indicated it was easy to use. Other remarks can be seen in table 13 below. For the 2D CAD format, 5 participants stated the 2D CAD helps them understand building layout and 3 stated it helps them understand where everything is. Additionally, 4 participants stated that the 2D CAD helps them understand access and entry locations. The 3D visualization format had higher number of responses in this regard with 6 participants stating that it helps them understand where everything is and builds an understanding of building layout. Two participants liked the color-coded sections in the NCDOT Century Center conference room map as it was helpful at quickly identifying the target area in the facility. Furthermore, the 3D visualization provided good visuals (6) and a remote experience (6). The combination format had a higher number of participants state the visualizations clarified where everything was at inside the building with 8 statements. Overall, there was 1 participant that did not respond to question #8 in the 3D visualization format category and 3 that did not respond in the Combination format. In the combination format, 8 firefighters stated the formats together were helpful in knowing where everything is in the building and 6 indicated the formats helped them know where to go inside the building.

Table 13: Open-Ended Themes for Question #8

Open-Ended Themes	2D CAD	3D Navigation	Combination	Total Across all Formats
Where everything is at	3	6	8	17
Building layout	5	6	3	14
Ease of operation/Understanding	-	5	1	6
Remote access/experience	-	6	1	7
Color coded sections	3	-	1	4
Hallways	1	-	1	2
Travel paths	2	-	1	3
Room numbers	2	-	1	3
Entry and exit locations	4	-	1	5
Fire alarm and sprinkler locations	-	-	1	1
Accurate labeling	-	-	1	1
Map	3	-	2	5
Good visuals	-	6	3	9
Where to go	2	3	6	11
Hazard items	1	1	-	2

AED	2	1	-	3
Measurement tool	-	1	-	1
Fire flow Calculations	-	2	-	2
Shows divisions	1	-	-	1
Sizes of rooms	2	-	-	2
Window locations	2	-	-	2
Phone based pdf	2	-	-	2
Door locations	3	-	-	3
No response	-	1	3	4
Total	41	38	34	-

The responses for question #9: *How do you think the design information can be improved to help you better understand the layout and interior configuration of the building?* also received a variety of responses. Across all formats of visualizations, 15 participants stated that the visualization needs to have the fire department connections (FDC) listed in the 3D space. Eleven participants stated the 3D spaces need to be improved by including all interior spaces (i.e., locked rooms, closets, etc.) in the visuals to make the spaces complete and realistic. Additionally, 10 participants stated the room labeling and door labels need to be complete, accurate, and included in the model if it is to be used in a practical application. Nine participants suggested removing unnecessary info and adding scaled dimensions to the 2D CAD drawings and the 3D format. For the 2D CAD format, 7 participants would like the FDC, FACP, and room labels included on the maps. Six participants would like to see the CAD format improved by adding the FACP location. Additionally, participants suggested adding scaled dimensions (5), and removing unnecessary info from the plans. Four firefighters wanted the target hazards, standpipe, fire alarm zones, water shutoff, and street orientations listed on the map. For 3D, 9 firefighters stated they wanted to see all areas included in the 3D spaces. Four indicated that they wanted increased access to door locations and 3 indicated they wanted FDC's, smoke detectors, and roof ventilation hatches included in the 3D space. Additionally, 3 firefighters wanted an exterior walkaround of the structure. A total of 4 firefighters stated that nothing needed to be improved in the 3D format alone. Lastly, 5 firefighters thought the combination format needed FDC's listed, and the system needed an exterior walkaround so they could locate exterior items. Four firefighters indicated a need to remove unnecessary info from the 2D drawings in the combination format.

Table 14: Open-Ended Themes for Question #9

Open-Ended Themes	2D CAD	3D Navigation	Combination	Total Across all Formats
FDC	7	3	5	15
Include all interior areas	-	9	2	11
Door/access locations	3	4	3	10
Room labeling	7	2	1	10
FACP	6	1	2	9
Remove unnecessary information	5	-	4	9
Scaled dimensions	5	2	2	9
Sprinkler/riser rooms	7	-	2	9
Exterior walkaround	-	3	5	8
Multiple layers	3	2	3	8
Street orientation	4	2	2	8
Smoke detectors	1	3	3	7
Roof hatches	1	3	3	7
Link to Active 911/First Due	1	3	3	7
Water shutoff	4	1	2	7
Electrical shutoff	3	2	2	7
Hydrant locations	3	2	2	7
Fire alarm zones	4	-	2	6
Gas shutoff	2	1	2	5
Standpipe locations	4	-	1	5
Nothing to improve	-	4	1	5
HAZMAT	-	2	2	4
Hazard locations	4	-	-	4
No response	-	3	1	4
Window locations	2	1	-	3
Interior connections	3	-	-	3
Knox box	-	1	1	2
Key holder info	1	-	1	2
Mechanical	1	1	-	2
Add simulated smoke conditions	-	1	-	1
Add 2D map	-	1	-	1
Refuge/safe areas	1	-	-	1
Construction details	1	-	-	1
Column corner references	1	-	-	1
Load bearing/firewalls	1	-	-	1
Total	85	57	57	-

The responses for question #10: *How do you think the design information can be best used for pre-incident planning?* received clear and thoughtful feedback. Overall and across all formats, 21 participants stated the 3D and combination formats allowed for effective remote site visits, 20 indicated they would use the formats in a group setting, and 18 stated the formats were useful for learning building layout. Seventeen firefighters would use the formats to plan fire attack tactics for a variety of emergency scenarios and 12 stated they would use the formats to identify hazards and 11 for entry locations. In the 2D CAD format category, 6 participants stated that they would use the documents in a group setting and to learn the layout of the buildings. Six also stated they would use the documents to plan for fire tactics for a variety of situations and 5 said they would use them to list hazards. There were 2 firefighters that did not respond to this question in the 2D format. In the 3D category, 11 participants stated they would use the format for a site visit when getting a crew out to a site is impractical or they would respond to the building for mutual aid when buildings are outside of their response districts. A total of 8 firefighters stated they would use the format to learn the layout of the building and 7 would use it in a team setting. The combination format is closely aligned with the 3D format. For 3D, a total of 10 participants would use the combined 3D and 2D CAD visuals to conduct a remote site visit and 7 indicated they would use it in a team setting. A total of 5 participants indicated they would use the formats to plan fire tactics for various scenarios.

Table 15: Open-Ended Themes for Question #10

Open-Ended Themes	2D CAD	3D Navigation	Combination	Total Across all Formats
Remote visit	-	11	10	21
Learn layout	6	8	4	18
Use in a team setting	6	7	7	20
Plan for fire attack based on location	6	6	5	17
Identify entry and exit locations	4	5	2	11
Create lists of hazards	5	4	3	12
Identify FACP locations	2	3	2	7
Estimate hose lays	2	2	1	5
Locate FDC	-	2	2	4
Learn about interior contents	1	1	1	3
Not sure	1	1	1	3
Upload to Active911/First Due	1	1	-	2
Identify fire suppression systems	-	1	1	2

Use with a 2D map to build pre-plan	-	1	1	2
Locate smoke detectors	-	1		1
Use it with walk through	3	-	1	4
Would not use for pre-planning	2	-	1	3
Estimate building size and dimensions	1	-	-	1
Estimate equipment needs	1	-	-	1
Identify HAZMAT locations	1	-	-	1
Fire prevention audits	-	-	1	1
Find electrical panel	-	-	1	1
No response	2	1	1	4
Total	42	54	44	-

The responses for question #11: *How do you think the design information can be best used during an active response?* also received clear and thoughtful feedback. Overall and across all formats, 21 participants stated the formats would be best used at the command post during active incidents with 17 stating all formats would be useful to help firefighters identify interior travel routes and during rapid intervention (RIT) scenarios. A total of 9 participants stated the formats could be used onboard apparatus/firetrucks while responding to a call. For the 2D CAD format, 7 stated the 2D should be used at the command post, 4 stated it should be used to track the location of interior crews, and 3 stated the documents could be used to identify interior travel routes, locate entry points, locate victim/patient locations, and locate fire locations. Two participants stated the 2D CAD should be uploaded into the Active911 and/or First Due systems. For the 3D format, 7 participants stated the 3D visuals should be used at the command post and for RIT scenarios. A total of 6 stated the system should be used to identify interior travel routes and 4 stated it should be used onboard apparatus. One firefighter stated the 3D visuals should be linked to the Active911 and/or First Due systems. For the combination format, 9 firefighters indicated the visuals were useful for RIT scenario, 8 stated it should be used to help communicate travel routes, and 7 stated it should be used at the command post. A total of 3 firefighters did not answer this question in the 2D CAD category and 1 firefighter did not answer in either the 3D or combination format categories.

Table 16: Open-Ended Themes for Question #11

Open-Ended Themes	2D CAD	3D Navigation	Combination	Total Across all Formats
Used at command post	7	7	7	21
RIT	1	7	9	17
Identify interior travel routes	3	6	8	17
Used onboard apparatus	1	4	4	9
Locate entry point	3	1	2	6
Track interior crew locations	4	1	1	6
Multi agency/complex incidents	-	3	2	5
Locate victims/patients	3	2	-	5
Would not use	1	2	1	4
Locate hazards	-	2	1	3
Locate FDC	1	1	1	3
Uploaded to Active911/First Due	2	1	-	3
Locate fire location	3	-	-	3
Locate FACP	1	-	1	2
Used by police	1	-	1	2
Locate electrical rooms	2	-	-	2
Locate knock box	-	-	1	1
Locate HAZMAT	-	1	-	1
Not sure	-	1	-	1
Locate mechanical rooms	1	-	-	1
Locate ventilation areas	1	-	-	1
Locate standpipes	1	-	-	1
Locate HVAC	1	-	-	1
Locate apparatus parking locations	1	-	-	1
Locate gas shutoffs	1	-	-	1
Locate hazardous conditions	1	-	-	1
Locate sprinkler rooms	1	-	-	1
Prioritize search locations	1	-	-	1
Used during fire alarm activations	1	-	-	1
No response	3	1	1	5
Total	43	39	39	-

Chapter 7. Limitations

This study has a few notable limitations. First, care was taken to ensure the target facility of the study was appropriate for the study and represented actual NCDOT facilities. Although the facilities selected contain various size characteristics and multiple floors, multiple occupancy uses, and intricate layout, the results of this study may not hold true for other facilities with different layout and configurations and end occupancy uses. More hypothesis testing around facilities, buildings, and even residential structures is needed to understand how these formats of visualizations affect firefighters' perceptions on their use for pre-incident planning and response activities. Therefore, the results of this study are limited to facilities of similar size, layout, configuration, and occupancy uses.

Second, although care was taken to ensure that the results are generalizable to NCDOT and the fire service industry, all study participants were native to the Northeast Central and Coastal Plains regions of North Carolina within the United States. Further samples of fire service industry practitioners are needed to further generalize these research findings to a broader and global audience. For this reason, the results of this research may not be generalizable outside of North Carolina and the United States. Although a diverse population of firefighters were solicited for participation; the results may not hold true for those outside of the scope of municipal operations. For this reason, future research is needed to test these hypotheses across populations outside those municipal fire service industries and on a global scale.

Third, although care was taken to ensure sufficient sample size to test the research hypotheses across a homogenous population of firefighters, different sample characteristics may have yielded different results. For this reason, a limitation is noted relating to the unbalance in firefighter organizational rank among firefighters. In future studies, a balanced sample across organizational rank would allow researchers to test the effects of visualization format on organizational ranks. Additional testing and further validation are suggested to test these effects.

Lastly, the authors recognize the potential limitations arising from the interpretation and analysis of Likert data as interval data. The authors humbly recognize that true Likert scale data is ordinal data since it can be ranked while the distance between each rank value is not quantitatively measurable or equidistant. However, the use of four formats of visualization being randomly prescribed to participants across three facility conditions establishes the appropriateness of the research team to use Analysis of Variance (ANOVA) as the statistical technique for hypothesis testing. Additionally, all data were found to be normally distributed across all formats of information for questions Q1-Q7. Although this limitation is noted, the authors believe the use of ANOVA as a non-parametric test within the study design is most appropriate. Although these limitations are humbly recognized, the authors believe the strength of this study lies in the target population, random assignment, experimental rigor, and robust visualizations.

Chapter 8. Conclusions

Firefighting is a dangerous occupation that calls for quick decisions in high stress environments. The lack of information surrounding emergency incidents and the associated hazards within NCDOT facilities that firefighters face upon arriving and working on scene has the potential to create hazardous situations for firefighters. One way to combat the challenges of these hazards and to better prepare fire departments to save NCDOT property and life is to develop pre-incident emergency response plans that address these hazards and identify various types of potential exposures. Although the necessity of pre-incident emergency response plans is documented (Perry and Lindell, 2003), there is limited research to date examining how various visualizations of facilities, buildings, and residential structures may be communicated or affect the quality of emergency response plans or on-site firefighting operations. The objective of the current study was to explore the effects of the format of design visualizations on firefighters' perception of their use for pre-incident planning and during emergency response activities. Specifically, the objective of this research was to measure the variability of firefighters' perceptions of a set of 2D CAD drawings, 3D navigable imagery via Matterport, and a combination of the two on the perceptions of their use for improving conceptualization of the navigational aspects of buildings, the conceptualization of building layout and configuration, and the conceptualization of division connectivity. Additionally, this is the first research to implement the use of a mixture of 2D CAD and 3D navigable imagery in a controlled quasi-experimental study to evaluate the feasibility and practicality of these formats of information on pre-incident planning. The research was conducted by completing the following objectives: 1) developing 2D CAD and 3D navigable imagery visualizations for testing, 2) soliciting participants, 3) administering experiment design, and 4) data analysis.

The results of this study advance the theoretical knowledge in firefighter safety and pre-incident planning and assists researchers, firefighters, emergency management professionals, and NCDOT professionals in developing effective visualizations to facilitate increased target and high hazard building knowledge and pre-incident planning. The primary contribution to the body of knowledge is that firefighters perceived that both the 3D navigable imagery and the combination of 2D CAD and 3D improved the conceptualization of the navigational aspects of buildings, an understanding of the layout and interior configuration of the buildings, and division/floor connectivity (all $p < 0.05$). Overall, these results suggest the provision of 2D CAD and 3D navigable imagery should increase firefighters' knowledge of the structure and may lead to improved search and rescue times.

The ANOVA results for hypothesis Ho1: "*The format of design information does not affect navigational understanding.*" suggested a significant difference between the formats across building locations. The mean response for the 2D CAD Image visualization format was 5.6296 and the mean response for the

Matterport visualization format was 6.1481. Lastly the mean response for the Combination (2D CAD and Matterport) was 6.3333 ($p < 0.05$). There is sufficient statistical significance to reject the null hypothesis and conclude that the 3D and combination formats are superior for helping firefighters gain an understanding of how to navigate throughout the building. However, it was found that all three formats are useful for this purpose as participants mean values were above 5 in all 3 format categories indicating agreement that all formats are useful for gaining an understanding of how to navigate throughout the studies buildings.

The ANOVA results for hypothesis Ho2: “*The format of design information does not affect understanding of building layout and configuration.*” suggested a significant difference between the formats across building locations. The mean response for the 2D CAD Image visualization format was 5.8148 and the mean response for the Matterport visualization format was 6.4074. Lastly the mean response for the Combination (2D CAD and Matterport) was 6.3333 ($p < 0.05$). There is sufficient statistical significance to reject the null hypothesis and conclude that the 3D and combination formats are superior for helping firefighters gain an understanding of how to navigate throughout the building. However, it was found that all three formats are useful for this purpose as participants mean values were above 5 in all 3 format categories indicating agreement that all formats are useful for gaining an understanding of building layout and configuration.

The ANOVA results for hypothesis Ho3: “*The format of design information does not affect understanding of floor connectivity.*” suggested a significant difference between the formats across building locations. The mean response for the 2D CAD Image visualization format was 5.4444 and the mean response for the Matterport visualization format was 6.3704. Lastly the mean response for the Combination (2D CAD and Matterport) was 6.1481. ($p < 0.05$). There is sufficient statistical significance to reject the null hypothesis and conclude that the 3D and combination formats are superior for helping firefighters gain an understanding of how to navigate throughout the building. However, it was found that all three formats are useful for these purposes as participants mean values were above 5 in all 3 format categories indicating agreement that all formats help build an understanding of floor connectivity.

The ANOVA results for hypothesis Ho4 (Ease of Use), Ho5 (Interactivity), and Ho6 (Comfort) suggested a significant difference between the formats across building locations similar to Ho1, Ho2, and Ho3. The results suggest that the 3D and Combination formats are superior to 2D CAD alone (both $P < 0.05$). However, it was found that all three formats are useful for these purposes as participants mean values were above 5 in all 3 format categories indicating agreement that all formats are easy and comfortable to use and interactive.

Lastly, the ANOVA results for hypothesis Ho7: “*The format of design information does not affect pre-incident response planning.*” suggested a significant difference between the formats across building locations. The mean response for the 2D CAD Image visualization format was 5.8518 and the mean response for the Matterport visualization format was 6.5555. Lastly the mean response for the Combination (2D CAD and Matterport) was 6.3703 ($p > 0.05$). There was not sufficient statistical significance to reject the null hypothesis. Statistically, it must be inferred that all three formats are equal in their use for pre-incident planning. However, the PI must conclude – in absence of statistical significance – that all three formats are useful for these purposes as participants mean values were above 5 in all 3 format categories indicating agreement that all formats are useful in pre-incident planning.

Qualitative analysis of question #8 “*What specifically about the design information was useful for you to understand the layout and interior configuration of the building?*” suggests that firefighters found all 3 formats useful for gaining and understanding of building layout. In total, 17 participants stated that the visualization was helpful in helping the understand where everything was at, 14 stated that it helps them understand building layout, 11 stated that the formats helped them understand where they needed to go. Additionally, 9 stated the formats provided good visuals and 7 stated the Matterport software provided remote access experiences and 6 indicated it was easy to use.

Additionally, qualitative analysis of question #9 “*How do you think the design information can be improved to help you better understand the layout and interior configuration of the building?*” resulted in suggestions for improving all 3 formats. 15 participants stated that the visualization needs to have the fire department connections (FDC) listed in the 3D space. Eleven participants stated the 3D spaces need to be improved by including all interior spaces (i.e., locked rooms, closets, etc.) in the visuals to make the spaces complete and realistic. Additionally, 10 participants stated the room labeling and door labels need to be complete, accurate, and included in the model if it is to be used in a practical application. Nine participants suggested removing unnecessary info and adding scaled dimensions to the 2D CAD drawings and the 3D format.

Qualitative analysis of question #10 “*How do you think the design information can be best used for pre-incident planning?*” provided feedback on the formats use in pre-incident planning. Overall and across all formats, 21 participants stated the 3D and combination formats allowed for effective remote site visits, 20 indicated they would use the formats in a group setting, and 18 stated the formats were useful for learning building layout. Seventeen firefighters would use the formats to plan fire attack tactics for a variety of emergency scenarios and 12 stated they would use the formats to identify hazards and 11 for entry locations.

Finally, qualitative analysis of question #11 *“How do you think the design information can be best used during an active response?”* provided feedback on the formats use in emergency response activities. Overall and across all formats, 21 participants stated the formats would be best used at the command post during active incidents with 17 stating all formats would be useful to help firefighters identify interior travel routes and during rapid intervention (RIT) scenarios. A total of 9 participants stated the formats could be used onboard apparatus/firetrucks while responding to a call. This feedback and qualitative analysis can be used by NCDOT employees and the authority having jurisdiction (AHJ) to better develop pre-incident plans and integrate them into dispatch systems to ensure efficient and effective planning and response activities.

For the fire service industry, the current work implies that that the provision of 2D CAD, 3D navigable imagery, and a combination of the two may all have their unique place in pre-incident emergency response planning and during active emergency response activities. Specifically, 2D CAD can be used to identify specific hazards in a building and identify the locations of life safety systems. As another example, 2D CAD can be used to estimate the length of hose stretches inside a building so crews know how much hose it will take to stretch from a pumper apparatus to the seat of the fire. However, obtaining 2D CAD may be impractical or infeasible in all situations. While limited in use, 3D navigable imagery has the potential to be used to facilitate a virtual walkthrough of a building to gain an understanding of the characteristics of construction and materials used in a simulated first-person view. The 3D imagery can also be used to train firefighters on building navigation and the connection between the divisions, or floors of the building. It is important to note that the researchers used a costly Matterport Pro2 system that may be impractical and infeasible for all municipal and volunteer fire departments to employ for all – or any – buildings in their respective response districts.

Although the limitations exist, the theoretical contribution remains as a result of this study. Further work in this area is warranted. Future research is needed to understand how to increase firefighters’ capabilities to read, understand, interpret, and communicate the information presented in 2D CAD visualizations. Additionally, future research is needed to further expand on the suggestions of using 2D CAD during active response events and how relevant information can be found accurately and efficiently. Additionally, future research is needed to explore more cost efficient and effective methods of developing 3D navigable images to remove the technological and cost prohibitive barriers of employing this type of technology. Furthermore, research is needed to understand the best practices of employing these technologies when facilitating pre-incident emergency response plans and what type of visual data should be captured in these systems. In addition to this, research should investigate methods to establish interoperability of each of the systems across various emergency response organizations during active emergency response

events. Creating an industry wide mechanism to facilitate the employment of these technologies during active emergency events may create an opportunity to increase life safety of responders in a uniform and consistent manner across the fire service industry and potentially save NCDOT life and property in a variety of emergency situations.

Chapter 9. Recommendations

Primary recommendation is for NCDOT to continue to work with municipal and volunteer fire departments to build effective pre-incident emergency response plans for target and high hazard facilities. The results of this research suggest that Matterport alone and the combination of Matterport visualizations and 2D CAD documents hold the greatest utility for pre-incident planning when compared to 2D CAD alone. Although there was sufficient statistical significance to make these determinations, participants did agree that all three were useful for pre-planning purposes. It is recommended that NCDOT make a financial decision on whether to continue to fund Matterport accounts or develop 2D CAD documents instead. It is further recommended that NCDOT complete a self-study of building locations and occupancy types based on a risk-based approach to determine which buildings possess the largest exposure to fire damage, property damage, and occupant safety and survival. Once this is complete, NCDOT can use a risk-based approach to determine which buildings are appropriate for Matterport space capture and for the development of 2D CAD pre-plans. Once Matterport spaces are captured and loaded into the Matterport cloud account and 2D CAD files have been developed following the recommendations below, they can be provided to emergency response organizations. It is important to note that pre-plans need to be changed as the buildings are remodeled, repurposed, or have a change in occupancy classification. Additionally, it is important to update the pre-plans if there is a change in fire alarm or fire protection systems or if hazardous materials are added or changed inside the facility. This will ensure the pre-plan information is relevant and up to date for emergency responder use. A discussion about building 2D CAD and Matterport pre-planning materials are discussed in the sections below.

9.1 Recommendations for 2D CAD

The recommendations are for NCDOT to develop a series of 2D CAD drawings for a variety of selected high-risk buildings and for these documents to be provided to the appropriate AHJ. The following recommendations for developing 2D CAD documents are developed from PI fire-service experience and from the suggestions from the firefighters included in the study. NCDOT should ensure all pre-plans contain, but are not limited to, the following information:

- Building information including address, fire department jurisdiction, construction type, height, and occupancy
- Floor plans and site layouts
- Entry and exit points and physical barriers
- Utility locations and shut offs
- Energy sources including electrical, gravity, hydraulic, mechanical, pressure, biological, radiation, and chemical sources

- Fire protection and suppression systems
- Fire alarm detection and activation systems
- Hazardous materials information
- Special occupant considerations
- Fall hazards and confined spaces
- Lists of equipment categories that contain the potential to entangle or entrap an occupant
- Water supply information including hydrant access, on site water supply tanks, exterior fire dept. connections (FDC), and possible drafting sources

Considerations for the development of these 2D CAD documents include but are not limited to the following suggestions. Drawings should layer items by categories on separate pages to reduce clutter and make drawings easier to read and extract information. For example, a general sheet can be developed that contains building information and shows a general floor plan layout with room numbers, interior sections (i.e., hydraulics division in Century Center) as separate colors on the page and shows parking lot and street orientation so firefighters know where to park the apparatus based on emergency location.

Additional sheets can list specific room numbers so firefighters can get an idea of the expected travel routes. Items including fire suppression and fire alarm and control panels can be on their own sheet. It was suggested that plans contain information relating to hazardous material location and roof ventilation hatches in the building. These items could be on a single sheet in the plan. Elements should be color coded on a legend on its own page for general information. Figure 19 below shows a picture of a suggested pre-plan document from firehouse.com which is a leading online resource and portal for the fire and emergency services community.

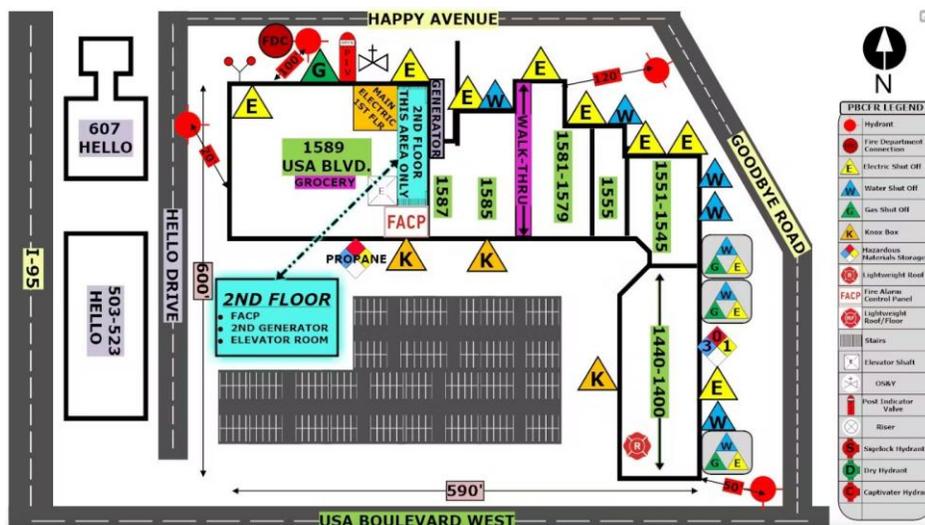


Figure 19: Example General 2D Pre-Plan Drawing (Firehouse, 2025)

The following figure 20 is an excerpt from the Century Center floor plan pdf file that the firefighters received as a part of this study. In this image, the firefighters liked the color coding of the divisions but suggested adding room numbers and ensuring the exit door labels (i.e. A8) match what is visible on the building. They also suggested showing it in relation to the street. The following image in figure 21 shows an example of the image overlaid with street designations and entry labels. It is recommended that these types of images be constructed in NCDOT CAD software and exported to pdf files so they may be emailed to the firefighters so they may upload into Active911 and/or First Due software.

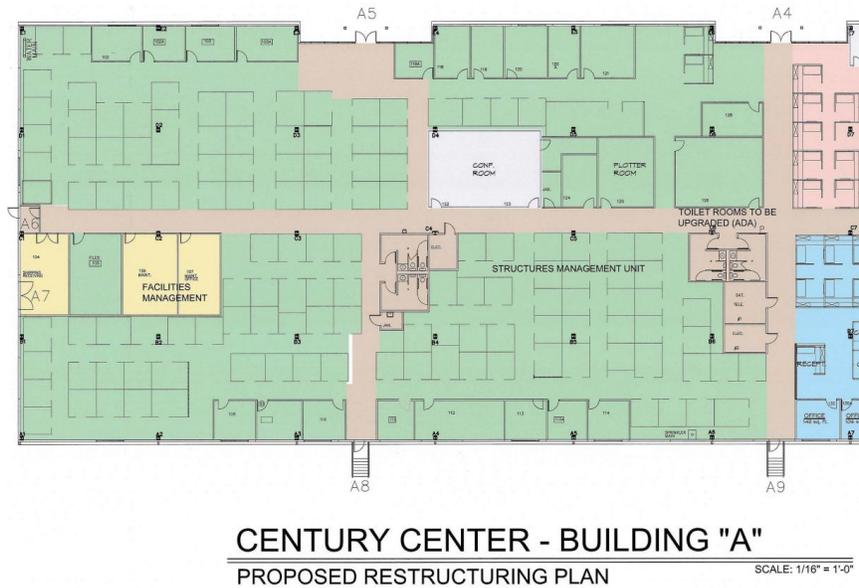


Figure 20: Century Center Plans without Street Labels

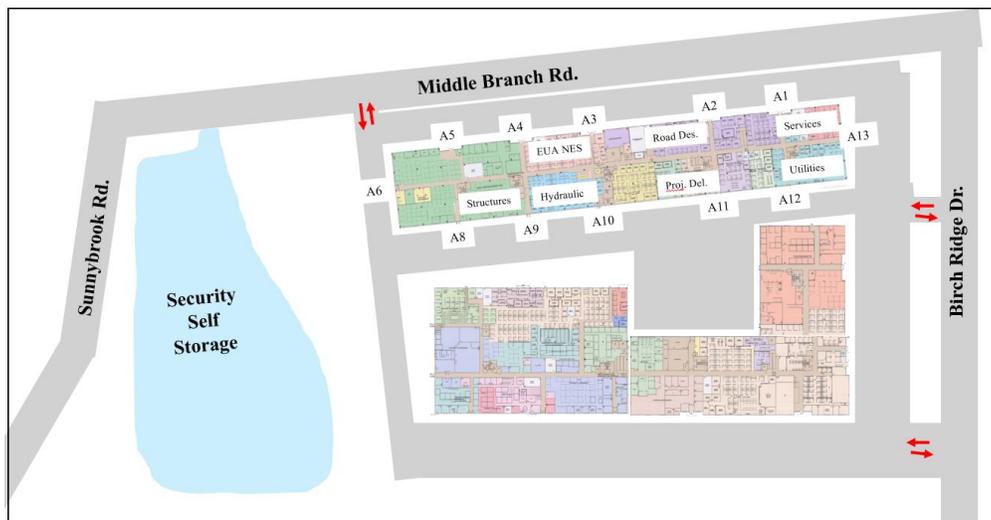


Figure 21: Example Century Center (Building A) Overlay with Street and Entry Door Labels

9.2 Recommendations for Matterport

The recommendations are for NCDOT to continue to capture the interior and exterior of NCDOT buildings into the cloud accounts. It is recommended that NCDOT capture all compartments inside the buildings such as hallways, chases, and hallways so the spaces contain all the relevant geometry. Large spaces such as the NCDOT Century Center may require multiple spaces to capture the entire building due to its size. It may be necessary to capture the interior elements and exterior elements in separate spaces due to their size. It is recommended that the spaces are uploaded into the Matterport cloud account and the links made public in the sharing options. Once the links are active and public, NCDOT staff can build a Microsoft Word document with the link and building information in it and save the document as a pdf. This pdf can be emailed to the fire departments, and the departmental personnel can upload the pdf as a document into the Active911 or First Due systems so first responders with access to the systems can open the file on their cell phones, tablets, and PC's. These files can also be accessed in the apparatus during dispatch and used on-scene at the command post during active emergencies. Firefighters can also pull the spaces (and 2D CAD) up on station computers and conduct virtual walkthroughs and develop internal emergency action plans.

Chapter 10. Implementation and Technology Transfer Plan

- **Research Products** – The research products include captured Matterport spaces in the NCDOT Matterport cloud account and the associated 2D CAD files used in this study. NCDOT currently has these research products, so no transfer from the PI to NCDOT is needed. NCDOT may enable the sharing options in its Matterport account and send the links to the AHJ's.
- **Affected Parties** – The affected parties include NCDOT employees involved in 2D CAD pre-plan development and Matterport data file transfer and the appropriate emergency response agencies. NCDOT employees may decide on target facilities to be included in future pre-planning and coordinate with the appropriate AHJ on how the transfer of files should happen.
- **Training Needed** – Training should be provided for NCDOT employees who will operate Matterport camera systems and software to capture NCDOT spaces. Training should also be provided to NCDOT employees that will develop 2D CAD pre-planning documents that will be provided to the fire departments and other county emergency management agencies. NCDOT staff may choose to train AHJ personnel on how to operate the Matterport software. However, the PI believes this is unnecessary due to the platform's ease of use.

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Appendix A. Complete List of Open-Ended Responses

Q8: What specifically about the design information was useful for you to understand the layout and interior configuration of the building?	
Format	Response
2D CAD	Seeing how everything is gridded off helps so we know where to start.
	Having a PDF is good because you can't accidentally move the icons like you can in first due as it is locked. We could use it on a fire alarm call, not really a structure fire.
	Helps us know where to enter the building.
	The first thing I am looking for is a map. This is laid out nicely.
	Entry location and building numbers.
	Having color-coded sections inside. The labeling of sections is nice. The drawings are simple and not too busy.
	It's always good to see a map of building so you can see what's inside.
	You can easily see egress points and Pathways in the building. You can see the visitor and main entrance. To get an idea of what to expect inside based on the entrance doors that you choose.
	The color drawings were like house plans showing windows and stairs and door swing directions. The conference room map does not have details but has AED. Both show safe spaces and locations of potential buildups of people.
	Shows hallways and rooms and the size of each room. We can view it while responding to know what to expect.
	It's basically an overhead to show you where everything is at.
	The good details are helpful to get a look at where everything is.
	It shows you where everything is.
	The way you have the plan on each page helps explain where everything is.
	Everything is well labeled.
	You have dimensions and doorways and entrances and other stuff like that. You can see the windows.
Good top view of layout. I can track your movement based on what you say.	
Shows you which way doors open and overall layout. We can use this with a site visit and make notes on what's here.	

	It's good that the exits are visible. And that the drawing is scale for the size of the rooms.
	Having room numbers lets me know where to go for an alarm activation. Contains secrets of the whole building.
	You can see the main entrance and follow the outline to navigate around the building.
	I like this in blueprint format. It helps us know the square foot of the room and door swing directions. It shows details about toilets and sinks and other types of mechanical fixtures which are helpful
	Being able to see the entrance, exits, hallways, swing direction of doors, and access points is good.
	Having the original overlays with divisions listed by color is very nice. The room numbers help having the entrance and exits, and AED locations would be important.
	The conference center map and unit map are nicely organized. This is the type of map we are interested in for a pre-plan.
	I like how the dimensions are scaled so we can see travel distances and hose lays. This is important for buildings of larger size so we know what we need to take inside.
	I like how a small pdf can be opened on a cell phone so everyone can see the locations on scene. It keeps you from having to leave your assignment to travel to the command post to get the information.
3D Navigable Imagery	Gives a good visual of the building.
	No response from participant.
	It's a real world visual that you can use to help build a pre-plan it is remote and easier to facilitate them going to an actual site.
	It's good to be able to see the building like this since it's going to be there firsthand.
	It is helpful to be able to see what's inside and what to expect. Photographs are nice but this gives you a larger picture.
	Not having to physically walk through the building.
	Great visual of the building layout.
	Takes you inside and gives you a picture. You can tell the AED is at column C14.

	<p>This is as close as you are going to get to being in the building without being there. The pictures were good quality and that's good. It's user friendly on an iPad and a laptop.</p>
	<p>You can walk through on your own. I have experience with Matterport. It's easy once you get the hang of it. You can look for yourself without relying on others for info.</p>
	<p>Locate the primary and secondary exits. It shows window locations, and you can see the types of spaces like restrooms and the kitchen. Gives me an expectation of what's in the building. You can also see the hazards and their locations. This type of map helps me know where I need to go.</p>
	<p>It's a plus to visualize where accesses are and what hallway layouts are like. I like the dollhouse view. It is better than the walkthrough as it gives you a faster snapshot of what is visible. Overhead view is beneficial even with the dead spots in the map that don't have the info.</p>
	<p>Ease of operation. It can't be any clearer than this. Its like you're inside the building. This will help the next generation of firefighters. They struggle with everyday tasks but know how to use an iPad.</p>
	<p>The Matterport gives more details than a 2D plan about the building layout.</p>
	<p>Decent program. I like how quickly you can access the materials shown on the map. Probably good to calculate fire flow measurements. Can use to get basic dimensions and to calculate hose flow.</p>
	<p>You only get so much detail from a 2D drawing. This system is beneficial for buildings that are complex. It gives you details of the 2D drawing cannot.</p>
	<p>Matterport is good for people who have a tough time reading 2D drawings and images. You can see where everything is, and the measurement tool is nice.</p>
	<p>It allows us to do a walk-through of a structure and helps us see quick egress points faster than 2D.</p>
	<p>The Matterport allows us to see the nooks and crannies of the building. You can see the nice details and important items for firefighting.</p>
	<p>I like the speed of how fast you can move around.</p>
	<p>It is nice having the ability to move around the structure, but some areas are off access in the model.</p>
	<p>The visuals are nice since you can walk around. Having a measurement tool in the doll house view helps us calculate hose lays and fire flows.</p>
	<p>Pretty simple to use system.</p>

	I like using the doll house view at the start and choosing my look around locations.
	As a shift Captain, I can tell you that this has the ability to save us travel time doing a walkthrough. Its impossible to get three separate shifts inside one building in your district without causing schedule issues for other items. This system would help with that since it's a remote visit.
	I like how you can scroll into the 3D images and see the smoke detector head numbers and room numbers in the images. It might be faster than 3D if we had a 2D map with the info on it.
	It's like a real estate camera when I was buying a house. It gives you an idea of what things will look like when you get there. It allows you to think about questions before you arrive and get overloaded with info.
Combination	No response
	2D clear accurate labelling. Matterport is not useful.
	Matterport lets you know the layout, ceiling type, building materials, people and dead loads, fire loads, and what's inside. 2D is nice having the color and the layout.
	Both Matterport and the maps are useful. The Matterport tells us stuff that the 2D does not tell us. You can see more of the building in Matterport than in the maps.
	The maps are a fast way to find locations. The Matterport takes longer but is a better visual.
	Both are good for command posts. Map is a good way for a quick response inside the building.
	Helps firefighters see where they're going before, they get there. They can use the Matterport to train on fire attack.
	Just being able to see the buildings on a map and digitally is nice to know what to expect when you get to a scene.
	No response from participant.
	I like how you can see all the details of the fire alarm and sprinkler heads. You can look around like in google maps but its inside the building and in better detail.
	Can see what rooms look like.
	Pretty damn cool - can't lie. You can click and move in 360. You can look around and know where you're at.

	Reminds me of google maps. It gives you an overhead overview and you can click to get inside the room you want.
	The 2D shows open floor plans on all commercial plans. Matterport shows real life images of the building. There are no questions when you have the blueprints but the Matterport is helpful.
	Matterport has clear images. The 2D is clear of where the hallways are. The scene size up will give you a reference point of where you need to go and you can take time to study these before going in. 2D is good when you can't take the pictures. 2D and 3D gets us access when the owner doesn't want us inside.
	The 3D graphics are good and it's a smooth transition from room to room. It's a lot better than a bunch of photos thrown together in a word file. The 2D floor plan is good for fast quick route detection.
	I think the top-down 2D view is more beneficial. I will not use the walk through. Takes too long. I just need to know where to go and how to get there.
	No response from participant.
	The way you can move in the 3D system is like real life, so you get to walk around. The 2D map shows hallways and room locations.
	The 2D shows room id's and how to navigate from an overhead view. The Matterport takes you inside the building, so you get to walk around and look at stuff.
	They both help you see where you need to go.
	You can see where you need to go in both.
	You can id travel paths in both.
	You get an overhead view in 2D and an inside view in 3D.
	No response from participant.
	The 2D drawing with multiple colors show division locations since its such a large building and the conference map shows corner id's. This is good for navigating the building. The Matterport takes longer but gives you an inside view.
	They help you know what's inside and how to get there.
Q9: How do you think the design information can be improved to help you better understand the layout and interior configuration of the building?	
Format	Response

2D CAD	Show fire department connection hookups in the hallways. The dimensions are not equal. Connections are not to scale at the conference center map. Have a printout for the captain in the front seat.
	There is too much information. You need layers by item category. We don't need fire extinguishers. We do need to know where standpipes are and connection boxes. We need sprinkler controls and mechanical and electrical rooms listed in the drawings.
	Add fire department connections and hydrants. Add road orientation lines. Add hookups inside the buildings and dimension labels to hallways.
	Having the zone listed on the map would be helpful. Overlay the visitor map over the layout map.
	Adding alarm panels so we know what detectors have alarmed is important. Please add areas of Refuge.
	Label the map by layer of fire activation zoning. Add map of control panel shown next to its location. Add connection locations outside the building. Maybe have multiple layers and add sheets and hydrant locations.
	Add the alarm panel and sprinkler room locations. Also need hydrants, roof ventilation locations, and building construction details.
	Better explain what the reference to the columns in the conference center drawing mean. Drawings need to be to scale.
	Would take color image and add the symbols of common rooms from the conference map to them.
	Have this on an iPad and type in an address at the meter box, gas shutoffs, water shutoff and FDC.
	Change the labeling of the rooms in the floorplan to explain what is included and make sure they match the interior door labels.
	I wouldn't change anything. But I would condense the info. Then I would break the sheets apart by items like floorplans, and electrical.
	Add furniture so you know where your obstacles are and the electric and water shutoffs.
	Easier and faster information would be helpful instead of 15+ pages.
There is enough detail so I wouldn't remove anything. I would include water shutoff and FDC locations.	
Include windows as a point of access in the drawings for the preplan. Simplify the drawings remove the grid patterns. Add the fire alarm system zones as an overlay on a separate page in the map.	

	<p>There is too much noise in the drawings. We don't need room numbers or labels. They are all going to be searched anyway. Add the vision corners in relation to the main road. Keep the names of the offices and main rooms but remove small closet labels and such. Include load bearing firewalls so we know if it is a wall we can breach. Include gas lines, sprinkler locations, rise pipes, FDC, and FACP. Add the construction type and occupancy load.</p>
	<p>Include all exit doors in drawings.</p>
	<p>Add water meter, gas meter and sprinklers. Add electrical and alarm panel locations. Keep all this info on one page.</p>
	<p>Add dimensions to the rooms and hallways. Remove plumbing pipes.</p>
	<p>Add parking inside streets, hydrant locations, entrances and exits on one sheet. Need a general overview map that shows where everything is in relation to the street. Include dimensions for fire flow for hoses. Keep images without architectural lines. Just lines with room IDs and locations of detector heads on the image. It should list the FACP location.</p>
	<p>Add parking inside streets, hydrant locations, entrances and exits on one sheet.</p>
	<p>We need a map in a simple format that includes hazards, electrical access panels, riser rooms, gas and utility shut offs and standpipe location. Please place these in multiple zones on multiple sheets in one PDF map.</p>
	<p>Labeling bathrooms would be helpful. Listing the key holder info and alarm company information with fire control and suppression system locations and information like panel locations. Labeling smoke detectors on the overhead as they are laid out in the building. Show the location of FDC's and sprinkler heads.</p>
	<p>Multicolored rooms with room numbers and labels would be helpful. Add standpipe connections. Swing directions. FACP's would be helpful and FDCs. Could include information about hazardous material and certain hazards that we might have to respond to for unique dispatch.</p>
	<p>Have FDC, FACP, Risers, Interior connections, and sprinkler heads on one page of the drawings.</p>
	<p>List FDC and streets so I know where to park based on the fire location. If I can see the fire glowing from the street, I can look at the map for the closest entry point and FDC location.</p>
3D Navigable Imagery	<p>Have big items like hydrants fire department connections and control panels shown along with the Knox Box locations on the map. Include schematics.</p>
	<p>No response</p>

	Having a well labeled map would serve us better than Matterport for quicker location of a lost firefighter for RIT.
	Add overhead view icons for important items in the building. Add roads to overhead map in Matterport
	I would like to know where the streets are so I can orient myself to the trucks and I can issue assignments. Adding layers to the dollhouse view like fire department connections, exits, electrical and maintenance, exit points, and hydrants would be helpful. It needs control panel labels.
	Have a running length count feature so you can see how long hose stretches need to be from the door to where you are in the model.
	Being able to see a 360 visual of the compartment areas would be nice.
	And smoke conditions.
	Add outside images with FDC and utility locations. Include a 360 walk around. Fix the areas where you can't get into in the system. Make it accessible. Can't really improve the interior much but could add to the outside. Mark exits in the doll house view
	Nothing to improve.
	Include all rooms in the system including passageways and secondary doors.
	Open every compartment show the roof and scuttle hatches and all the confined spaces and possibly add icons in the 3D dollhouse view. Keep multiple floors on separate files.
	Not really anything. It's not buggy and doesn't lag.
	Doesn't need improvement. But it would help to make the 3D model crisper in the future.
	Add a 2D single overhead drawing with layout, doors, windows, entry/exit, electrical, water, gas, HAZMAT, and a spreadsheet of chemical hazards.
	Link the space to active 911 or first due systems. Supplement them with a 2d drawing. That would be very helpful.
	I think it looks good, but it would be nice to do an actual walkthrough.
	Label hallways, divisions, FACP, FDC, and other important landmarks.
	No response from participant.
	Get pictures of roof.
	Include a walkaround of outside of structure.
	Have it so it can display on a phone.

	Include all rooms in the building.
	Take pictures over the suspended ceiling.
	Take more pictures so you can see around all corners in large buildings.
	No response from participant.
	No changes are needed.
Combination	Add standpipe locations in the 2D drawings. Id doors you can access without forced entry. Id streets, FDC, hydrants, parking, utility shutoffs. Mechanical roof doors for ventilation could be listed in 2D. Add sectional lengths and show HAZMAT locations in 2D. Not much to add to the Matterport stuff.
	Don't improve the Matterport. It takes too much time to move around during a real emergency. The drawings can be improved by adding FACP and sprinkler zones to the maps. Include labels of smoke detector and sprinklers. Include the map of the in-house sprinkler system in the revised pre-plan. Add HAZMAT locations and FDC.
	Add door labels to the inside of the Matterport. Add smoke detectors and fire alarm panels in the map. Include hyperlinks in the map to other drawings to add detail.
	No response from participant.
	Add FDC locations in both. Add hydrants, Knox box, street locations on the maps.
	Add the Matterport links to Active911.
	Label the maps with detector heads in the rooms and the sprinklers. Scuttle holes for the roof. Conduit access. Roof holes for ventilation can be added. Add building controls to both
	Add door labels in Matterport so we can see where we're at in the building
	Make sure the content of the maps is correct. Add the information that we need for scene response into the maps. Make all the Matterport content available in one file.
	Be able to walk around the outside. Show the externals and room with attic areas and see above suspended ceilings. It would be nice to be able to click on an item and pull up important information about it. Add FDCs, smoke detectors, and sprinklers to the plans.
	Add measurements to the 2D drawings. Nothing in 3D.
	Add outside pictures to the Matterport so you can walk around.
	Take Matterport photos of the entirety of every room. No improvements to 2D.

	<p>Matterport-add FACP, sprinkler system, electrical meter, breaker boxes, FDC, water shutoff on exterior and list the target hazards.</p> <p>2D- Add locations of server room and it's fire extinguisher media. The blueprints have too much going on. Please remove unnecessary info.</p>
	It would be nice to export Matterport data into a SCBA facepiece. Load contact info in Matterport for keyholder. Add occupancy load. No changes in 2D.
	On 2D show windows and doors. In Matterport take pictures on the outside of the building.
	No suggestions.
	More of an overhead view in the Matterport system. No changes to 2D. The drawings showing the various compartments in multicolored layers is nice.
	Include utility such as natural gas or electric into the 2D drawings.
	I would improve the 2D drawings by making them digital and having access to them on site.
	Including information on utilities such as electrical lines in the walls and gas lines in both the Matterport and the 2D drawings.
	Add FDC to 2D. No changes to Matterport.
	No response from participant.
	Add hazards to the 2D drawings.
	Show roof ventilation hatches on the 2D drawings. Nothing to improve in 3D.
	I would reduce the 2D blueprints to something manageable like a few pages of overlay info on each for individual systems and hazards.
	I would get the Matterport into the trucks so we can use it in route.
Q10: How do you think the design information can be best used for pre-incident planning?	
Format	Response
2D CAD	Look for fire panel locations to know where to start fire attack.
	Using the scale drawings so we can see how much hose we need for certain scenarios.
	Could bring ladder 12 in the training room and look at egress points.
	Going to the building is the best for pre-planning. We could take this and take notes on it. We could list the hazards and other important items.
	Look at the drawings and the layout to know the locations for a variety of scenarios. I could use it to run tabletops.

	Use it to go over the layout of where everything is located. We can check the accuracy of the map with a walkthrough.
	I probably would not use this for training.
	Use it to estimate building size and dimensions.
	Understand personnel load and hazard locations. It shows us where security in the building is. We can have a way to understand the hazards.
	Review it with the crew to learn layout. We can learn what each room is used for and discuss equipment needs.
	Have each company use the drawing s to establish a preplan. Keep a copy on the truck so we have specifics of what we are going into.
	Do whatever you want to with it.
	Learn the layout of the building.
	Learn where the exits are and how to get around the building.
	Use it to see what is inside.
	See your way around.
	Not sure how I would use it.
	Learn entry points. Learn your way around so you don't get lost and die.
	No response from participant.
	Look at this to identify hazards before we get to the establishment.
	Project it over the whiteboard to discuss fire response tactics. We can discuss where to park and how to operate.
	No response from participant.
	It would be useful for pre-planning but would not be my first go to.
	Look at hazmat locations, fire control systems and suppression systems so we can see the basic day to day operations for fire response.
	You can see the location of all items. We can use it to make decisions to designate certain aspects of the building for different purposes. I can look at hazardous items, fire control tactics, and discuss tactics with our crew in class.
	Take the drawings with us to a building and take notes on them.
	Upload into Active911 and/or First Due so we have access at station.
	Use it to find fire department connections and smoke detectors and be able to find this quickly.

3D Navigable Imagery	Establish main entry point if you view this a few times at the station so we can have an idea of what we were walking into. Use it to look at hose lays.
	Used at the station and take a virtual tour for training
	Learn the details of where the exits are and what the layout of the building is. Learning how to navigate the building.
	Use it for a round table discussion for various types of emergencies. The visual tool is good for coming up with internal action plans.
	No response from participant.
	Visually see special hazards, hookups, and alarm panels.
	You can use it for a pre-planned fire study. We could run a tabletop exercise for various fire conditions. We can look for obstacles like hose lengths and construction type.
	Pull this up on the smartboard as a group to review and see what equipment and hose we will need. Add it to the iPad an preplan in the truck.
	Look for annunciator panels in buildings so we know what door to go into at 3am in the morning.
	Locate exits office access points and secondary access points.
	Use this to save time doing a rough sketch of the building. We grid paper hand sketches of floorplans by hand, so this is much faster and helpful. We can use it for tabletop fire simulations to practice radio traffic.
	Use it to show new people who have never been in the building how to get around.
	It would allow someone to visit the building on the internet to get an idea of its layout without going there.
	Save time not having to meet at the building and could use it as a tabletop exercise.
	This is a good training tool since you can pull up any building in the district and run various fire scenarios from the station for training.
You can use it to estimate hose lays for various situations and discuss search and rescue operations and fire attack. You can look for hazards and areas that might be blocked off for access.	
This would be helpful in mutual aid districts where we don't have enough time to go look at the structures. This allows us to see the building easily.	
You could take a team into the virtual system without having to go to the building and get in people's way. You can use it to figure out exits and which	

	routes to take based on where you might need to go in the building, and you can simulate fire attack and look for hazards and points of exits.
	I don't know. I am not involved in pre-planning.
	Show new recruits the inside of a building when we cant actually visit the site.
	Get an idea of the use and occupant load remotely.
	No response from participant.
	Learn travel routes and hazard locations.
	Understand the type of fire suppression systems in the building.
	Hold company meetings to discuss fire loads and tactics.
	Use it with a 2D map to develop a paper pre-plan for the trucks.
Combination	Use the drawings and Matterport to quiz firefighters on the standpipe locations, sprinkler, access points, FACP location, and the riser rooms, etc. Use the Matterport so we can train on making sure we know where this stuff is before we go out there for an emergency.
	Not sure. I'm not sure I could remember all of the layouts just from using the Matterport. We train in ways to move around but not in this way. It could be used for a fire prevention audit if the images were recent.
	Use them to know your entry points and exits and know where your hazards are.
	Looking for hazards and the buildings that are the most hazardous. Territorial familiarization. Sit with people and have a conversation about fire load and tactics with crews remotely.
	Use the Matterport for virtual training and walkthroughs to navigate from a random door to a specified column in the building.
	Use the Matterport to get an idea of the fire load in the building. I wouldn't use the maps in training. Help us identify what we might run into during RIT situations.
	Use the systems to remotely train captains on fire attack.
	Use this to train our crews on where to connect apparatus to FDC's.
	Use it to get a good familiarity of the building virtually so we don't have to send crews out to every site.
	Use the imagery before a walkthrough to identify target items that you want to see if they are there when you visit the building.

	Both give you an inside view of the building. I would use the Matterport if we had it. We can move around and see where the FACPs and FDCs are. It would be quicker than having to get each shift from each department out there.
	Include in officer discussions for preplans and tabletops.
	We can print out the drawings and hand draw on them. We can look at 3D.
	Run tabletops for company officer training. Give a scenario of victim rescue and have them plan it out.
	I would not use this for preplanning.
	Show us where all the electrical is. We can use it to measure the rooms to show us how much hose we need.
	Use both systems to go to understand building the layout which would be good for training new officers.
	We use these to simulate fire attack and rescue simulation scenarios.
	As a team, being able to visualize and see inside the building without having to go out to the place and get the idea of the layout is very nice for pre-planning.
	We could use it to train new recruits as well as training officer prospects in command tactics.
	Use both to discuss tactics in tabletop exercise.
	Integrate these into formal department training.
	I would use the 2D as a template to create a pre plan on using the Matterport imagery for group discussions.
	Multi company training and planning.
	Good to use for mutual aid buildings you can't leave the district for on shift days.
	No response from participant.
	Use 3D to verify locations of tactical items and write them on the 2D plan.
Q11: How do you think the design information can be best used during an active response?	
Format	Response
2D CAD	Looking for mechanical and ventilation and finding HVAC units on the roof. Would need to know where the standpipes are also.
	No response from participant.

Having dispatch give us info based on locations inside the building would be helpful if they had this information. It would help for fire and electrical investigation as to where the command post is located.
If we know the location we can find the alarm error on the map. This could help me as a driver to know where to park.
Having the names of the sections would be helpful if the 911 caller stated that name to dispatch. Then the fire department would know what door to use.
Use it on board with the PC in the truck and try to get info from the pre-plan in active 911.
I would let incident command use it to find locations in the building.
The labels on the color drawing can be used to identify the location of the fire inside the building.
If we got called to a fire in the hydraulics division, we could know where to start. We know where to start based on landmarks.
Find exact location of patient for calls at areas like medical offices and use it to find locations of gas shut off valves at gas leaks.
Keep it in the command center so the crews can be relayed information about entry points so they can meet at specific locations from all divisions.
Use it to keep track of the crew. Incident command should have this on paper and ipad so they can make locations of crews routinely.
Use it before you go inside to familiarize yourself with the building.
Any company could use this or command, so they know the layout for interior fire attack. Command can see where firefighters are in the overhead drawing.
Police could use this if they had a standoff with a shooter.
Use it to communicate locations of victims.
If we know we have to do a rescue we can look at the 2D plans for travel and alternate routes and entry and exit points.
Communicate hazardous conditions listed to firefighters inside. Command would be the one to use it.
No comment from participant.
No comment from participant.
I would use this mostly for fire alarm activations. If you pull up and can see the fire, you would not need this initially, but you might use it to find sprinkler

	room locations and such. You could use the handwritten drawings to write locations for items on.
	I would use it to prioritize search locations for a structure fire.
	I would not use a full set of engineering drawings for active response. I would like a one-page topo map with room numbers on it only.
	Pull the PDF up on the cell phone or in the truck to find the pre-plan before we get to the scene.
	Incident command can pull up the 2D drawing and see the location of where firefighters are in the building. You can also see the hazards and where they're at and you can find your way around to find a trapped victim.
	Find landmarks to help lost firefighters on inside.
	Command could use it to keep track of personnel.
3D Navigable Imagery	Not useful in routine calls other than finding the fire department connection. Having a good image of the site would be helpful. Be helpful for the head incident commander or RIT team to work and communicate
	If things are coordinated well and accurate we can get to know where to go and not get lost in the building.
	See this as a tool for someone on the outside to use to help firefighters navigate on the inside.
	There is not enough time to study this before we go on a call. However, I think a paper map might be helpful.
	Know the entry points in relationship to where the fire is. Using it in overhead view is most helpful when riding to the call.
	I would not use this. We are 75 seconds to the building there is not enough time to use it. Also, with smoke in the building the conditions are not going to be like they are in the software.
	Use as incident progresses by command.
	Long incident uses when multiple agencies are involved. Should be used to communicate building features.
	Useful at the command post. You can tell command where you are at if you are lost in a structure. They could help you out in a mayday situation. Could be a useful tool.
	No response from participant.
	You can locate seat of the fire before we get there so we can locate the fire quickly.

	Use it during mayday. Command can give access routes and RIT instructions for down firefighters
	Useful during mayday situations to pinpoint locations better than 2D.
	Everyone can use this if we have the time. I can pull it up on my phone in the captain's seat to see where the nearest hydrant is. I can also look at the building layout during response.
	The emergency type is going to dictate if we have time to look at it. I probably would not look at it unless it was a complete building collapse or building explosion. 2D would give us faster route identification.
	Useful for incident command at the command post. They could link the incident command and Captain's computers to the system. They could use it to identify the travel routes to find the victims.
	If you had a 2D map to lay out the rooms, the Matterport could be used to see interior details while the 2D is an overhead shot. Useful for mayday situations to help find trapped firefighters.
	Could use it to look for hazardous material locations inside the building instead of sending firefighters inside to look for possible locations. Could save manpower on site.
	The command post could use the information about firefighter locations in Matterport to direct rescue teams to their location
	I would not use Matterport on an active call unless it is a massive multi company incident that requires slow advances.
	No response from participant.
	Incident command or captain should use this on an iPad. Pin this to Active 911 to look at before arrival. Use it to look at the layout and exits and where hazards are. You can see how to get around the building.
	This takes to long to use at a structure fire. Command has too many other things to worry about, so they probably wont use it.
	Use it in the truck on the way if there is time.
	For RIT and mayday situations.
	Find landmarks in the building said over radio traffic.
	Not really sure.
Combination	Use both to find out where we should park to access the FACP or annunciator panels. Find the Knox box location.

Command could use the Matterport to help lost firefighters navigate in the building. They could use the maps to find entry points.
Use system to help RIT navigate to an injured or trapped firefighter. Possibly police and active shooter drills.
In complex situations with complex structures.
Run both in situation where you have a downed firefighter. The more information the better. They could be used to help communicate information.
Command would use the Matterport more since they have time to pull it up on scene. I don't know if it could be used by the firefighters, but it could be used by command and RIT.
I think this would be very nice for RIT. A Division Chief could use this to have accurate views of the pre-fire and could be used to find a safe place for a down firefighter to escape.
Both could be pulled up at the mobile command on the tablet.
Visually communicate the exact location of a downed firefighter to the RIT team
Can't use Matterport while responding to an emergency. But you can use 2D to find FDC locations before you arrive.
Have command post use 3D on a tablet. Use to identify hazards in the inside. They can use it during mayday situations
Command can use both to help firefighters get out of a building.
You can use them while responding to see the path of how to get around and get a gameplan of what we need to do.
Use it enroute through active 911 and pull up locations in 2D drawings. Open the preplan and see the floor plans. Use Matterport to know how to get around.
Use it during fire or RIT response. Use them in the truck on the way to the fire.
I don't have time to deal with an iPad for stuff like this. I want a quick piece of paper with access to important information.
Use a top-down view of both to see the layout of where the fire could be and how to get to it.
Command could use this at the command station for a variety of emergencies.
The 2D and 3D combination can be used to identify hazards and travel routes.
It can help on large buildings when looking through wide spaces and hard to find travel paths.

	No response from participant.
	I would use the 2D much more than Matterport. Paper is quicker and I can take it inside with me.
	I would use them together if I was at the command post.
	Use them during RIT to help firefighters find lost firefighter.
	Use them to coordinate with county emergency management.
	I would have multiple pieces of paper for the building in a folder that I can write on as the incident progresses. I would have the Matterport on the trucks iPad if needed.
	I wouldn't really use the iPad or Matterport. I would use the 2D since its quicker.

Appendix B. Example Matterport Link PDF

Building Address: 1000 Birch Ridge Dr., Raleigh, NC 27610

Building Name: NCDOT Roadway Design Unit

of Buildings: 2 (Bldg. A and Bldg. B)

Building Size: Bldg. A – 92,238 Sq. Ft.
Bldg. B – 103,646 Sq. Ft.

Key Holder Contact: Jane Doe (919 ### #)

Hazardous Materials: None

Matterport Link: <https://my.matterport.com/models/pBBEjG9w3Ek>