Methods for Scenario Modeling of Post-disaster Temporary Housing

By

Daniel V. Perrucci

Dissertation

Submitted to the Faculty of the

Graduate School of Vanderbilt University

in partial fulfillment of the requirements

for the degree of

DOCTOR OF PHILOSOPHY

in

Civil Engineering

September 30th, 2021

Nashville, Tennessee

Approved:

Hiba Baroud, Ph.D.
Beth Shinn, Ph.D.
Mark Abkowitz, Ph.D.
Yasin Alan, Ph.D.
Janey Camp, Ph.D.
Juline Mills, Ph.D.

DEDICATION

To P.J. (aka Peege)

Without you, this document would not exist. It is
as much your accomplishment as mine, you are
forever a part of me.

ACKNOWLEDGEMENTS

To start, my family. All of you have provided memories and experiences of which have shaped who I am today and who I will become in the future. Thank you. To my late grandfather, your letters and our conversations continue to encourage me. And to my mother, you have been the light that allowed me resilience and determination to keep moving forward.

Dr. Hiba Baroud, I cannot imagine reaching this point under anyone other guidance. I thank you for the unrelenting support during my challenges and encouragement to always chase opportunity.

To the members of my indispensable dissertation committee, Dr. Beth Shinn, Dr. Janey Camp, Dr. Yasin Alan, Dr. Mark Abkowitz, and Dr. Juline Mills, thank you. Your examinations, assistance, and encouragement ensured my success.

Thank you to everyone I encountered at Vanderbilt University and in FGH 263, I will always look fondly at my years in Nashville. And a special thanks to Ms. Jackie White who went above and beyond to resolve many registration/administrative problems on my behalf.

Cheers to Dr. Jinzhu Yu, we did it. Thank you for becoming the academic brother I never knew I needed. I look forward to running into you at conferences in the future.

I would like to thank Vanderbilt University and IBM for the financial support, and the Curb Center at Vanderbilt University for enabling the exploration of art, policy, and enterprise in the scope of disaster response. The provided fellowship support diversified my dissertation research, and I am proud of what I was able to accomplish. And to Dr. Christopher Vanags, for the guidance during the development of the drone imagery survey evaluation.

To the many faculty members and friends at the University of New Haven, thank you. Most especially, to Dr. Jon Aktas and Bianca Vazquez who helped me find my passion for research, Dr. William Adams and Dr. Allana Adams for an introduction to academia that most only dream of, and finally to Dr. Juline Mills who went from professor to employer, to mentor, to a dissertation committee member, and to a pillar in my past, present, and future.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

FEMA	Federal Emergency Management Agency
MCDA	Multiple Criteria Decision Analysis
THU	Temporary Housing Unit
PDA	Preliminary Damage Assessment
LEED	Leadership in Energy and Environmental Design
STEP	Sheltering and Temporary Essential Power
WS	Weighted Sum Method
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
MAUT	Multi-attribute Utility Theory
SVI	Social Vulnerability Index
CDC	Center for Disease Control and Prevention
UAV	Unmanned Ariel Vehicle
NGO	Non-governmental Organization

CHAPTER 1, INTRODUCTION

The frequency and severity of disasters has amplified since the late 1900s and is only expected to further increase due to climate change, population growth, increasing coastal density, and inadequate disaster preparedness (Atmaca, 2017; Opricovic & Tzeng, 2002; Perrucci et al., 2016). To counteract the impact on human life from these extreme events, relief and response efforts will need to be carefully planned to ensure effective recovery and community wellbeing (Yi & Yang, 2014). In the event of a disaster, temporary housing is utilized by the displaced residents until they can return to their pre-disaster residence. Of the different types of housing/sheltering phases, temporary housing encompasses the most substantial amount of time and it is the phase which enables resuming pre-disaster life activities (Opricovic & Tzeng, 2002). In 2018, disasters led to the prolonged displacement of over 400,000 people globally and required temporary sheltering or housing before resettlement (Venable et al., 2020).

Post-disaster housing is one of the nation's persistent preparedness challenges, with a single deployment of manufactured housing costing upwards of $100,000 (Windle et al., 2019). As a result, there is a critical need for sustainable, cost-effective, and efficient temporary housing (Perrucci et al., 2016; Schmeltz et al., 2013). A lack of prior planning and outdated post-disaster housing strategies has created a complex trade-off between long-term and short-term investment, which impacts the effectiveness of disaster relief (Hidayat & Egbu, 2010; Vitoriano et al., 2011). On one hand, the investments in manufactured temporary housing units during Hurricane Katrina were excessive and short-lived due to the unit's single usage and ultimately, the inconvenient or isolated unit placement which deterred the displaced population from returning for reconstruction and resettlement (Campanella, 2006; Perrucci et al., 2016; Perrucci & Baroud, 2018). On the other hand, the long-term investment in pre-existing and reusable housing infrastructure (e.g., rapid maintenance to pre-disaster homes, available rental properties, and hotel rooms) during Hurricane Sandy led to increases in the assistance monies (i.e., higher living costs) provided to individuals for accommodations and ultimately, led to prolonged periods of sheltering (Bucci, Steven P. Inserra, David. Lesser, Jonathan. Mayer, Matt A. Slattery, Brian. Spencer, Jack. Tubb, 2013; "Hurricane Sandy FEMA After-Action Report," 2013; Perrucci & Baroud, 2018). Failure to address this trade-off and recent innovation within temporary housing has led to prolonged disaster recovery and over expenditure in individual assistance such as with the Hurricanes Katrina ($5.7 billion), Sandy ($1.4 billion), and Harvey ($1.5 billion) (FEMA, 2018; Fugate, 2013; Mickelson et al., 2019; "Rebuilding Stronger and Faster After Natural Disasters In the Aftermath of Hurricanes," 2019; Womack, 2015).

In hindsight, Hurricane Katrina and Hurricane Sandy represent two sides of the post-disaster housing trade-off spectrum (i.e., Hurricane Katrina utilized mainly short-term investment in manufactured units and Hurricane Sandy mainly utilized long-term investment in pre-existing infrastructure). Given the challenge of balancing multiple considerations in temporary housing management (e.g., unit proximity to critical infrastructure and pre-disaster residence, lack of available hotels/rentals, cultural requirements of the region, etc.), all potential temporary housing options must be included in planning considerations and if appropriate, utilized during an event.

This dissertation presents a modeling approach that considers a multi-stage planning process for disaster scenarios to manage temporary housing for displaced populations. The methods presented in this work consider a diverse portfolio of temporary housing alternatives, optimize the short/long term investment trade off through inventory management, and evaluate property damage and relief appropriation in post-disaster scenarios. The methods are illustrated with case studies of different stages of temporary housing preparedness in various disaster scenarios.

1.1. Background

1.1.1. Defining Temporary Housing

When a disaster strikes, the impending population displacement requires post-disaster housing accommodations while conducting the necessary reconstruction to their permanent residence. There are three phases for post-disaster accommodations, which are shown in Figure 1 (Bashawri et al., 2014b; Félix et al., 2013; C. Johnson, 2007b; Alcira Kreimer, 1979; Perrucci & Baroud, 2018; Quarantelli, 1991).

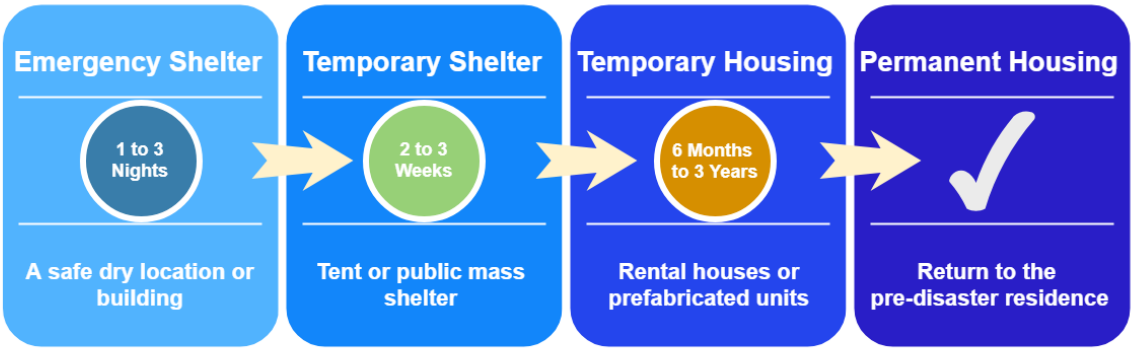


Figure 1: The three phases of post-disaster temporary housing

The first phase of the post-disaster housing is Emergency Sheltering, where for a series of nights the displaced reside in a safe dry location until they can safely navigate the devastated region. The second phase is known as Temporary Sheltering and is made up of public mass shelters or designated camps. This phase will last 2 to 3 weeks, or until a temporary accommodation is available, and is the transitional period between sheltering and housing. The longest and last segment of post-disaster housing before returning to the pre-disaster residence is the Temporary Housing phase, which can last between 6 months and 3 years depending on the severity of the devastation. This substantial length of time is spent in a variety of different places, including rental houses, vacant hotel rooms, pre-fabricated kit units, and manufactured temporary housing units (Bashawri et al., 2014b; Félix et al., 2013; C. Johnson, 2007b; Perrucci & Baroud, 2018; Quarantelli, 1991). Once the reconstruction is concluded, the displaced population will return to permanent housing.

A standardized way to define temporary housing stems from section 408 of the Stafford Act and FEMA's empowered Individual Assistance Program, which describes it as transitional housing for the victims whose homes have been destroyed by disasters. The United States standards for temporary housing state that it is only expected to subsist the amount of time between sheltering and permanent housing, which lasts for up to 18 months. The first type of temporary housing initiated is available rental properties, although these can be limited or largely unavailable, as seen during Hurricane Katrina's recovery effort (FEMA, 2008). When rental properties are lacking, mobile and manufactured homes are used. More specifically, mobile homes are utilized when the recovery effort is expected to be short-term, while manufactured homes are commonly used for both short-term (two months or less) and long-term (several months) recovery events (FEMA, 2008; Force, 2013). Contrastingly to FEMA's timeline, academic research suggests temporary housing is expected to last from six months to three years (Bashawri et al., 2014b).

Beyond these usage timelines, temporary housing units are expected to be easily erected/dismantled, lightweight/transportable, energy-efficient, and "green" with aspects of recyclability and reusability (Song et al., 2016). Temporary housing must allow for normal daily activities (work, schooling, and relaxation) and provide a feeling of security and privacy to the affected (Bashawri et al., 2014b). When attempting to achieve these pre-disaster activities and safety requirements, there are a series of dilemmas which cause adverse impacts and limit the overall success of the temporary housing implementation.

1.1.2. Temporary Housing Dilemmas

The procedures in temporary housing design, deployment, and management influence the occupant's success in recovering (Biswas, 2019). In theory, the supplier of temporary housing seeks to provide the most cost-effective unit that sufficiently increases occupant wellbeing and reduces the displacement duration. As a result, three dilemmas arise.

- Dilemma one is the decision between temporary housing options. A tent is inexpensive, easily constructed, and flexible in placement; however, there are safety (e.g., no rigid walls or locking mechanism) and wellbeing concerns (e.g., sanitation and privacy). In comparison, the costlier manufactured trailer provides increased security and wellbeing with the rigid walls, locking exits, and private living quarters (e.g., a kitchen and bathroom) (Biswas, 2019).
- Dilemma two involves the site selection for temporary housing. A temporary housing site is most effective when placed closest to the original housing because it allows the displaced direct access and inclusion during the reconstruction process. However, achieving this proximity can be detrimental to occupants due to ongoing hazards (e.g., fallen trees and disconnected powerlines) (Campanella, 2006; Perrucci & Baroud, 2018).
- Dilemma three is the cost of temporary housing planning and management. A proactive temporary housing approach requires a significant upfront cost to ensure readily available units at the onset of an event. A delayed order of units during the aftermath of an event minimizes the upfront financial risk but can lead to extreme manufacturing/delivering delays and quality control issues (C. Johnson, 2007a; Maddalena et al., 2009).

Addressing these dilemmas through research is critical to avoid additional disaster impacts resulting from temporary housing mismanagement. Adverse impacts from these dilemmas have been experienced in previous disasters and they can be grouped into three categories that include expenditure, displacement duration, and wellbeing; an explanation of each category and how this research impacts them is explained in the following subsections (Biswas, 2019; Bris & Bendito, 2019; Nigg et al., 2006).

1.1.2.1 Expenditure

The relationship described in dilemma one, between unit cost and satisfaction, is experienced during Indonesia's temporary housing effort after the Tsunami in 2004. The temporary housing consisted of cost-effective tenting inside barracks to provide safety and security. While tents helped reduce costs and the use of barracks mitigated security issues, occupants were still concerned about safety and security (Biswas, 2019). The MCDA analysis implemented in this research gives regions, such as Indonesia, the ability to evaluate various tenting options with other temporary housing designs (e.g., prefabricated kit designs may be a viable option) to reduce the expenditure but also increase quality of living.

In response to lessons learned during Hurricane Katrina, the United States government financed pro-active temporary housing planning. This financing came through the alternative housing programs led by Congress and the Federal Emergency Management Agency (FEMA), allocating a combined $4 billion towards temporary housing development and maintenance (Omar El-Anwar et al., 2010a; FEMA, 2005). Two years later, the United States Government Accountability Office determined that FEMA's disaster planning was insufficient and was causing complications (e.g., increased expenditure and delays) when providing temporary housing (Pierre et al., 2008). These newly funded programs and the confirmation from the United State Government Accountability office illustrate how dilemma three's upfront cost for proactive management and planning is necessary for an efficient implementation. This research provides a solution for reducing the expenditure not warranted by demand of temporary housing by the implementation of the newsvendor model which suggests stocking inventory based on optimal losses with simulated demands.

When Hurricane Sandy landed on the densely populated regions of New York and New Jersey in 2012, 1.75 million people required temporary sheltering; in addition to this, over $1 billion worth of individual assistance was provided (Fugate, 2013; "Hurricane Sandy FEMA After-Action Report," 2013). The increased assistance accounted for the higher cost of living in the impacted region and was the result of utilizing pre-existing infrastructure such as hotels, rental properties, and essential repairs for sheltering in pre-disaster homes as the main methods of transitional and temporary housing. The utilization of pre-existing infrastructure achieves the desired proximity to the pre-disaster housing but has led to prolonged sheltering and raised assistance expenditure due to an increased cost of living (Bucci, Steven P. Inserra, David. Lesser, Jonathan. Mayer, Matt A. Slattery, Brian. Spencer, Jack. Tubb, 2013; "Hurricane Sandy FEMA After-Action Report," 2013; Perrucci & Baroud, 2018). Therefore, the utilized temporary housing methods satisfied dilemma two, at the cost of dilemma one where the chosen temporary housing options led to circumstances which could have been avoided with a diverse portfolio of temporary housing options. This is a situation which would benefit from the results from the MCDA and newsvendor chapters of this research. The MCDA results enable the consideration of a diverse portfolio, and the newsvendor model supports lower manufacturing costs with upfront wholesale orders.

1.1.2.2 Displacement Duration

During Hurricane Katrina, 20,000–30,000 people were displaced and housed in a football stadium nicknamed "The Superdome" for a period of approximately two weeks. However, the amount of people in the shelter quickly deteriorated its conditions and a human health crisis led to wide displacements of citizens around Louisiana and other southern states (Masozera et al., 2006; Nigg et al., 2006; Waugh, 2006). This broad distribution of temporary housing site locations across states hindered the ability to return to the pre-disaster site and prolonged the recovery overall (Campanella, 2006). The deteriorating conditions led to haste in temporary housing site location decisions, where the consequences of dilemma two disrupted the recovery. The larger pre-stocked inventory, as suggested by the newsvendor model, eliminates one of the contributing factors which led to mass and prolonged housing in a football stadium by providing a larger number of readily available units which are not subjected to manufacturing delays.

For the most severe situations, FEMA has allotted a time span of 30 to 60 days before temporary housing is provided to communities. This means that a family of four will be displaced in a shelter for up to two months after a disaster and before placement in appropriate temporary housing (Dombi, 2011). During hurricane Sandy, lack of effective planning in the usage in the usage of hotels, rentals, and emergency repairs, (Birkland & Waterman, 2008; Gheytanchi et al., 2007; Levine et al., 2007), and an underutilization of manufactured temporary housing resulted in 11,000 families in shelters for nearly six weeks after the storm (Sewell, 2012). These shelters held 11,000 families for almost three months in their damaged homes or in "tent cities" provided by FEMA as artic cold snaps hit the area (Bucci, Steven P. Inserra, David. Lesser, Jonathan. Mayer, Matt A. Slattery, Brian. Spencer, Jack. Tubb, 2013). A similar situation occurred during Hurricane Harvey where an estimated 100,000 homes were affected by the hurricane and over 30,000 people were still in emergency shelters more than one month afterward (i.e., substantially longer period then the expected design life for emergency shelters of 1-3 days) (Bashawri et al., 2014b; Fessler, 2017). Prior research demonstrates that people who have relocated or are unstably housed for a prolonged period are at increased risk for adverse physical and mental health problems (Fussell & Lowe, 2014; Merdjanoff, 2013; Nigg et al., 2006; Paxson et al., 2011). These health consequences support significant investment into a proactive temporary housing approach as introduced in dilemma three. Any reductions in transition times between initial displacement, sheltering, and temporary housing would directly reduce the risk of physical or mental health problems. The desired reductions in transition and implementation time can be achieved with the analyses in this research. A larger pre-stock inventory of temporary housing can be ready for implementation rapidly after a disaster occurs and the consideration of a diverse portfolio using the MCDA results enables units with easier construction, transportation, and implementation.

Another example is the Haitian earthquake in 2011 where more than 300,000 homes were destroyed or damaged, and which caused the migration of nearly 605,000 people in a single province. The temporary housing efforts included distributing tents or tarps for improvised emergency shelters; however, the implementation had logistical problems in demolition, rubble removal, appropriate rehousing of victims, and the acquisition and deliverance of relief supplies. These logistical problems are attributed to a lack of Haitian governance and coordination in humanitarian relief (e.g., inadequate assessments of structural integrity, concerns over the historical significance of buildings, and debates on disposal of rubble which decelerated the appropriation of supplies and the reconstruction of the area). A year later, Haiti had 1.4 million residents still occupying shelters. The temporary housing type, site selection, and neighborhood design increased exposure to other hazards including landslides, debris flows, flash floods, and a cholera outbreak. This exposure reiterated the importance of temporary housing organization and unit design (dilemma one and two) due to the impact on recovery prospects (Ritchie & Tierney, 2011). Situations with mass-displacement and economic restrictions similar to the Haitian earthquake are beneficiaries of the MCDA results and are able to implement a similar low-cost unit which provides more specifically for the region's needs (e.g., prefabricated kit supplies or the tenting supplies) and reduce exposure to other risks which prolong recovery (e.g., a reduction in cholera is expected with the raised floor of pre-fabricated kits eliminating contact with contaminated water and flooding).

1.1.2.3 Health and Social Wellbeing

Poor temporary housing management can be harmful to human health. For example, when Hurricane Katrina struck the southern coast of the United States in 2005, formaldehyde and 32 other volatile organic chemicals were measured in a selection of temporary housing units. These measured chemical levels in the temporary housing units are from the construction materials and poor airflow (Levine et al., 2007; Maddalena et al., 2009). The presence of these chemicals is a consequence of dilemma three and indicates the importance of quality control through proactive temporary housing planning. One method to reduce these occurrences of manufacturing errors is to increase the amount of time for manufacturing, and the larger pre-stock from the newsvendor model will not be subjected to shortened manufacturing periods caused by disaster demand.

The Tōhoku Earthquake in 2011 led to the creation of a Japanese word "Kodokushi", which describes a suicide inside temporary housing, demonstrating the extreme negative impact of temporary housing mismanagement and neighborhood design with regards to mental health (Bris & Bendito, 2019; Koyama et al., 2014). This criticism of temporary housing has been consistent over the past decade for the lack of sufficient unit and location conditions (dilemmas one and two) for displaced families (Amin Hosseini et al., 2016; Chen et al., 2012). The importance of the stakeholder informed MCDA is made evident by the cultural requirements, and consequences if cultural requirements are ignored, during the Tōhoku Earthquake. Ideally, the multiple criteria will provide a more suitable temporary housing design which mitigates or minimizes the cultural disruption.

Overall, the success of temporary housing management relies on approaches that consider multiple criteria to address dilemmas and achieve multiple objectives. An optimization of the procedures and designs utilized during temporary housing management will ensure efficiency and the well-being of the recovering population. A review of previous research is needed to evaluate the progress towards solving these three identified dilemmas and recognizing unexplored pathways in the design strategies, decision-making methods, and optimization for successful temporary housing implementation.

1.2. Research Objectives

The goal of this research is to develop methods to inform the decision process of post-disaster temporary housing management by addressing dilemmas in expenditure, displacement duration, and wellbeing. The proposed methods can ultimately improve the efficiency of United States' post-disaster housing and recovery during disaster scenarios (e.g., reduced financial risk, diverse post-disaster housing portfolios, lessened resource requirements for damage evaluations and enable scalability for relevance on a global scale).

Towards this goal, the research objectives of this dissertation are as follows:

1. Review and synthesize prior modeling research in temporary housing to identify significant gaps in current knowledge
2. Develop and demonstrate a decision analysis, which integrates stakeholder opinion, to identify the best type of temporary housing, create a diverse portfolio of housing options, and enable scaling to satisfy stakeholder needs worldwide
3. Develop and demonstrate a stocking inventory management model on temporary housing to reduce financial risk and allocation delays for United States response agencies
4. Develop and demonstrate a novel methodology for evaluating initial residential disaster damages and iterative community recovery that will reduce housing uncertainty during recovery and ensure equitable relief

The successful completion of these objectives will provide response agencies a novel methodology to evaluate residential property damage, prepare for the impending temporary housing requirements, and allocate a diverse and satisfactory temporary housing solution; all of which reduce financial and housing risk while provide a greater level of efficiency to the processes.

1.3. Dissertation Overview

After an introduction and background pertinent to post-disaster temporary housing, this dissertation presents a review of temporary housing management, modeling and design strategies. This work identifies gaps within current research which includes major deficits within novel unit decision evaluation, sustainable unit designs, maximized storage capacities and inventory management, and community resilience.

Many of these deficits, including sustainable unit design, maximized storage capacities, and community resilience, can be solved through novel unit decision evaluation. In the United

States, the government housing unit has stayed relatively constant with mobile home units and manufactured housing units (FEMA, 2021c). By considering novel temporary housing designs, the modern designs may be more environmentally friendly (e.g., local material usage, recyclable materials, etc.), easily storable (e.g., modular designs, prefabricated kit supplies, etc.) or accommodating to cultural requirements to aid community resilience (e.g., private kitchens, natural lighting, etc.). Chapter 3 implements a multi-criteria decision analysis (MCDA) which considers stakeholder opinion for a series of key interim housing aspects to determine temporary housing unit designs based on disaster scenarios. This MCDA analysis considers global temporary housing options which, at minimum, have a working prototype for implementation. Each temporary housing design ranges in terms of sustainability, cost, and safety, among others. and stakeholder opinion is required to weigh these attributes to ultimately recommend. An illustrative case study of the proposed decision model shows that Manufactured Housing is preferred in the case of the United States.

Even after determining the best temporary housing design based on stakeholder feedback, there are still decisions to be made to pro-actively prepare for disasters and housing displacements. The pro-active storage of THUs requires quantifiable support to realistically maximize pre-stock inventories and by implementing a newsvendor optimization for inventory management, the pre-stocking of units is supported by the hedged (i.e., minimized or avoided) losses. The United States' preference for Manufactured Housing is carried into Chapter 4 which implements a simulation-based inventory management model. This model simulates the property damage based on historical hurricane damages for each county in a selection of southeastern states (i.e., the Gulf Coast states and the South Atlantic states up to North Carolina). State level and nationwide inventory management conclusions are made using the newsvendor model for Manufactured Units based on aggregated county damage simulation values and corresponding estimations of temporary housing demand.

The accuracy of results from the newsvendor model in the fourth chapter is heavily dependent on the residential property damage estimation which include uncertainties and assumptions on estimated property damage values. Chapter 5 is inspired by this importance of residential property damage in the previous chapter and establishes a novel methodology to evaluate initial property damage and recovery progress after disaster events. This methodology utilizes iterative drone imagery of devastated regions and stakeholders from the government and NGOs to determine its efficacy for utilization, the implemented case study demonstrates its ability to evaluate communities efficiently and effectively.

Finally, conclusions and a synthesis of the dissertation are presented in Chapter 6.

CHAPTER 2, A REVIEW OF TEMPORARY HOUSING MANAGEMENT MODELING: TRENDS IN DESIGN STRATEGIES, OPTIMIZATION MODELS, AND DECION-MAKING METHODS

2.1 Motivation

To effectively solve the temporary housing dilemmas described in section 1.1, this research first investigates previous studies and presents a synthesis of existing unit designs and various models developed for utilization in temporary housing management.

We specifically focus on optimization models, multi-criteria decision models, and unit design strategies (qualitative and quantitative) because of their ability to address critical challenges in the planning for temporary housing including design, site selection, and occupant assignment. The review describes trends in prior studies and proposes directions for future temporary housing research to address gaps in design strategies, sustainability, and community resilience. Specifically, this research shows the importance of proactive temporary housing management, the merit behind modular housing for large-scale storage, the benefit of applying a Leadership in Energy and Environmental Design (LEED)-like evaluation system to temporary housing and the importance of hedging against demand uncertainty with unit pre-stock and a diverse portfolio of temporary housing options.

Overall, the success of temporary housing management relies on approaches that consider multiple criteria to address dilemmas and achieve multiple objectives. A review of previous research is needed to evaluate the progress towards solving these three identified dilemmas and recognizing unexplored pathways in the design strategies, decision-making methods, and optimization for successful temporary housing implementation.

2.2 Methods

This research reviewed 107 publications representing five individual publication types, including academic journals, government agency releases, conference publications, news articles, and books. The studies analyzed have been published between the years 1979 and 2020 and cover a wide range of geographical regions including 18 different nations worldwide across North America, South America, Europe, Asia, and Australia.

2.2.1 Key Words

Multiple terms have become synonymous with disaster relief housing. Table 1 provides the description of the three terms that are most commonly used in this research field (Facilities & Paper, n.d.; Kar & Hodgson, 2008; Liu et al., 2011).

Table 1: Key Words

Terminology	Definition
Temporary Housing (TH)	The placement of manufactured housing units at individual home sites, existing mobile home parks or newly designed and constructed community group sites when an event has rendered existing homes uninhabitable (Facilities & Paper, n.d.).
Temporary Shelters (TS)	Disaster prevention facilities in densely populated urban areas in developed countries (Liu et al., 2011).
Emergency Shelters (ES)	Dual use shelters where the primary purpose is for another public function (Kar & Hodgson, 2008).

The first stage of the disaster relief process with regards to housing is the emergency shelter. These emergency shelters include any type of public building, including sport venues, universities, and community centers, and are ideally allotted to provide a few days of relief before transitioning to a dedicated disaster relief shelter (Bashawri et al., 2014b). This transition leads to the use of temporary shelters, which includes a short stay (few weeks or less) in a mass shelter (Félix et al., 2013). These shelter types, emergency shelters and temporary shelters, require the absence of normal life activities and the alteration of known life for the affected population (Quarantelli, 1982). Unlike the previous shelters, temporary housing allows for pre-disaster daily activities to be restarted and are intended to house people for several months or years depending on the severity of the disaster. Once the permanent housing is rebuilt, there is no longer a need for temporary housing unless the unit is updated to provide permanent housing standards (Hany Abulnour, 2013; Mcintosh, 2013).

2.2.2 Meta-Analysis Description

This section provides a meta-analysis examining the spatio-temporal and thematic distribution of publications.

2.2.2.1 Categorization of Articles and Distribution of Geography

The examined articles have been categorized according to specific themes. These themes are determined by an assessment of each article's outcomes, methodologies, and overarching focus. As seen in Figure 2, the top five categories correspond to social aspects, optimization methods, agency reporting, sustainability, and design.

Additionally, the geographic distribution of first authorship is examined under each theme. Scholars from 14 countries have been contributing to post-disaster housing research. Articles published by authors in the USA constitute the largest portion across all themes except for ones that include life cycle analysis, decision-making, review, and humanitarian aspects. In contrast, agency reporting, news articles, policy, and resilience are themes corresponding to authors in the USA only. Decision making, social, design, and sustainability are global themes with a wide geographic distribution and articles published by authors from across the world.

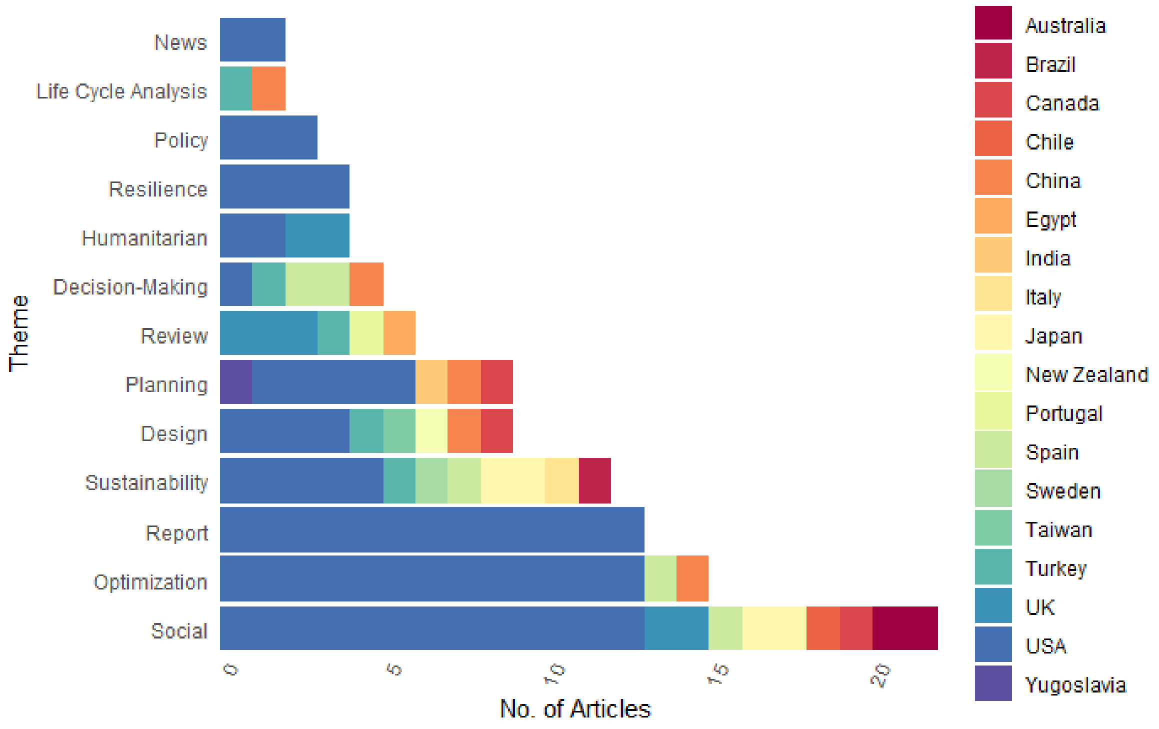


Figure 2: Distribution of the number of articles according to theme categories and countries of first authors

2.2.2.2 Distribution by Publication Year

Figure 3 is the breakdown of articles by publication year, with the one hundred and seven articles spanning from nearly 1979 to 2020. Major impact disasters are also indicated on the x-axis. It is interesting to note the fluctuations and corresponding nature to the disaster events. Since 2005, temporary housing research has seen a cyclical pattern with productivity peaks around a year after a major disaster (e.g., 2007, 2011, 2013, 2018, 2019). This pattern corresponds to a series of international events that reiterated the importance of temporary housing through the mass displacements of people.

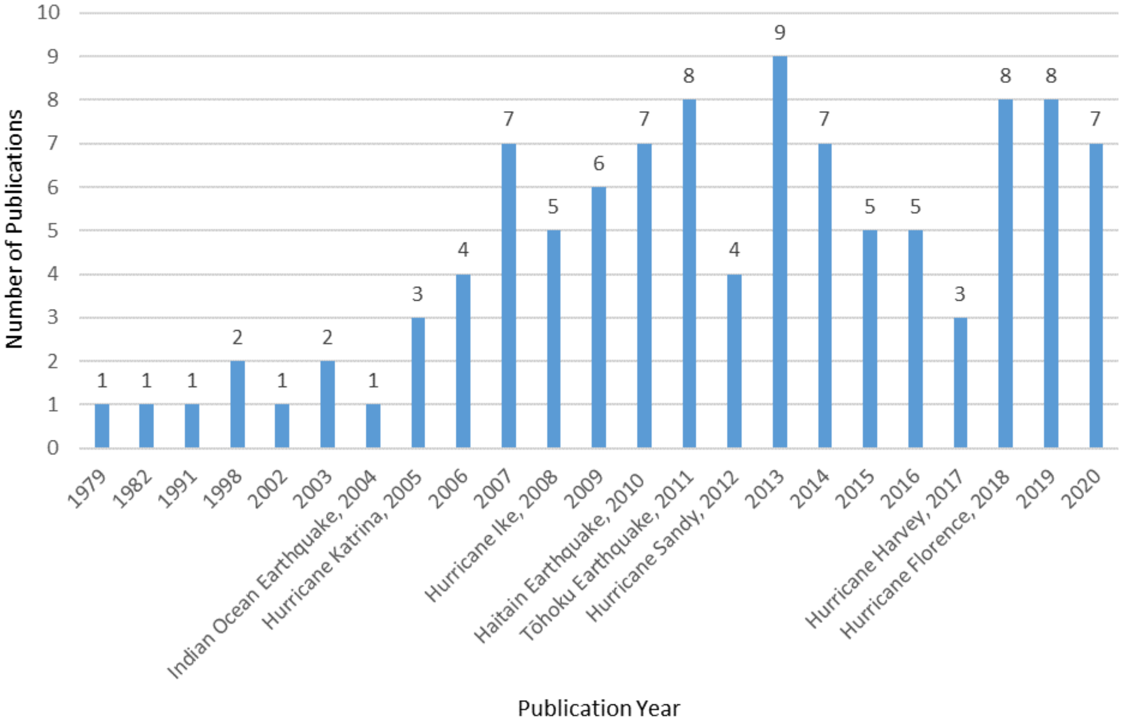


Figure 3: Number of publications by year and corresponding major disasters

2.3 Results

Prior studies in temporary housing focused on various aspects, such as sustainability, humanitarian aid, public policy, health impacts, and legal issues. The most significant contributions to advancing temporary housing research can be categorized into three areas, (i) decision-making methods, (ii) design strategies, and (iii) optimization models because of their focus on addressing the dilemmas of unit design, site selection, and proactive management.

The studies were categorized according to the methodological approach, which includes optimization, decision-making methods, and design strategies. When applicable, the studies were further classified depending on whether they address the unit (e.g., housing type, occupant needs, and design considerations) or the allocation (e.g., site selection, logistics, and distribution). A summary of these models is provided in Table 2.

Over a span of more than a decade, a series of proposed designs and models have been developed to increase overall effectiveness with regards to various aspects of temporary housing within social, environmental, and economic requirements. Among the early methods considered was a decision-making model developed to integrate temporary housing into prior-planning efforts through the macro-issues (e.g., understanding local conditions, choosing suitable locations, identifying required services), leading to a series of optimization models (C. Johnson, 2007b).

Table 2: Summary of past temporary housing research

Date	Type	Focus	Qualitative	Quantitative	Key Methods	Case Study	Hazard Example	Source
2007	Decision-Making Method	Allocation	X		Case Study	Various	Earthquake	Johnson 2007
2007	Design Strategies	-	X		Physical Model	Beci, Turkey	Earthquake	Arslan 2007
2007–2010	Optimization	Unit and Allocation		X	Multi-Objective Weighted Integer, Multi-Objective Genetic Algorithm	General	-	El-Anwar et al. 2010a El-Anwar et al. 2010b El-Anwar and El-Rayes 2007 Chen et al. 2012
2009	Design Strategies	-	X		Multi-Objective Design	Turkey	Earthquake	Sener and Altun 2009
2009–2010	Optimization	Unit and Allocation		X	Multi-Objective Genetic Algorithm	General	-	El-Anwar et al. 2009b Kandil et al. 2010 Chen et al. 2012
2009–2010	Optimization	Allocation		X	Multi-Objective Genetic Algorithm	General	-	El-Anwar et al. 2009a El-Anwar et al. 2010 McLaren et al. 2009 Chen et al. 2012
2011	Decision-Making Method	Allocation	X		Case Study	Haití	Earthquake	Ritchie et al., 2011
2012	Optimization	Allocation		X	Multi-Objective Optimization	General	-	El-Anwar et al. 2012a
2012	Optimization	Unit and Allocation		X	Multi-Objective Optimization	General	-	El-Anwar et al. 2012b

*The background color refers to different study types (e.g., Optimization, Decision-Making Methods, Design Strategies)

2012	Optimization	Unit and Allocation		X	Multi-Objective Optimization, Cost-Benefit Analysis	General	-	Chen et al. 2012
2013	Design Strategies	-	X		Review	General	-	Felix et al. 2013
2014	Design Strategies	-	X		Review	General	-	Hany Ablunour 2014
2014	Design Strategies	-	X		Physical Model	New York, USA	-	Ford et al. 2014
2014	Optimization	Allocation		X	Greedy Heuristics	General	Hurricane	T.R. Rakes et al. 2014
2014	Design Strategies	-	X		Case Study Method	USA, Australia, New Zealand	Earthquake, Hurricane, Fire	Zhang et al. 2014
2015	Design Strategies	-		X	Information-Based Mechanisms	Indonesia	Earthquake	Tsai 2015
2016	Optimization	Allocation		X	Multi-Objective Optimization	General	-	El-Anwar et al. 2016
2016	Decision-Making Method	Unit		X	MIVES Method	Tehran, Iran	Earthquake	Hosseini et al. 2016
2017	Design Strategies	-	X		Case Study	Various	Earthquake, Hurricane, Typhoon	Hong 2017
2018	Design Strategies	-	X		Case Study	Japan	Earthquake	Seike et al. 2018
2018	Optimization	Allocation		X	Newsvendor Method	USA	Hurricane	Perrucci and Baroud 2018

*The background color refers to different study types (e.g., Optimization, Decision-Making Methods, Design Strategies)

2018	Design Strategies	-	X		Review	Various	Earthquake, Hurricane, Refugee	Sagiroglu et al., 2018
2018	Design Strategies	-		X	Social LCA	Chile	Fire	Mora et al., 2018
2019	Design Strategies	-	X		LCA	General	-	Cascone et al. 2019
2019	Design Strategies	-	X	X	Case Study	Japan	Earthquake	Bris and Bendito 2019
2020	Optimization and Decision-Making Method	Unit		X	MIVES Method, Backtracking	Bam, Iran	Earthquake	Hosseini et al., 2020
2020	Optimization	Allocation	X	X	AHP, TOPSIS, Multi-objective Optimization	China	Earthquake	Geng et al., 2020
2020	Optimization	Allocation		X	ArcGIS Optimization	Macao	Typhoon	Zhao et al. 2020

*The background color refers to different study types (e.g., Optimization, Decision-Making Methods, Design Strategies)

The first temporary housing optimization model focuses on optimizing structural safety, economic impact, and distances from the preferred location; however, that proved to be insufficient and this model is later expanded (Chen et al., 2012; O El-Anwar et al., 2009; Omar El-Anwar et al., 2009). The newly expanded model included optimal location options and a method to achieve the desired social, economic, safety, and environmental objectives; although, consideration for occupant preference is not included (Chen et al., 2012; El-anwar et al., 2010; Omar El-Anwar et al., 2009; Omar El-Anwar & El-Rayes, 2007). A fourth, more complex model, developed with user preference, resulted in increased computational expense, a combination that hindered the model's feasibility and brought to light a tradeoff between effectiveness and efficiency (Chen et al., 2012; El-anwar et al., 2010; O El-Anwar et al., 2009; Omar El-Anwar et al., 2010b).

In order to address these shortcomings, more advanced methods use a model that considers equivalent distances for allocation and a hybrid housing approach between temporary housing and alternative housing (i.e., hotels, inns, rental properties); while maximizing the socio-economic wellbeing of the occupant. However, the run times are impractical for large-scale implementation (Omar El-Anwar, 2012; Omar El-Anwar & Chen, 2012). As such, a web-based optimization model was developed by Chen et al. (2012) to solve the prolonged runtime and computational expense of past models while minimizing cost and maximizing the social, economic, and physiological benefit of displaced people. The approach heavily depends on a reliable and updated database of temporary housing alternatives (Chen et al., 2012). Rakes et al. further expand on occupant-specific needs and assignments to temporary housing units by optimizing the access and proximity to support services (Rakes et al., 2014). A novel and holistic planning framework is designed to manage expenditure while offering customized housing plans to satisfy these occupant specific social, economic, and psychological needs (Omar El-Anwar & Chen, 2016).

Much of these optimization models do not consider pre-stock warehouse quantities and inventory management considerations. Recent models address this gap by including occupant needs with sheltering requirements, capacities, and pre-stock warehouse quantities to determine the best distribution of the displaced people (Geng et al., 2020). Other approaches optimize pre-stock inventory as a form of hedging against demand uncertainty, higher costs, and manufacturing delays (Perrucci & Baroud, 2018). One case study of pre-stock inventory consideration optimizes the evacuation distance for displaced citizens with established (i.e., pre-stocked) shelters to promote capacity planning in Macao (Zhao et al., 2020).

In addition to optimizing the management of temporary housing units, a successful implementation also depends on the unit type and design strategies (Félix et al., 2013). Five key recommendations for temporary housing unit design include rapid availability, utilization of local resources, compatibility with local living standards (comfort, service, location), planned design life, and the environmentally-friendly removal of units (Hany Abulnour, 2013).

One approach to achieve these five recommendations is modularity. The modularity in temporary housing design is promoted as a universal unit that adapts to specific occupant needs, raises the quality of life, simplifies storage, and increases deployment and collection speed (Ford et al., 2014; Sener & Altun, 2009). A novel design from Italy shows how a low-cost modular housing design can improve occupant wellbeing and provide a reduced installation time with improved sustainability (Cascone et al., 2019). However, a separate study of three prior disasters found that modular designs may not be universally suitable and avoided when social appropriateness does not agree with technical innovation (Zhang et al., 2014). However, the low cost, short construction period, simplicity of assembly, and sustainable upcycling nature of modular container housing make it a favorable option moving forward (Hong, 2017).

Another aspect of unit design to help lower the environmental impact of temporary housing is sustainability. Sustainable options require the utilization of new resources unlike the reutilization of past units (Sagiroglu, 2018). There are designs promoting the reusability and recyclability of temporary housing, however, governments struggle to achieve the desired sustainable waste management (Arslan, 2007). The key design flaws that discourage the re-use of housing units include material usage (i.e., screws and foundation types) that deter the dismantling of the unit and the inflexibility from the original floor plan. To maximize re-use, designs must account for material usage or apply circular economy methods. If applied correctly, a circular economy transitions previously occupied temporary housing units towards being a material source and a component in the supply chain of new products/units (Seike et al., 2018).

These life cycle costs propagate past unit design and require models to sustainably assess temporary housing site locations, especially to achieve re-utilization (Amin Hosseini et al., 2016). However, it is important to keep occupant wellbeing in mind while adapting temporary housing designs. A social lifecycle analysis (S-LCA) can measure the social impact of unit designs and delivery methodologies, to ensure minimal social impact (Mora & Akinci, 2018).

2.4 Discussion

The current compilation of academic research has addressed the limitations in temporary housing allocation, providing models and decision methodologies for optimal site location and the satisfaction of occupant specific needs (Chen et al., 2012; Omar El-Anwar & Chen, 2016). Increased global demand for temporary housing has led to significant research advances and innovations in design strategies which satisfy user needs, reduce expenditure, and provide rapid installation (Bris & Bendito, 2019; Cascone et al., 2019). However, current approaches fail to account for future temporary housing demands, combined novel and existing designs, island relief efforts, social consequences, and the absence in reusing and recycling of temporary housing. Climate-driven severities are feared to increase temporary housing demands, resulting in a gap in current research pertaining to unit storage efficiency and strategies. In the case of island relief, the widely varying requirements and demand as well as the inability to evaluate both novel and existing temporary housing designs produces a gap in pro-active management of temporary housing. Addressing these gaps requires consideration of community resilience in disaster recoveries; however, the social consequences of temporary housing are only starting to be investigated. Finally, from an economic and environmental standpoint, the main concern is the inability to recycle and reuse temporary housing units, which makes accommodation efforts unsustainable due to the short utilization period and raw material consumption. As such, these research gaps are organized into four categories including unit storage strategies, pro-active temporary housing management, community resilience, and sustainability.

This review has identified directions for future research and proposes the following recommendations:

- A decision analysis to simultaneously evaluate existing and novel designs and support pre-stocking of units
- The utilization of prefabricated housing kits and modular units to increase storage capacities
- The creation of a LEED-based rating system to ensure uniform temporary housing sustainability
- An implementation of circular economy methodology to enable recycling and re-use
- An emphasis on social and cultural considerations during the temporary housing process.

The recommended research will advance an exhaustive field of study and prepare to transition and respond to increased climate-driven event severities and temporary housing demand.

2.4.1 Pro-Active Temporary Housing Management

2.4.1.1 Modeling and Design Strategies

Temporary housing management has benefited from the previous decision and optimization models which compiled a variety of methods for site selection and occupant need-based assignment (Chen et al., 2012; Omar El-Anwar et al., 2009; Hosseini et al., 2016; Zhao et al., 2020). The benefit from design strategies are harder to recognize due to a lacking framework to implement the findings. For instance, these design strategies focus on investigations into modular units, enhancing temporary housing environments, and the creation of novel unit designs. In order to consider innovative designs as plausible options for governments, humanitarians, and other stakeholders looking to supply temporary housing, a formal decision-making process is needed to provide a mechanism for comparing different strategies under different criteria. Additionally, these approaches allow for a collaborative decision-making environment that includes multiple stakeholders from different sectors. Past research is missing a significant piece where novel design and previously utilized temporary housing methods are compared simultaneously using social and wellbeing attributes (e.g., privacy, security, lighting) of the units (Akdede, 2018).

2.4.1.2 Implementation

When looking at Hurricane Maria's recovery, the United States' territories can benefit from the proactive management of temporary housing. Puerto Rico became a humanitarian crisis as 300,000 homes were damaged, resources became scarce, and a portion of the population shifted to informal reconstruction (Talbot et al., 2020). To reduce the impact of disasters on these territories and increase resource availability, the United States can pre-stock a larger variety of temporary housing options (i.e., kit supplies and tenting) to ensure availability and ease of intercontinental shipping or pre-stock warehouses on territories for immediate relief. This implementation requires a temporary housing decision-making method to provide the best choice for stakeholders and an updated inventory optimization model to hedge financially against the demand uncertainty.

2.4.2 Innovative Storage Designs and Strategies

2.4.2.1 Modeling and Design Strategies

Depending on the severity of a disaster, displacement can lead to increased demand and a potential inventory management problem with temporary housing units. Studies that attempt to provide an inventory management solution find that temporary housing, especially manufactured units, will require new methodologies for efficient storage (Perrucci & Baroud, 2018). Moving forward, design strategies should transition to prefabricated kit supplies or ease of storage included in considerations when designing a manufactured unit. A partial solution for manufactured unit storage is in the utilization of recycled shipping containers as the base design. The modularity and rigid structure of the containers enable the stacking of units to multiply storage capacities.

2.4.2.2 Implementation

While research includes storage considerations for temporary housing units, the unit design and practical implementation will become more important as demand grows (Chen et al., 2012; Perrucci et al., 2016). In practice, using shipping container units as temporary housing alternatives results in practical storage options at ports or on ships for an added benefit of mobility to disaster locations (Akdede, 2018; Perrucci et al., 2016). Pre-fabricated kits are an alternative option to increase storage capabilities, reduce shipping costs, and still maintain quality of life standards (Cascone et al., 2019).

2.4.3 Sustainability

2.4.3.1 Modeling and Design Strategies

Temporary housing research must consider sustainable solutions. Sustainability aspects have been considered in prior research through modeling and design strategies; however, improvement is needed in two main areas. These areas include an evaluation system for the sustainability of temporary housing units and the implementation of a circular economy for recycling temporary housing at the end of the design life (Cascone et al., 2019; Hosseini et al., 2016). For temporary housing designs, there is a missing evaluation system for sustainability. For instance, novel and established designs can be evaluated using a Leadership in Energy and Environmental Design (LEED) based approach. The LEED approach uses a certification system to evaluate the sustainability of a project based on points obtained with eco-friendly design attributes (Castro-lacouture et al., 2009). A sustainable LEED approach on design, construction, and material composition, increases the upfront cost to provide larger savings over a building's lifetime (Azhar et al., 2011; Heerwagen et al., 2006). Once a LEED-based approach is established for temporary housing units, the sustainability of novel unit designs can be uniformly compared.

Additionally, the lack of re-use in temporary housing is a predicament that research continues to investigate for a number of years (Hosseini et al., 2020; Perrucci et al., 2016; Seike et al., 2018). Re-use of a housing unit can present health and maintenance concerns which led response agencies to auction used units (Government Auctions and Sales Government Sales of Seized and Surplus Property, 2019; McCarthy, 2010). Moving forward, re-utilization can be achieved through a circular economy. One definition for circular economy is an economic system that revolves around reducing or alternatively reusing, recycling, and recovering materials for future uses, where rather the recovered waste becomes the new inputs (Abreu & Ceglia, 2018). Using shipping container units again as an example, the metal shell of the unit can be recycled, and the interior design optimized for the recovery of valuable materials. Implementation of this circular economy requires modeling of the ecological exchange of recovered materials and updated design strategies.

2.4.3.2 Implementation

LEED is the most widely adopted sustainable building rating system in the USA and globally, being used in over 167 countries and territories. The feasibility of implementing a LEED-based system would depend on the LEED presence in the specific country. At the end of 2017 certain countries had thousands of LEED projects (e.g., USA, Canada, and China had 30,669 in the USA, 2970 in Canada, and 1211 in China) while other countries have seen a slower implementation of LEED projects (e.g., 275 in Germany, 106 in Korea, and 245 in Turkey). Lack of infrastructure and prior experience with LEED projects are among the main barriers to the implementation of a LEED-based system (Azhar et al., 2011; Stanley, 2018). Given the prior experience with LEED projects and the fact that temporary housing provisions are part of the housing assistance offered by the Federal Emergency Management Agency (FEMA), the implementation of a nationwide LEED-based system in the USA for temporary housing would be feasible. However, the upfront cost or "green premium" is a deterrent for the certification of LEED standards. Therefore, response agencies around the world may be less likely to adopt sustainable attributes (Mosier & Gransberg, 2013).

A sustainability ranking system has never been implemented for Temporary Housing and requires a multi-criteria development plan with aspects of LEED's Neighborhood Development. This type of adapted credit system would ensure the desired sustainability through unit design and site development, including credits awarded for reduced resource consumption, indoor air quality, energy efficiency, public spaces, walkable streets, transit facilities, and mixed-use neighborhood centers (Szibbo, 2015). With a Temporary Housing LEED accreditation system, the certification of novel and established temporary housing units can contribute to a successful recovery and promote sustainable units and neighborhood resourcefulness (Campanella, 2006; Chamlee-wright & Storr, 2011). In doing so, the application of a LEED-based system provides a uniform evaluation process which is sustainable and enables credit considerations for an optimal design that supports re-use. In addition, the system enables key factors that increase community resilience such as an improved quality of life, cultural fulfillment, and greater access to transportation and resources.

A shift from linear to circular consumption of resources is expected as resource scarcity increases. Employing a circular economy for temporary housing units will enable the currently unachievable re-utilization and recycling of valuable resources, while potentially reducing disaster expenditure due to the newfound income. Interestingly, the implementation of a circular economy is historically problematic for certain countries yet almost naturally achieved by others (Abreu & Ceglia, 2018). For effective implementation of circular economy methodologies, the economic benefits must comply with regulatory requirements (Bain et al., 2010). In the case of a circular economy revolving around temporary housing units, the newfound income and recycling of previously ineligible materials would satisfy these requirements. In addition, the federal involvement and optimized unit design with pre-defined reusable waste helps address the communication and supply chain trust, which are critical for successfully implementing a circular economy. However, the uncertainty in temporary housing demand can negatively impact the results of a circular economy, where manufacturing would rely on the re-utilization of parts from the deployed temporary housing units (Gibbs, 2003; Mirata & Emtairah, 2005; Veleva et al., 2015). In these cases, the only way to ensure productivity is a prior planned secondary supply chain of the required materials.

2.4.4 Community Resilience

2.4.4.1 Modeling and Design Strategies

Researchers agree that ecological, social, and economic considerations make up three of the main categories in community resilience (Cutter et al., 2008; Gillespie-Marthaler et al., 2019). Existing temporary housing models consider socio-economic factors, which partially address community resilience. However, emergency planning, which includes temporary housing planning, must account for specific social indicators such as regional connectivity, public engagement and trust, inclusion, and awareness (Gillespie-Marthaler et al., 2019).

Design strategies benefit from the inclusion of social indicators. For instance, illustrated 3-D unity design descriptions improve public engagement in the planning and construction phases of temporary housing units (Tsai, 2015). Decision-making methods also benefit from the consideration of social indicators. For instance, a model focusing on local government temporary housing decisions would require a decision-making method where the public feature as a key stakeholder with solicited importance weightings and veto capabilities.

In addition, the optimized balancing of supply and demand of temporary housing is important for maximized resilience, especially, considering overages can be used for future events and shortages can lead to extended sheltering with mental health implications (Casey, 2012; Gillespie-Marthaler et al., 2019; Kessler et al., 2008). An allocation and inventory management model is required to hedge against demand uncertainty and reduce adverse social consequences.

2.4.4.2 Implementation

Prior research establishes that a societal connection or social capital is linked to increased community resilience (Bolin & Stanford, 1998; Chamlee-Wright, 2010; Chamlee-Wright & Storr, 2009; Murphy, 2007; Paton, 2007; Pelling, 1998; Pelling & High, 2005; Shaw & Goda, 2004). It is important to maintain this societal inclusion with post-disaster management issues (Ueda & Shaw, 2015). Temporary housing is the first step to providing normalcy and wellbeing for the affected community after a disaster (Barakat, 2003; Félix et al., 2013). The public should be active participants in all temporary housing planning processes due to potential social impact and varying perceptions from differing locations, cultures, and educations (Faure et al., 2020; Venable et al., 2020). A program similar to FEMA's past pilot program known as Sheltering and Temporary Essential Power (STEP) would allow the emergency shelter, temporary shelter, temporary housing, and permanent housing to be combined into one singular entity, enabling homeowner inclusion through the entire process and efficiency of time and resources. While this option improves feasibility, expenditure, and wellbeing during implementation, it has not been fully established in temporary housing research due to a lack of data regarding the success of the recovery activities (Harriss et al., 2020).

2.5 Conclusion

As the world population continues to grow and disasters become more frequent and devastating, temporary housing will increasingly be a critical aspect of disaster response and recovery (Opricovic & Tzeng, 2002; Perrucci et al., 2016). The increased frequency and the enlarged number of displaced peoples will require a series of novel designs, decision-making methodologies, and optimization models for temporary housing to ensure the safety, wellbeing, and ability to recover. Overall, this review of the literature reveals that the previous designs and models focusing on temporary housing have made necessary steps; however, there is a major deficit to be filled by novel unit decision evaluation, maximized storage capacities, sustainable unit designs, and community resilience indicators.

This current compilation of temporary housing designs, decision methodologies, and optimization models require further expansion to solve future challenges of temporary housing dilemmas. One of the major gaps identified by this review is in the pro-active management of temporary housing (i.e., planning and preparing in advance of the next extreme disaster scenario). The next two chapters of this research are aimed at solving this gap within pro-active management. In Chapter 3, a multi-criteria decision analysis is conducted using stakeholder input to evaluate various temporary housing designs for a set of disaster scenarios. The temporary housing design results from Chapter 3 feeds directly into Chapter 4, which utilizes a Monte-Carlo driven newsvendor model to optimize pre-stock inventories of temporary housing solutions in preparation for upcoming disaster events.

CHAPTER 3, PLANNING FOR TEMPORARY HOUSING THROUGH MULTI-CRITERIA DECISION ANALYSIS

3.1. Motivation

For the past two decades in the United States, areas with excess post-disaster housing demand (i.e., those displaced who cannot find a rental property) received an allocated government housing unit (FEMA, 2021c). Past studies agree that the temporary housing unit design is a critical aspect in achieving efficient disaster recovery, however, it is currently a problematic phase that is preventing the desired results during post-disaster situations (Félix et al., 2013; C. Johnson, 2007b). The allocated government housing unit has altered minimally over these decades, and remains a mobile home unit or a manufactured housing unit (FEMA, 2021c). Mobile and manufactured housing units benefit from their prebuilt structure (i.e., quick utilization after shipment) and higher quality of living than other temporary housing options, although these benefits have been overshadowed by disadvantages, including the associated costs, poor quality control, transportability, and sustainability of the units (Perrucci & Baroud, 2020). Outside of the United States, global temporary housing solutions also range in design and unit type and corresponding pros and cons. Prefabricated kit units and tenting are popular global options which benefit from ease in transportation and local construction, however, they are criticized for lack of security and failing to sufficiently meet user needs. Modular units (i.e., a hybrid of manufactured and kits units) are one option which provides the user satisfaction from mobile and manufactured homes, while enabling ease of transportation similar to kit units or tenting. More specifically, a modular unit design breaks manufactured units into segments which are designed for separate transportation, local setup at the site, and increased user satisfaction compared to traditional kit designs (Hong, 2017; Perrucci & Baroud, 2020; Perrucci et al., 2016).

A systematic evaluation method for a compiled list of global temporary housing designs and unit types would enable a flexible response to disasters by allowing countries to utilize one, or multiple, from another country's established designs to create a diverse portfolio of options and inform implementation decisions based on the scenario and desires of the nation.

A United States response agency's post-disaster allocation efforts would benefit from a diverse portfolio of approved temporary housing options (i.e., multiple established designs). Each unit design provides unique benefits for a range of disaster scenarios and promotes hedging of multifactorial risks (e.g., climate conditions, family size, security requirements, etc.). This diversification in temporary housing portfolios is well supported due to the proven success from similar diversification in financial portfolios to hedge economic disruptions (A. Kreimer et al., 2003). For example, in a scenario where 25,000 people require temporary housing, United States response agencies will provide a number of readily available manufactured and mobile housing units, however, it may not be feasible for current designs to store 25,000 units and therefore, the full demand may not be supplied by the end of the sheltering period (i.e., approximately 1 month after the disaster). A diverse portfolio of units will hedge this risk of insufficient units and manufacturing-based delays to temporary housing allocation by including cheaper, easily stored, and efficiently transported units (e.g., prefabricated kit supplies which are low-cost and constructed on-site or modular units which ship in smaller pieces). Therefore, the diversity in available unit type will enable increased storage capacity for total units, reduce manufacturing and housing costs, and be able to provide more accurately and efficiently for the displaced population which contains varying individual/family requirements (e.g., family needs, climate requirements, displacement length and quality of living expectations, ease of transport, level of sustainability, etc.). Puerto Rico during Hurricane Maria is a unique example of a United States' housing mass-displacement (300,000 homes damaged) where a diverse portfolio of housing options would have lowered the costs associated and kept more Puerto Rican residents from emigrating from the territory. The temporary housing efforts during the recovery consisted mainly of Operation Blue Rook (i.e., reinforced plastic sheeting over damaged roofing), Direct Lease (i.e., vacant rental units), Transitional Sheltering Assistance (i.e., hotels or motels), and various reconstruction programs; notably, there is an absence of temporary housing units (FEMA, 2021a; Perrucci & Baroud, 2020; Severino, 2018). Although it may have been unfeasible to provide the popular manufactured and mobile home units due to transportability concerns, prefabricated kit supplies may have benefited the region.

Another benefit of the expanded diversity of global temporary housing portfolios is the inclusion of novel temporary housing units which aim to solve various dilemmas in current designs (e.g., quality control, sustainability, cost, etc.). Historically, the United States struggled with material utilization/quality control in designs (e.g., formaldehyde found in travel trailers during Hurricane Katrina) and end of life recycling/re-utilization of the units (i.e., most utilized units are auctioned or discarded) (Maddalena et al., 2009; Perrucci & Baroud, 2020). These quality control and end of life processes in the post-disaster housing problem are not only concentrated in the United States, with countries worldwide struggling with quality assistance and sustainable end of life transitions (Arslan & Cosgun, 2008; Comerio, 1997; Maddalena et al., 2009). There are a series of studies which attempt to solve this dilemma of poor material utilizations and end of life transitions with new and novel designs, one of the most recent being Cascone et al., in 2019 with their easily constructed modular temporary housing unit. Cascone's proposed unit is dry assembled (i.e., mechanical fasteners and attachment mechanisms) with modular panels and is designed to meet local architectural requirements (i.e., a modular floorplan/structure which is flexible before/after dismantling). The positive implication of novel designs, using Cascone's novel unit as an example, is limited by a lacking methodology for systematic evaluation and therefore, decreases its potential for inclusion in temporary housing portfolios(Cascone et al., 2019; Zhang et al., 2014).

A diverse portfolio of temporary housing designs would enable the United States to weigh the pros and cons of each design, while addressing a variety of concerns during implementation with novel designs (e.g., costs, quality control, transportability, sustainability of units, etc.). To achieve this diversity in designs and update the United States two unit options (i.e., mobile home and manufactured housing units), response agencies require an interdisciplinary and systematic temporary housing evaluation method for various scenarios and stakeholder perspectives (Perrucci & Baroud, 2020). This research proposes the application of a multi-criteria decision analysis (MCDA) for the evaluation and selection of different global designs. A multi-criteria decision model enables an expanded portfolio of possible temporary housing designs and the integration of local stakeholders' perspectives. For instance, a stakeholder who prefers a more sustainable unit will be able to prioritize this in the systematic comparison. Considering local stakeholder input also enables response agencies to avoid the negative health connotations associated with historical temporary housing allocations, such as the impediment of the health/wellbeing of occupants during Haiti's 2011 earthquake and the mentally traumatizing cultural experiences during Japan's Tōhoku earthquake.

The proposed temporary housing decision model in this chapter can be applied to any stakeholder globally for insight and an answer to the rising demand of temporary housing. The decision model enables prior planning and encourages the consideration of novel temporary housing solutions through the utilization of a multi-criteria decision-making model. Such an analysis is designed to be completed in advance of a natural disaster to solidify the supply chain and ensure the fulfillment of the displaced population's needs. This chapter is organized to provide a background of necessary information in section 3.2, a case-study description in section 3.3, details of the methodology in section 3.4, an instance of the output and results in section 3.5, a discussion of the results in section 3.6, and a conclusion of the results and acknowledgment of required future study in section 3.7.

3.2. Background

3.2.1 Temporary Housing

During the substantial length of time is spent in Temporary housing (i.e., 6 months to 3 years) a variety of options for accommodations are available, including rental houses, prefabricated kit units, and manufactured temporary housing units. An extensive literature review identifies and gathers appropriate information on potential temporary housing designs, which are either in development or in use. The identified temporary housing designs are listed in Table 3 and the full description/information is in Appendix A (Browne, 2015; Container Weight, n.d.; EX-CONTAINER PROJECT, n.d.; Shelter Box: Providing Shelter, Supporting Recovery, n.d.; Hany Abulnour, 2013; Ohlson, 2014; Perrucci & Baroud, 2018).

Table 3: Temporary Housing Alternatives

Type	Temporary Housing Design	Abbreviation
Prefabricated Modular Units	Ex-Container: two adjacent units	Ex.1
	Ex-Container: two stacked vertically	Ex.2
	Ex-Container: two units with gap in between	Ex.3
Manufactured Temporary Housing Units	Manufactured Home (Katrina cottage)	M.H.
	Manufactured Trailers (Katrina trailers)	M.T.
Prefabricated Kit Supplies	Blog House	B.H.
	HHi Emergency Shelter	HHi
	Superadobe Dome Shelter	S.D.
Tenting	Shelter Box	S.B.

This research considers nine different temporary housing designs which are organized into four categories: tenting, prefabricated kit supplies, manufactured temporary housing, and prefabricated modular units. These nine designs are strategically chosen to represent the United States' most common unit implementations (i.e., Manufactured Homes and Manufactured

Trailers) and to include innovative global alternatives that have been previously utilized, or are ready for implementation during, disaster scenarios (i.e., passed the initial design stage and at minimum has a functioning model). This research does not consider any theoretical designs; however, it does allow for the inclusion of future designs and alternatives.

Each design and type of temporary housing has pros and cons. Manufactured temporary housing units tend to have a higher quality of living and faster setup when compared to prefabricated kit supplies, however, the prefabricated kit supplies are a fraction of the cost. Similarly, the Ex-container provides a modular unit design which has a flexible floorplan, but transportability is a significant concern compared to the Shelter Box which is design for remote allocations. The range of pros and cons between designs and unit types requires a systematic comparison during a set of scenarios and perspectives, a multi-criteria decision analysis (MCDA) is one method for successful comparison and planning for temporary housing (Akdede, 2018; Ram et al., 2011).

3.2.2 Multi-Criteria Decision Analysis (MCDA) and Disaster Relief

Multi-criteria decision analysis methods provide support to decision makers where there are conflicting attributes in available options and ranging opinions (Montis et al., 2000). These models produce an overall value/ranking based on the decision maker's feedback/input on a variety of scenarios and objectives (Peters et al., 2019; Ram et al., 2011). The use of decision-making methodologies, including but not limited to decision-support systems and multi-criteria analyses, commonly assisting with mitigation decisions and various aspects of disaster relief to enable prior planning for resource allocation (Bastian et al., 2016; He et al., 2017; Samanta et al., 2016).

More specifically to temporary housing, in 2007 Johnson conducted an extensive study on the decision-making sequence specifically for temporary housing, providing a figure of the entire planning process and identifying eight steps required to implement a strategic temporary housing plan, which include: 1. organizational design, 2. identifying the vulnerable populations, 3. understanding local, social, economic, and climatic conditions, 4. developing an overall reconstruction strategy, 5. design and materials, 6. choosing suitable locations, 7. identifying services, and 8. planning for long-term uses or outcomes of temporary housing (C. Johnson, 2007b).

A 2020 review of temporary housing management (e.g., design strategies, optimization models, and decision-making methods) which covers the timespan since the publication by Johnson in 2007 reveals significant progress in the allocation procedures for, and novel designs of, temporary housing units. However, the review identifies gaps within the current research for temporary housing, including a systematic evaluation methodology of housing alternatives and inclusion of novel designs during unit implementations (Perrucci & Baroud, 2020). Rakes et al, identified a similar gap within the research in 2014 and provided a decision support system that utilized integer programming to make housing unit type recommendations based on individual needs from a set of alternative housing options (Rakes et al., 2014). These recommendations based on family needs provides an answer on the micro scale (i.e., individual level needs); however, it fails to provide a macro-scale (i.e., response agencies, decision makers, etc.) method to evaluate existing and novel designs for updating the set of alternative housing options.

The required macro-scale methodology for evaluating designs is investigated from a sustainability perspective by Hossieni et al, and resolves the sustainability aspects for two of Johnson's required steps to achieve strategic temporary housing plans, specifically, "design and materials" and "choosing suitable locations". Hossieni's work on sustainable site location, sustainable unit evaluation, and the unit's interior design proves the applicability of multi-criteria decision analysis for temporary housing decisions (Amin Hosseini et al., 2016; Hosseini et al., 2016, 2020). A thesis by Akdede further supports the successful implementations of MCDA towards accomplishing a macro-scale approach for evaluating temporary housing units, but the significance of the progress is limited to relevance of the three case studies, the reduced evaluation criteria (i.e., only 5 criteria were included in the applied methodology), and the limited temporary housing alternatives (i.e., only 4 unit designs were evaluated) (Akdede, 2018).

The focus of this research is to provide a holistic macro-scale method (i.e., expanding on Hossieni's sustainability focus and Akdede's limited application scope) for Johnson's fifth requirement, "Design and Materials: Identifying, as far as possible, designs and suppliers that use locally available materials or units that can be supplied in a quick and cost-effective manner", which revolves around identifying and evaluating viable temporary housing options (C. Johnson, 2007b). To do so, a multi-criteria decision analysis is employed to evaluate the temporary housing designs which were identified during the literature review. A MCDA is chosen due to the ability of effectively including stakeholder input shown by Bostick et al., the prior successes of Hosseini et al. on the sustainability of temporary housing designs and locations, and to ensure consistency through temporary housing research as this research expands towards holistic and multiple attribute design evaluation (Amin Hosseini et al., 2016; Bostick et al., 2017; Hosseini et al., 2016, 2020).

3.3. Case Study

3.3.1 Scope

The United States post-disaster temporary housing efforts are the focus of this research, including both housing displacement for U.S. populations and humanitarian populations (i.e., populations outside the U.S. who receive relief from the U.S.). The importance weightings paired with these types of housing displacement are elicited from experts/stakeholders from the United States. For this research, an expert is defined as a person who has published an article on temporary housing or post-disaster housing allocation while at a United States' academic institution. This outlined case study approach can be adapted to include additional stakeholder elicitations to fit other contexts, including but not limited to, geographic areas (additional states or varying countries), types of disasters, and social and economic factors.

3.3.2 Scenarios Descriptions

The Multi-Criteria Decision Model intends to evaluate the success of temporary housing designs based on a set of criteria and their corresponding importance weightings. This research considers multiple scenarios for which a decision needs to be made about the best temporary housing design to account for the differences in situational relief need (i.e., colder climates require insulated housing, remote allocations focus on transportability, desired quality of living versus cost restraints, etc.). The scenarios are described below.

Scenario 1

A disaster causes mass displacement in the **southeast region** of the **United States**. Due to the severity, the population cannot return to their original housing until the reconstruction process completes, which is expected to take **approximately six months** from the **devastation in June**. Temporary housing will be utilized for much of this duration, however, a switch to the original permanent housing is expected.

Scenario 2

A disaster causes mass displacement in the **southeast region** of the **United States**. Due to the severity, the population cannot return to their original housing until the reconstruction process completes, which is expected to take **approximately one to two years** from the **devastation in June**. Temporary housing will be utilized for much of this duration and **periods of below freezing temperatures** are expected. A switch to the original permanent housing is anticipated.

Scenario 3

A disaster causes mass displacement in the **United States territory of Puerto Rico**. Due to the severity, the population cannot return to their original housing until the reconstruction process completes, which is expected to take **approximately two to three years** from the **devastation in June**. The United States will be providing a form of Temporary housing. This housing will be utilized for much of this duration and there is an opportunity that this temporary housing may **transition to permanent housing**.

Scenario 4

A disaster causes mass displacement in the **country of Haiti**. Due to the severity, the population cannot return to their original housing until the reconstruction process completes, which is expected to take **approximately two to three years** from the **devastation in June**. The United States will be providing **foreign aid** in the form of Temporary housing. This housing will be utilized for much of this duration and there is an opportunity that this temporary housing may **transition to permanent housing.**

Each scenario is utilized to capture a different aspect of the United States temporary housing efforts, with comparisons between state relief, territory relief, and humanitarian relief. In addition, the scenarios include varying climate demands for temporary housing units, life span expectations, and end of life unit transitions.

3.4. Methodology

This research addresses the increasing global demand in post-disaster housing by applying a multi-criteria decision support model that combines stakeholder input and temporary housing characteristics. The outcome ranks potential and novel temporary housing designs according to their performance in achieving a series of criteria which are defined by certain attributes. Using this analysis, local governments, planners, and stakeholders are empowered to make post-disaster housing decisions prior to the onset of natural disasters; therefore, fortifying the supply chain to encourage improved resilience. The fundamental decision, criteria, attributes, and the overall hierarchy for the decision model are shown in Figure 4.

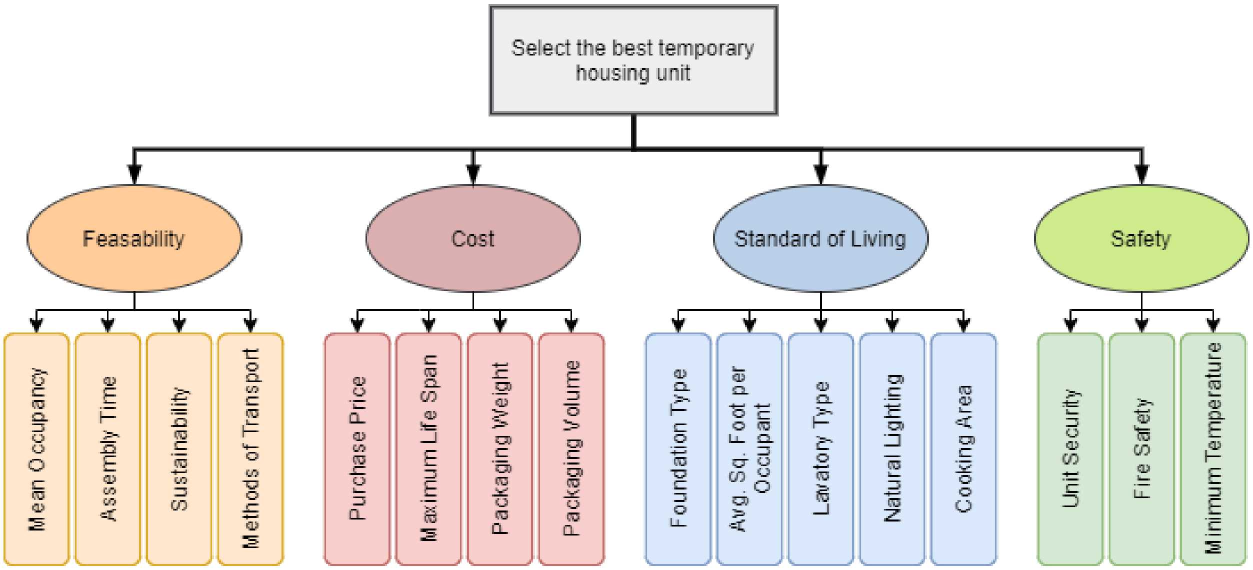


Figure 4: Hierarchy of Decision Model

The fundamental decision of this research is to determine the best temporary housing unit design given the criteria and their importance based on experts' perspective. This decision support model has four criteria that it considers, including: Feasibility, Cost, Standard of Living, and Safety.

3.4.1 Data Description

In each of the four criteria, the corresponding values for the attributes are collected through a literature review. Table 4 provides additional details on each evaluation criteria and Appendix A contains the values for each alternative's evaluation attributes.

Table 4: Description of evaluation attributes

Criteria	Attributes	Metrics	Metric Description	Label
Feasibility	Mean Occupancy	-	The average human capacity of unit	C1
	Assembly Time	Hrs	Amount of time the unit takes to assemble/place	C2
	Sustainability	Scale	1-5 scale based on design expectations	C3
	Methods of Transport	Scale	1-5 scale based on design expectations	C4
Cost	Purchase Price	$	Known cost of the specified unit	C5
	Maximum Life Span	Years	Number of years unit is designed to last	C6
	Packaging Weight	lbs	Total weight of the temporary housing unit	C7
	Packaging Volume	ft^3	Total volume of the temporary housing unit	C8
Standard of Living	Foundation Type	in	Height unit floor lies above soil	C9
	Avg. Ft^2 per Occupant	ft^2	Area specified per occupant	C10
	Lavatory Type	Scale	1-5 scale based on design expectations	C11
	Natural Lighting	Scale	1-5 scale based on design expectations	C12
	Cooking Area	Scale	1-5 scale based on design expectations	C15
Safety	Fire Safety	Scale	1-5 scale based on design expectations	C13
	Unit Security	Scale	1-5 scale based on design expectations	C14
	Minimum Temperature	°F	Minimum temperature to safely hold occupants	C16

Overall, there are four evaluation criteria and sixteen evaluation attributes in this research. When quantified values were unavailable for the evaluation attributes, a 1-5 scaling methodology was created for quantification and based on expectations of the described design. Table 5 depicts the scaling breakdown for one of the attributes (unit security).

Table 5: Unit Security Scaling Breakdown

	1	2	3	4	5
Unit Security	None	Privacy	Rigid Structure	Lockable Door	Flood Lighting

In this research for a temporary housing design to achieve a full score (i.e., a 5 ranking) on the scaled metrics, it must satisfy the requirements in order. For instance, if the design satisfied the requirement of a lockable door but does not have a rigid structure, it would receive a score of 2. This type of scaling methodology is implemented to customize scoring between attributes (i.e., scoring breakdown for unit security is unique from fire safety) and enable a systematic comparison between a variety of housing attributes which are traditionally non-quantifiable. The additional scaling breakdowns for each attribute are in Appendix A.

3.4.2 Surveys: THU Ranks and Importance Weightings

The survey targeted the United States' temporary housing academic experts, defined as someone who published a manuscript on temporary housing or a related topic while at a United States' research institution. For this research, responses were elicited for four unique scenarios, including:

1. A southeastern United States disaster causing a six-month displacement
2. A southeastern United States disaster causing a one to two-year displacement
3. A disaster striking Puerto Rico causing a two to three-year displacement
4. Humanitarian aid to Haiti for a two to three-year displacement

In each of these scenarios, the respondents were asked to outright rank each temporary housing alternative. Then, the respondents provided the importance of each criterion with a scale of 1 to 5, 1 being not important and 5 extremely important, for the success of temporary housing design implementations during each scenario. The survey provided relevant background information and required approximately 15 minutes to answer the 22 multiple choice questions and 4 optional short answer responses. There was a total of 18 targeted United States' temporary housing academic experts and 6 responses, resulting in a response rate of 33%. The 6 United States' temporary housing academic expert responses are considered sufficient for this research through comparison to similar studies, such as Hosseini's et al., which utilized 11 non-specialized (multidisciplinary) experts from two different countries (i.e., Iran and Spain) (Hosseini et al., 2020). For this research, the focused scope to temporary housing expert specializations and the singular country consideration of the United States, confirms that these 6 responses are sufficient with overwhelming support for the Manufactured Home in all four scenarios.

Based on the expert's responses, the ranking of each temporary housing design during each unique scenario are depicted in Figure 5.

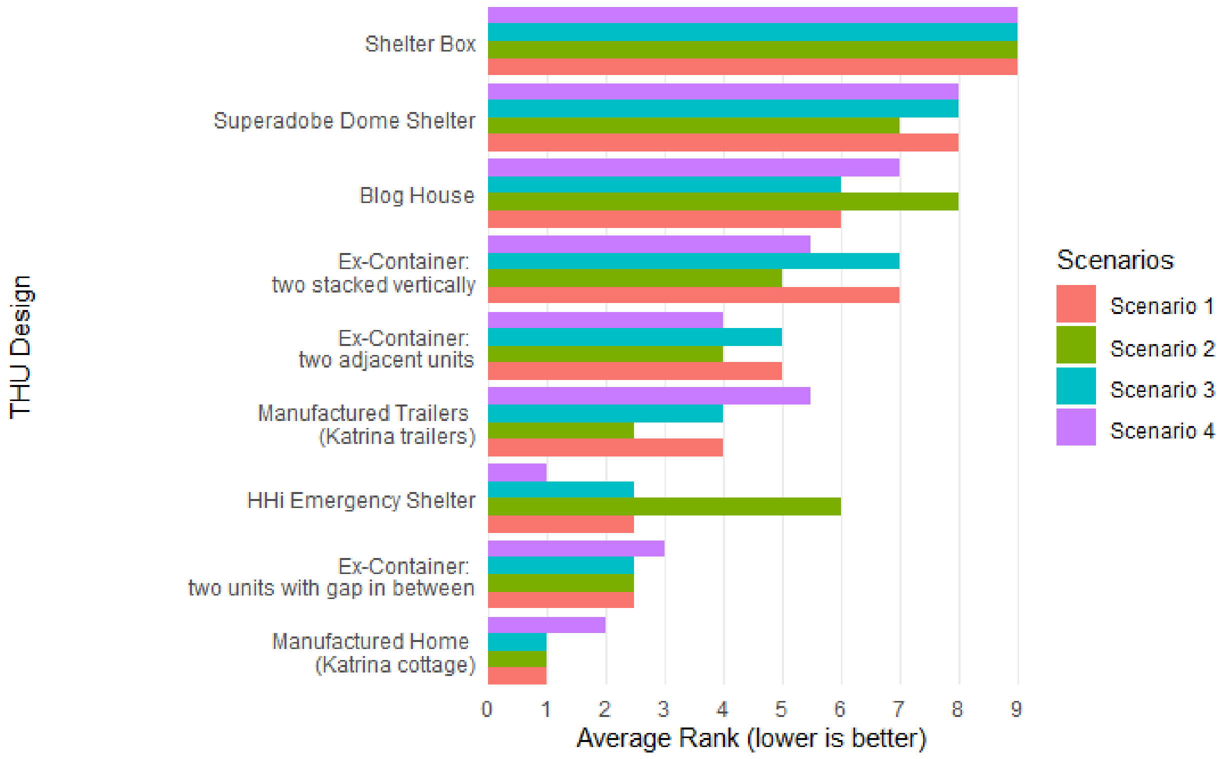


Figure 5: Surveyed Ranking Responses for THU Designs in each Scenario

From the rankings for the scenarios concerning the continental United States or the territories, there is consensus that the manufactured home is the best option, on average, for implementation. In scenario 4, where it is a humanitarian effort for population's displaced by an earthquake, the HHi Emergency Shelter (which is transitional for long term accommodation) is deemed most appropriate. In addition, there are several instances where the common manufactured trailer is surveyed to be less satisfactory compared to the HHi emergency shelter and variations of the Ex-Container. For prefabricated kit supplies, the HHi emergency shelter is the most preferred solution with the Blog House and Superadobe Dome Shelter ranking poorly with experts. As the sole tenting option considered in this research, the shelter box's low cost and efficient transportability is unable to make up for its downfalls (e.g., low quality of living, security, etc.), with experts consistently ranking the option as the worst alternative for all scenarios.

In addition to collecting ranking for the temporary housing designs, the importance of each criterion and attribute are elicited for the four scenarios. These values were elicited using a 1-5 scale (1 being least important, 5 being most important) and the responses were summed together and divided by the maximum possible score, to provide a raw importance weighting (i.e., weightings before normalization) percentage. These raw importance weightings for each criterion, attributes, and scenario are organized in
Table 6.

Table 6: Scenario Importance Weightings for Objectives and Criteria

Criteria Category	Importance	Attributes	Attribute Min / Max	Scenario Importance			
				1	2	3	4
Feasibility	0.97	Mean Occupancy	Max	0.77	0.80	0.80	0.83
		Assembly Time	Min	0.93	0.93	0.97	0.97
		Sustainability	Max	0.63	0.63	0.63	0.60
		Methods of Transport	Max	0.90	0.83	0.97	0.97
Cost	0.83	Purchase Price	Min	0.83	0.90	0.93	0.93
		Maximum Life Span	Max	0.73	0.73	0.90	0.93
		Packaging Weight	Min	0.77	0.70	0.77	0.80
		Packaging Volume	Min	0.80	0.73	0.80	0.83
Standard of Living	0.80	Foundation Type	Max	0.53	0.63	0.67	0.67
		Avg. Sq. Foot per Occupant	Max	0.77	0.80	0.80	0.77
		Lavatory Type	Max	0.57	0.67	0.67	0.70
		Natural Lighting	Max	0.70	0.77	0.67	0.70
		Cooking Area	Max	0.70	0.73	0.73	0.73
Safety	0.90	Unit Security	Max	0.80	0.80	0.77	0.77
		Fire Safety	Max	0.80	0.83	0.83	0.83
		Minimum Temperature	Min	0.87	0.93	0.70	0.70

*The importance values for category and scenario importance range from 0 to 1, with 1 representing greatest importance. Each attribute in the analysis is listed and labeled as minimization or maximization.

Overall, there are sixteen attributes being utilized to evaluate the success of temporary housing units from the compiled list. These importance weightings for each attribute, when appropriate, are inputted into a selection of multi-criteria decision analysis methodologies.

3.4.3 Multi-Criteria Decision Analysis Methods

The topic of post-disaster temporary housing requires a robust interdisciplinary approach which borrows expertise heavily from specializations such as engineering, risk management, economics, supply chain management, and sociology. When determining the multi-criteria decisions analysis methods utilized for this research, the expansive array of relevance and desired input for temporary housing decisions is matched up with previously noted areas of application of each MCDA methodology.

Weighted Sum (WS) is the most widely used and simplest MCDA methodology, it can be utilized for a large audience of diverse backgrounds and allows for easy understanding from a variety of education levels in a variety of countries. This model suffers from inconsistency in results and can vary dramatically without normalization and between normalization methods. This aggregation model is utilized heavily in business and financial management which pairs perfectly for temporary housing where the largest concern is almost always cost, upkeep, and profit salvageability (Akdede, 2018; El Amine et al., 2014; Perrucci & Baroud, 2021; Vafaei et al., 2018).

Compared to WS, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a more complex aggregation model but remains manageable even with increased number of attributes; however, it is important to note that it does not consider correlation of attributes in its analysis. The common areas of application for TOPSIS include a larger variety of fields including, but not limited to, supply chain management, engineering, manufacturing, and business (Akdede, 2018; El Amine et al., 2014). TOPSIS is commonly used in disaster scenarios, with several papers using TOPSIS for post-disaster housing and reconstruction fields; making it an obvious choice for this research (Chu & Su, 2012; Opricovic & Tzeng, 2002).

Unlike the aggregation methods WS and TOPSIS, the Multi-attribute Utility Theory utilizes a preference driven disaggregation of the attributes. The benefit of this different MCDA methodology (i.e., disaggregation) is the consideration of uncertainties and direct incorporation of stakeholder preferences (i.e., the favoured unit designs will gain preference in the MCDA outcome) (Akdede, 2018). This aspect of enhanced consideration of stakeholder preferences is valuable for a temporary housing decision model where the opinions on unit type/style changes drastically between different populations; however, this does require precise preferences to ensure accuracy of the method. In addition, the utility-based MCDA methodologies (e.g., MAUT, analytical hierarchy process (AHP)) are utilized intensively in sustainability related research; a topic which was recently identified as being one of the largest problems facing the future of temporary housing research (Cinelli et al., 2014; Perrucci & Baroud, 2020).

The MCDA methodology are carefully chosen to represent the interdisciplinary approach of temporary housing, consider the most pertinent topics in the field, and to maximize the potential audience and comprehension of the results. This section further describes the three MCDA methodologies utilized in the research and explains the fundamental equations.

Weighted Sum Method (WSM)

The weighted sum method, otherwise known as simple addictive weighting (SAW), is the most well-known and most basic type of multi-criteria decision method. This method applies relative weights to criteria rates and produces aggregated scoring for each alternative (s_i), as depicted in Equation 1.

$$s_i = \sum_{j=1}^{n} x_{ij} w_j \tag{1}$$

In equation 1, the variable x_{ij} represents the i^{th} alternative temporary housing unit and its corresponding value for the j^{th} criterion, while the w_j variable represents the relative weighting for the j^{th} criterion. In most cases, normalization of the criteria data is required to successfully conduct the WSM and the normalization method applied can significantly alter the alternative rankings. The WSM models in this research implements the Linear Sum normalization technique because prior research by Vafaei et al., suggests it is the best normalization method for the Weighted Sum model (Vafaei et al., 2018). The approach consists of dividing each units criteria performance by the sum of the total criteria performance for the benefit criteria, and by the reciprocal of the total criteria for the cost criteria (Vafaei et al., 2018).

Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

The TOPSIS method is a compensatory decision-making method (i.e., aggregation allows one criterion to compensate for the losses in another criterion) which calculates the n-dimensional Euclidean distance from the positive and negative ideal solutions to find the best solution (Cinelli et al., 2014; El Amine et al., 2014). The calculation of the positive ideal (d_i^+) and negative ideal (d_i^-) separation distances are depicted in Equation 2 and 3.

$$d_i^+ = \sqrt{\sum_{j=1}^{n}(x_{ij} - x_j^+)^2} \tag{2}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n}(x_{ij} - x_j^-)^2} \tag{3}$$

In equation 2 and 3, the variable x_{ij} represents the i^{th} alternative temporary housing unit and its corresponding value for the j^{th} criterion. The variables x_j^- and x_j^+ represent the minimum and maximum values for the j^{th} criterion. The alternatives are then scored (s_i) by relative closeness to the ideal solution, as depicted in Equations 4.

$$s_i = \frac{d_i^-}{d_i^- + d_i^+} \tag{4}$$

Similar to the WSM, normalization is important for ensuring the comparability of the data. Traditionally, and in this research, TOPSIS utilizes the Vector Normalization technique. The Vector Normalization method consists of dividing each units criteria performance by the square root of the squared total criteria performance sum for the benefit criteria, and one minus this value for the cost criteria (Anandan & Uthra, 2017; El Amine et al., 2014; Lakshmi et al., 2016; Vafaei et al., 2018).

Multi-attribute Utility Theory (MAUT) – UTASTAR

The UTASTAR method takes a different approach from WSM and TOPSIS and adopts the preference disaggregation principle. In this method the surveyed alternative rankings are utilized, instead of the surveyed importance weightings for each attribute, to infer value functions for the set of alternatives. The base UTA methodology infers an unweighted additive value function which follows as in Equation 5.

$$u(g) = \sum_{i=1}^{n} u_i(g_i) \tag{5}$$

$$\text{Subject to}$$

$$\sum_{i=1}^{n} u_i(g_i^*) = 1, \quad u_i(g_{i*}) = 0, \quad \forall i = 1,2,\ldots,n$$

In equation 5, the variable g_i represents the i^{th} temporary housing criteria values and u_i, i =1, 2,…, n are non-decreasing real valued functions (utility functions) normalized between 0 and 1 (i.e., $u_i(g_{i*})$ and $u_i(g_i^*)$) for each i^{th} criterion. The UTASTAR algorithm expands on the theoretical basis of UTA by including a double error function in the evaluation of each alternative, Equation 6.

$$u'[g(a)] = \sum_{i=1}^{n} u_i[g_i(a)] - \sigma^+(a) + \sigma^-(a) \quad \forall a \in A_R \tag{6}$$

Equation 6 expands on the base methodology (Equation 5) by adding the variables σ^+ and σ^- which represent the overestimation and underestimation error for the alternative's utility in each criterion during the linear program. These $\sigma^+(a)$ and $\sigma^-(a)$ are the potential errors relative to the optimal utility function, $u(g)$, for the specified alternative (a). Using these double error variables, the utility between alternatives is directly comparable, Equation 7.

$$\Delta(a_i, a_{i+1}) = (u[g(a_i)] - \sigma^{+}(a_i) + \sigma^{-}(a_i)) - (u[g(a_{i+1})] + \sigma^{+}(a_{i+1}) - \sigma^{-}(a_{i+1})) \qquad (7)$$

The difference between one alternative and another, $\Delta(a_i, a_{i+1})$, is simply the calculated different between the estimated utility of one alternative and another after the error considerations.

One assumption before the MCDA occurs establishes the monotonicity of the criteria (i.e., non-negativity). This is established through Equation 8.

$$w_{ij} = u_i(g_i^{j+1}) - u_i(g_i^{j}) \geq 0 \qquad \forall i = 1,2,\ldots,n \quad \text{and} \quad j = 1,2,\ldots,a_i - 1 \qquad (8)$$

Equation 8 explains that w_{ij} must be greater than or equal to 0. The variable w_{ij} is calculated by taking utility values for j^{th+1} and j^{th} for each i^{th} alternative and subtracting them from one another. The j^{th+1} utility must be equal to or larger than the j^{th} utility value for the same i^{th} alternative, or that each incremental step in the utility function must be larger than or equal to the previous for the same alternative.

This MAUT preference disaggregation principle and defined double error function enable the utilization of linear programming to infer optimal utility functions that reference decision-maker's temporary housing alternative preference, Equation 9.

$$\begin{aligned}
&[\min]z = \textstyle\sum_{i=1}^{m}[\sigma^{+}(a_i) + \sigma^{-}(a_i)] \qquad (9)\\
&\qquad \text{Subject to}\\
&\qquad \Delta(a_i, a_{i+1}) \geq \delta \quad \text{if} \quad a_i \succ a_{i+1} \quad \forall i\\
&\qquad \Delta(a_i, a_{i+1}) = 0 \quad \text{if} \quad a_i \sim a_{i+1} \quad \forall i\\
&\textstyle\sum_{i=1}^{n}\sum_{j=1}^{a_i-1} w_{ij} = 1\\
&\qquad w_{ij} \geq 0, \quad \sigma^{+}(a_k) \geq 0, \quad \sigma^{-}(a_k) \geq 0 \qquad \forall i, j, \text{and } k
\end{aligned}$$

where δ is a small positive number.

The goal of this linear program is to determine the alternative with the least overall error, [min]z, from the optimal utility function $u(g)$. The linear program finds the optimal net distance, the closest to the positive ideal ($\sigma^{+}(a_i)$) and farthest from the negative ideal ($\sigma^{-}(a_i)$) for error which are positive and zero, while also ensuring the monotonicity for each j^{th} in each i^{th} alternative as described in Equation 8. In addition, the UTASTAR method differs from WSM and TOPSIS because the utilization of utility functions reduces the importance of normalization for the UTA method (Anandan & Uthra, 2017; Jacquet-Lagreze & Siskos, 1982; Siskos et al., 2016; Vafaei et al., 2018).

In summary, the WS and TOPSIS are both aggregation methods which allow for compensation between negative and positive performances, while the UTASTAR method is a disaggregation method. The two aggregation methods require normalization to be applied for the MCDA analysis, whereas the utility functions in UTASTAR detract the need for prior normalization. Each MCDA is applied to different fields of study that are pertinent to post-disaster temporary housing decisions including, but not limited to, economics, sustainability, and engineering.

3.5. Results

3.5.1 MCDA Outcome

Between the three MCDA methods, there is variance in the ranking of alternatives and the reactions to each scenario. These results are in Figure 6.

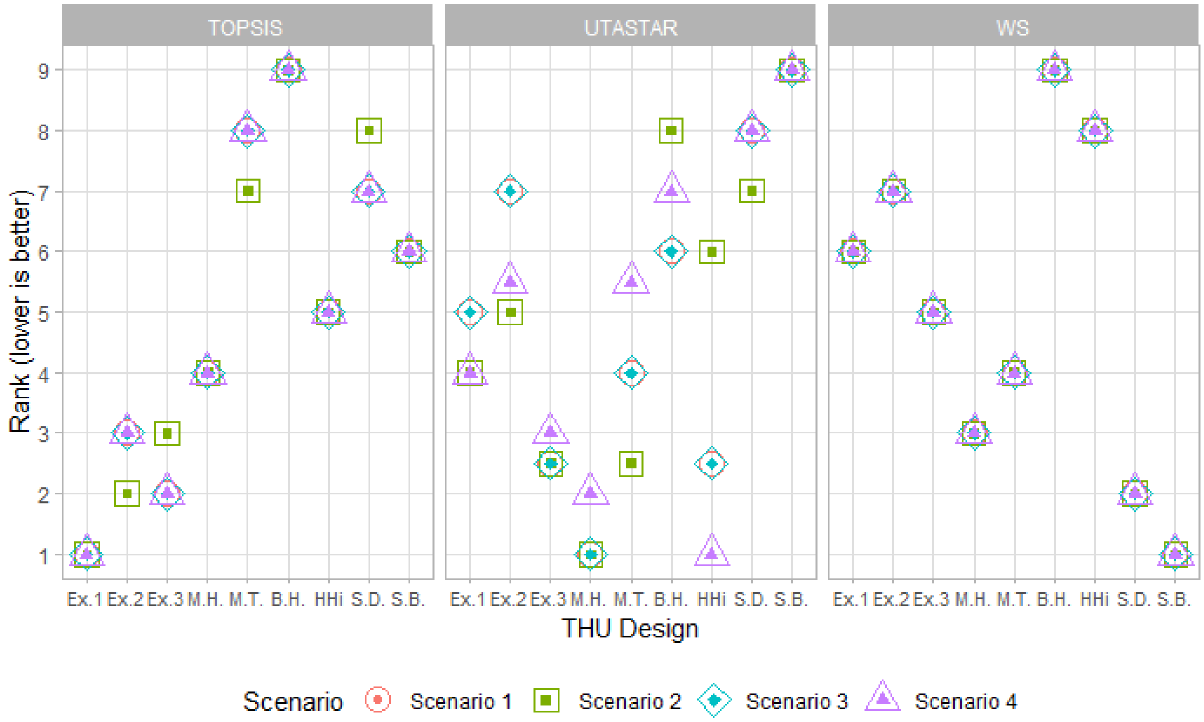


Figure 6: MCDA Ranking Results for Each Method

The WS model is not able to capture the different aspects and requirements from the set of four scenarios (e.g., climate restrictions, length of displacements, quality of living standards, etc.) and selected the most affordable options to be the two best options. However, the WS model may still be effectively implemented with prior filtering of inappropriate temporary housing options (e.g., filtering those without cold climate capabilities if cold climates are a requirement) adding to the realism of the outcome and a different normalization methods may be tested to determine if they increase or decrease the realistic nature of the model's outcome (Akdede, 2018; Vafaei et al., 2018). TOPSIS is able to account for the added conditions in Scenario 2 (i.e., longer displacement and cold weather), however, the final rankings suggest that it does not differentiate between Scenario 1, 3, and 4. UTASTAR shows significantly different temporary housing rankings for each scenario and as documented previously, the method is able to successfully account for the stakeholder preference (Akdede, 2018). UTASTAR's ability to incorporate stakeholder preference into the model causes drastic variation from the other method's results. The way the unit rankings change based on each scenario is investigated further in Figure 7.

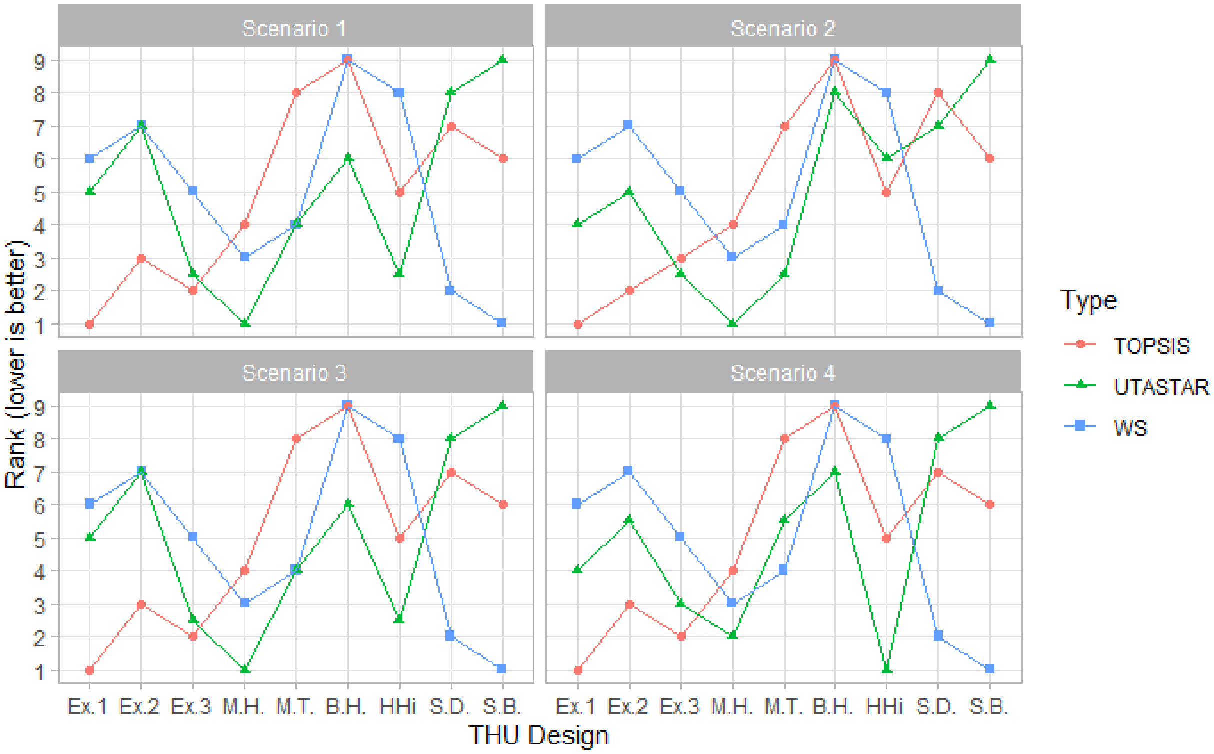


Figure 7: MCDA Ranking Results for Each Scenario

Throughout the four case study scenarios, the ranking of the nine temporary housing designs remained consistent for the WS methodology. For example, the weighted sum found tenting to be the best option for all four scenarios, but tenting would be a last option in the United States due to set standards of living and potential climate restrictions. If these unapplicable options are filtered out, then the decisions may be more realistic and equitable between methods. Similar to WS, the TOPSIS methodology is consistent between scenarios. TOPSIS did experience variation in scenario 2, where it adjusted the rankings to satisfy the climate restrictions (e.g., the cold-weather appropriate alternatives including the three ex-container variations, manufactured homes, trailer homes, and HHi emergency shelter topped the rankings).

The lack of variation in the WS and TOPSIS results across the scenarios does not suggest that the scenarios and their inherent requirements (e.g., climate, aid cost, standard of living) are insignificant to the overall decision. One potential cause is that the different aspects in each scenario were unsuccessfully translated into importance weightings by the elicited responses for criteria importance weightings. The UTASTAR results (which input outright unit rankings rather than attribute importance) may suggest that the elicited outright rankings are more effective at capturing stakeholder opinion.

Between scenario 1: a U.S.' displacement in warmer months and scenario 2: a U.S.' displacement with freezing temperatures, UTASTAR alters the rankings to acknowledge the units suited for restrictive climates (i.e., ex-container, manufactured homes, and trailers). The UTASTAR results, based on the outright rankings of units, between scenario 1: a U.S.' displacement in warmer months and scenario 3: a U.S.' territory displacement in Puerto Rico, suggest that U.S. territories should be provided the same housing aid as the continental United States. The UTASTAR results for scenario 4: humanitarian aid to Haiti alters the rankings to support the utilization of the HHi emergency shelter. When comparing these UTASTAR results between Scenario 3 and 4, the change in the ranking of the HHi emergency shelter contributes to the idea that a U.S. territory (i.e., Puerto Rico) is entitled to receive the same relief as the continental United States and be treated less like a humanitarian effort (i.e., Haiti) with which it shares similar shipment methods, living standards, and economic feasibility.

To further analyze the ranking of each MCDA methodology to the elicited rankings, Table 7 organizes the elicited rankings from the survey, individual MCDA ranking results, and the averaged MCDA ranking results between methods.

Table 7: Survey and MCDA Ranking Summary

Type	Temporary Housing Design	Avg. Survey Ranks	Average MCDA Ranks			Avg. MCDA Result
			WS	TOPSIS	UTASTAR	
Prefabricated Modular Units	Ex-Container: two adjacent units	5	6	1	5	3
	Ex-Container: two stacked vertically	6	7	3	6	5
	Ex-Container: two units with gap in between	2.5	5	2	2	2
Manufactured Temporary Housing Units	Manufactured Home (Katrina cottage)	1	3	4	1	1
	Manufactured Trailers (Katrina trailers)	4	4	8	4	4
Prefabricated Kit Supplies	Blog House	7	9	9	7	9
	HHi Emergency Shelter	2.5	8	5	3	6.5
	Superadobe Dome Shelter	8	2	7	8	8
Tenting	Shelter Box	9	1	6	9	6.5

*The average survey ranks are averaged across all four scenarios of the elicited responses and represent the average expert opinion. Similarly, the average MCDA Ranks are averages from the four scenarios and the average MCDA result is the average of all three methods over the four scenarios.

Table 7 enables the direct comparison between the surveyed rankings and the MCDA ranking results, revealing that the uncertainty in attribute importance weighting and temporary housing alternative ranking is causing variation in the expected outcome of the MCDA results. The best method to incorporate different types of scenario events without taking the additional steps of filtering to a feasible list of temporary housing options would be UTASTAR, however, the simplistic nature of WS and the ability of TOPSIS to handle many criteria makes them options for implementation. To further examine how the importance weighting of attributes influences the ranking of alternatives, a sensitivity analysis is conducted on the attribute importance for the WS and TOPSIS methodologies.

3.5.2 Sensitivity Analysis on Attribute Importance Weightings

This research focuses on a United States' response and elicits importance weightings from United States' academic temporary housing experts; however, disaster displacements and temporary housing decisions are of global concern. To enable global applicability of this research, the importance weightings are subjected to a sensitivity analysis.

A one-way sensitivity analysis is conducted on the raw importance weighting for each of the four criteria (i.e., Feasibility, Cost, Standard of Living, and Safety), and quantifies the impact of varying importance (which is expected between countries) on THU design ranking. This sensitivity analysis uses line plots to show which increment of importance (i.e., the importance weightings inputted into the MCDA method) caused rank alteration and the level of significance in terms of the final rankings. Figure 8 and Figure 9 present importance weighting sensitivity results for the MCDA method TOPSIS on the criteria of Standard of Living and Safety during each of the four scenarios. The remaining sensitivity results for TOPSIS and WS are provided in the Appendix A.

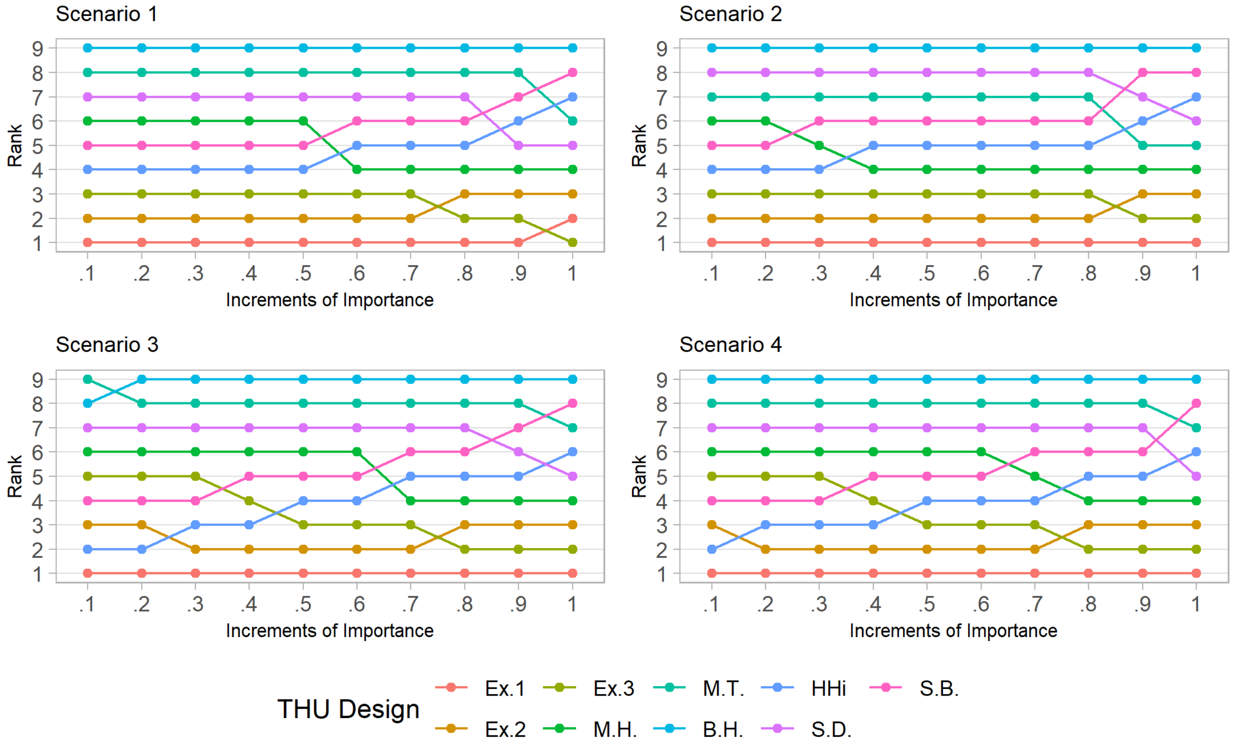


Figure 8: Sensitivity Analysis on Standard of Living for TOPSIS during all Scenarios

This sensitivity analysis reveals that the inputted importance weightings can cause variation in THU design ranking and that these changes are intensified depending on scenario. For the Standard of Living criteria all scenarios experience similar phenomena for HHi, the HHi Emergency Shelter, and S.B., the Shelter Box, making these THU designs the most sensitive to the importance of Standard of Living and altering their rankings by up to 4 places. This large variation in rankings for HHi and S.B. can be contributed to the lower quality of living in each unit which negatively impacts the overall ranking as importance of the criteria increased. The most consistent design rankings throughout all scenarios in Figure 8 are the adjacent ex-container unit design (the highest ranked design) and the blog house (the lowest ranked design), each only fluctuating once at the maximum and minimum importance increments.

In the sensitivity analysis for Safety using TOPSIS methodology, the Shelter Box proves to be highly volatile in ranking as the incremental importance of Safety reached 60 percent, where it jumped from being the best option to being the 4th best option. The Blog House, B.H., and the

HHi Emergency Shelter, HHi, also experienced reduced rankings as the importance of Safety increased.

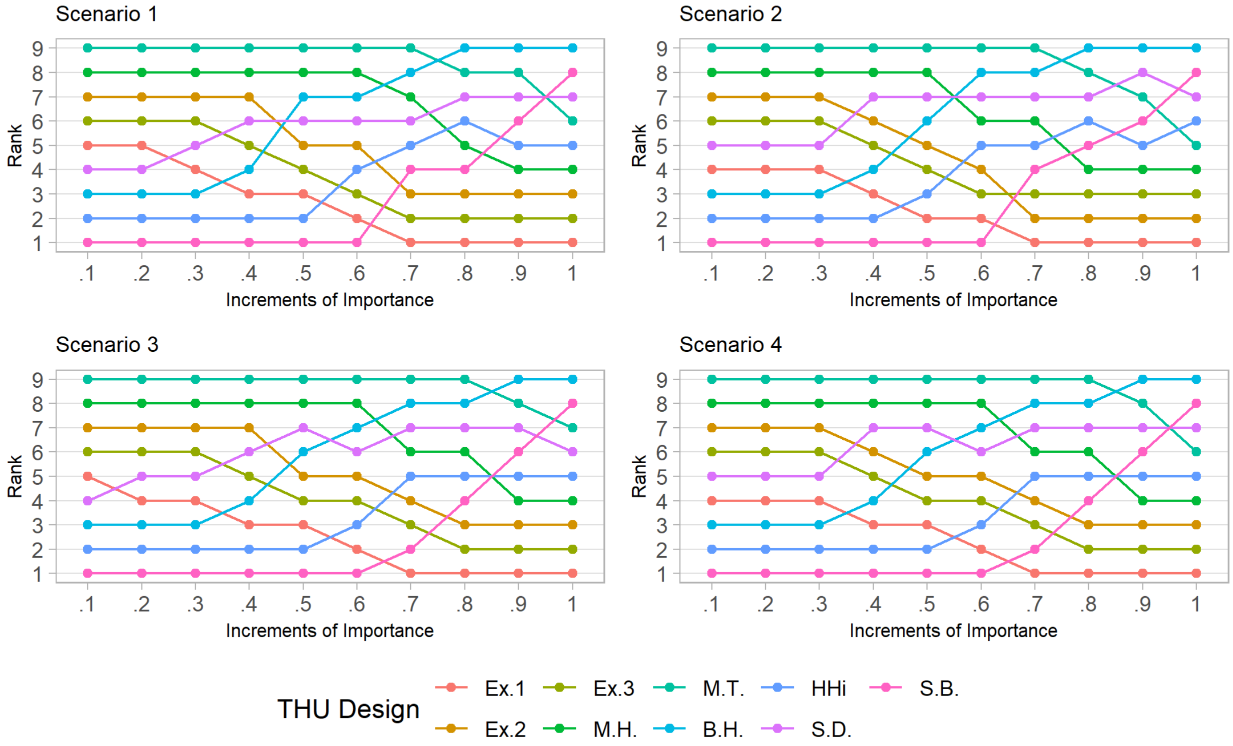


Figure 9: Sensitivity Analysis on Safety for TOPSIS during all Scenarios

Compared to the Standard of Living, the rankings from the TOPSIS model are significantly more sensitivity to the importance weightings for the Safety criteria for the scenarios. In all four scenarios the Shelter Box was the number one option until the importance for safety reached 60% or higher and consistently ranked 8th at full importance. On the opposite spectrum, Manufactured Housing experience the largest decreases in ranking, going from being ranked 8th to 4th. In addition, each temporary housing unit design experienced a ranking alteration of at least 2 rankings during the incrementally increased importance of Safety.

The safety criteria (e.g., unit security, fire safety, minimum temperature) is arguably the most impactful for human occupants and can drastically alter the success of the unit; therefore, this increased sensitivity in rankings between units is expected. As an example, the Shelter Box is a tenting unit and there is a noted struggle with tenting units achieving the desired level of safety and security for the occupants (Biswas, 2019). When the safety criteria are prioritized, the benefits inherent to tenting (e.g., low-cost, re-usable, quick erection, etc.) will be overlooked due to the increased safety concerns (e.g., non-lockable door, textile walls, reduced privacy, etc.). During past implementations tenting options have increased security levels through placement in military barracks or shelter-in-shelter (e.g., utilizing tenting in a warehouse); however, tenting options were still considered unsatisfactory to other temporary housing options from a safety perspective (Biswas, 2019).

This sensitivity analysis successfully shows the variation in design ranking that can be attributed to differences in decision maker's opinion. Moreover, the analysis reveals which area can be negotiated to receive the largest benefit. For instance, Figure 6 reveals that a set importance less than 60% for Safety during all scenarios is a threshold for consideration of cheaper units with reduced safety features (e.g., tenting and kit units). If decision makers desire a unit with improved safety features, the base importance for Safety may be encouraged to be above 60% and compromises may be required for other criteria.

3.6 Discussion

In past disaster recoveries, temporary housing allocation has been plagued by delays, construction errors, and quality control issues as a result of insufficient prior planning (Gheytanchi et al., 2007; Levine et al., 2007; Maddalena et al., 2009). The implementation of the multi-criteria decision analysis (MCDA) and development of this decision model helps emergency management agencies and local decision makers with proactively planning for temporary housing allocation, by enabling a:

- Re-evaluation of current temporary housing designs
- Diverse temporary housing portfolio for implementation
- Consideration of novel designs that better suffice the social and economic needs of the displaced
- Sensitivity analysis on the impact of the stakeholder's profile and opinion

The decision model enables evaluation of temporary housing designs for four case study scenarios, each of which contain inherent regional restrictions, such as cost, environmental, and geographical limitations. This research accounts for these restrictions and stakeholder opinion with the elicited responses from the United States experts (i.e., the importance weightings and unit rankings).

In application of these methods, a feasible set of temporary housing option filtered with stakeholder restrictions must be accounted for during the implementation of TOPSIS or WS (and would ensure the accuracy of the UTASTAR) in the final decision. Regardless of the final MCDA rankings, if there is a scenario where a state has a low budget of $10,000 per unit and is in a cold climate, the temporary housing options are limited to the HHi Emergency Shelter and Shelter Box. If this same budget is set for a region without climate restrictions, then the list of potential temporary housing options expands to include the Blog House and the Superadobe Dome Shelter. The cost of the design is only one attribute, and these stakeholder restrictions can be applied to all 16 attributes considered in this research.

Furthermore, the sensitivity analysis reveals the susceptibility of each temporary housing unit's final score to the alteration of stakeholder importance weightings and expands the scope of this studies results away from the United States' case study. This sensitivity analysis is vital to the stakeholder's reconsideration of the importance weightings and set requirements when making the decision by illuminating where compromises may be made to provide a higher-quality temporary accommodation (e.g., increasing the budget by 10,000 to increase the quality of living) or to provide accommodation cost savings (e.g., reducing the cost of allocation but still providing a sufficient accommodation. Figure 6 shows the sensitivity analysis for TOPSIS with the largest variation in temporary housing rankings caused by the incrementally increased importance weighting and suggests that the Safety criterion should be expanded to include additional criteria to reduce the potential volatility of the results. An additional sensitivity analysis on THU design (i.e., performance table) is potentially valuable in design alteration, however, that would benefit stakeholders outside of the scope of this research focused on government unit decision making and allocation.

This research introduces a decision model which enables stakeholders to make informed decisions regarding post-disaster accommodation and implement diverse temporary housing plans that can overcome critical limitations, such as the adverse impacts that displaced families' experience and housing deficits. By comparing these three MCDA methodologies and their corresponding outcomes for each scenario, this research can draw the following conclusions:

- MAUT – UTASTAR is the best option tested for incorporating stakeholder preference from a series of disaster scenarios and disaster aid types
- WS is simplistic and easy to understand, however, it does poorly at incorporating disaster scenarios causing unrealistic outcomes which may only be solved by the creation of a feasible housing set and may go unnoticed without comparison
- TOPSIS is a better option because it is easy to understand for a variety of education levels and still able to adjust its outcome for the cold-weather and longer duration housing displacement scenarios

In addition, this research relies on the opinion of academic experts to determine the importance weightings and temporary housing preferences to overcome the complexities inherent in all post-disaster housing implementations and the complexities added for each unique scenario. On average between the four scenarios, the experts identified the Manufactured Home as the best temporary housing option with the Ex-Container: two units with gap in between and HHi Emergency Shelter tying for second and third. The method which best captured stakeholder preferences, UTASTAR, ranked the top three options as the Manufactured Home, Ex-Container: two units with gap in between, and HHi Emergency Shelter, respectively. These expert opinions and results from the UTASTAR analysis suggest a diverse portfolio which drifts away from the current U.S. paradigm of only Manufactured Homes and Manufactured Trailers and supports the inclusion of units from the three categories of Prefabricated Modular Units, Manufactured Temporary Housing Units, and Prefabricated Kit Supplies.

Ultimately, the chosen MCDA model, and corresponding temporary housing unit/s, will feed into an inventory optimization model of temporary housing stocking inventory amount such as the one being developed by Perrucci and Baroud 2021, which utilized the newsvendor model to reduce economic risk of prior purchasing and storing temporary housing units.

3.7 Conclusion

This multi-criteria decision model enables preemptive planning that reduces supply chain ambiguity in advance of a disaster. The model enables stakeholders and government entities to re-evaluate current temporary housing, consider new/novel temporary housing designs, evaluate the range of pros and cons between designs and unit types, and to create diverse temporary housing portfolios to hedge against scenarios/risks. This model contains the potential to increase the quality control and sustainability of temporary housing, while reducing the number of delays and the financial toll which have historically impacted temporary housing designs and allocation. As a future addition, a cultural/social objective will be considered for a wider implication of this decision model and the safety criteria must be expanded to reduce volatility in rankings (as seen in sensitivity analysis).

Moving forward, this decision model has an opportunity to combine with optimization models to provide an optimal stocking inventory for one or a set of multiple feasible temporary housing accommodations. In Chapter 4, this research utilizes the THU design determined to be the most preferred by United States' stakeholders and uses the newsvendor model to provide optimal stocking inventories for the states most prone to large scale displacements and temporary housing unit demand.

CHAPTER 4, TEMPORARY HOUSING OPERATIONS: A SIMULATION-BASED INVENTORY MANAGEMENT APPROACH USING THE NEWSVENDOR MODEL

4.1 Motivation

Major historical disaster events demonstrate inadequate preparation and relief, and point to the concerns of potential mismanagement in temporary housing which include but are not limited to allocation delays and increased financial impacts stemming from the trade-off between pre- and post-disaster investment (C. Johnson, 2007b; Maddalena et al., 2009; Schmeltz et al., 2013). In the United States, hurricane Katrina's extreme costs led to international repercussions that questioned the efficacy of temporary housing management (Verderber, 2008). This spotlight on temporary housing led to an analysis by the Congressional Research Service which suggested the reduction of the 120,000 stocked temporary housing inventory to save $133 million dollars annually (McCarthy, 2010).

In Chapter 3, the United State's stakeholder preferred THU design is selected out of a list of global designs and is determined to be a Manufactured Home (i.e., the Katrina Cottage). This chapter addresses the concern of increased financial risk from uncertain demand in temporary housing (i.e., stocking inventory requirements) with the implementation of a simulation-based forecasting model, where probability distributions are utilized to quantify demand uncertainty. These quantified demands are then integrated with a data-driven newsvendor model to determine the optimal stocking inventories of the selected Manufactured Home (i.e., the Katrina Cottage) design. These inventory results address the pre- and post-investment concerns with financially supported pre-disaster inventory recommendations and improve demand response with larger quantities of readily available units.

The outcome of this chapter is a model which determines stocking inventory of temporary housing using simulated expected losses. A case study of hurricanes and tropical storms in the United States is used to illustrate the modeling approach with a focus on states with the largest history of temporary housing utilization, including Alabama, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Texas (Blake et al., n.d.). The proposed model provides the federal and state governments the ability to adopt a risk-informed decision-making approach towards disaster planning. The remainder of this chapter is organized as follows: background literature on community resilience and temporary housing is reviewed in section 2, section 3 presents the proposed approach and numerical results, with the discussion and conclusion in sections 4 and 5, respectively.

4.2 Background

4.2.1 Temporary Housing Units, Alternatives, and Duration

Shelter and temporary housing are the only protection from post-disaster devastation. Communities that are impacted by disasters rely on shelter and temporary housing from a few days, up to a few years, or even as permanent housing after expansions and updates. Figure 10 explains the transition between sheltering and housing through the post-disaster phases (Bashawri et al., 2014b; Félix et al., 2013; C. Johnson, 2007b; Alcira Kreimer, 1979; Quarantelli, 1991).

Figure 10: Temporary Housing During Natural Disasters

For an efficient and successful recovery, the temporary housing phase is vital for major disasters during the transition from disaster response to recovery; it enables the resettlement to the area and, therefore, the rebuilding and final restoration. An instance of extended communal restoration is during hurricane Katrina's disaster response, where temporary housing was located miles away, some even as far as neighboring states, prolonging and hindering New Orleans' recovery (Campanella, 2006; Perrucci & Baroud, 2018). However, the inclusion of temporary housing between disaster response and recovery is not as simple as providing a proximal location, and gains complexity with the variety of temporary housing types. This variety includes manufactured homes, trailer homes, available rental properties, vacant hotel rooms, tents, or affected properties that received repairs, creating political disputes over temporary housing quality and expenditure. Further, this uncertainty in housing-type usage disseminates into the supply chain and organizational structure that affects disaster preparedness and resource dynamics, leading to instances of post-disaster accommodation delays (Norris et al., 2008; Rudolph et al., 2002).

Post-disaster accommodations are a field of continued innovation and variation; however, the housing phases are well-defined. The categorical phases include emergency shelters and temporary housing, with further specification of temporary shelters, transitional shelters, progressive shelters and permanent housing, further explained in Table 8 (Bashawri et al., 2014a; Félix et al., 2013; C. Johnson, 2004, 2007b, 2007a; Perrucci & Baroud, 2018; Quarantelli, 1991; J. Y. Wu & Lindell, 2004).

Table 8: Summary of Housing Phases

Housing Phase	Expected Use Timespan	Examples
Emergency Shelter	1 to 3 Nights	A safe and dry location or building
Temporary Shelter	2 to 3 Weeks	Tent or public mass shelter
Temporary Housing	6 Months to 3 Years	Rental houses, hotels, or prefabricated units
Transitional Shelters	Months to Years	Relocated housing from temporary site to permanent site, recycled, expanded, or recycled and reused
Progressive Shelters	-	A shelter designed to be upgraded to permanent housing
Permanent Housing	-	A new, upgraded, or refurbished home

After spending on average two to three weeks in shelters, a period which can be prolonged if a lack of temporary housing exists, displaced people can spend approximately three years in temporary housing until permanent housing is established. Therefore, the more time spent in public shelters, the more prolonged the recovery period will be due to the displaced people's inability to return to their normal pre-disaster lives.

The critical temporary housing phases are organized under the umbrella of the Federal Emergency Management Agency's (FEMA's) Individuals and Household Program (IHP), which focuses on federally declared disaster events and supports eligible families or individuals during their housing dilemma. This program funds two types of temporary housing assistance: (1) vacant rental properties, and (2) Prefabricated temporary housing units (manufactured units or trailers). Out of these two options, prefabricated temporary housing requires the largest upfront investment with undefined uses afterward, yet it is considered a necessary expenditure in the event of large population displacement (FEMA, 2005; Lindsay, 2017; Perrucci & Baroud, 2018). Specifically, in the United States, the most common type of prefabricated temporary housing is manufactured FEMA units. These units' significant manufacturing cost has become an expected loss due to the unprofitable dismantling or auctioning after usage, however, these designs and supplies vary around the world from ready-made shelters to supply kits and largely depend on the transportation ability of the local infrastructure (Félix et al., 2013; Perrucci et al., 2016; Perrucci & Baroud, 2018).

When quantifying this trade-off between upfront investment and overall losses, modeling efforts must acknowledge spatial and temporal variability in event devastation and temporary housing demand. The spatial variability is ingrained by a specific state's hazard risk (e.g., geographic location, elevation, climate conditions, population density), and rental availability. For example, the high hazard risk state of Florida mitigates its temporary housing requirement due to the available rental properties from its considerable tourism sector. Whereas Alabama has lower hazard risk, yet fewer rental properties, creating a larger financial risk for temporary housing. The temporal variability is attributed to seasonal hazard potential and compounding hazard events. In cases of compounding events, there is increased potential for prolonged displacement and history of resettlement elsewhere. The variability in demographics also contributes to the temporary housing requirement, where more vulnerable communities have experienced longer and more widespread displacements/resettlements (Groen & Polivka, 2008).

4.2.2 Temporary Housing Management Methods

Prior research mostly focused on the development of optimization algorithms and multi-criteria decision analysis for the design and placement of temporary housing (Perrucci & Baroud, 2020). These studies began in the United States after devastating events such as Hurricanes Katrina and Rita, and focused on the main concerns of structural safety, environmental impact, and distance from preferred location; all of which were found to be important criteria contributing to post-disaster housing dilemmas.

One of the first optimization models developed in response to Hurricane Katrina, by El-Anwar et al. 2007-2010, focused on structural safety, environmental impacts, and displacement distance (Chen et al., 2012; Omar El-Anwar et al., 2010b, 2010a; Omar El-Anwar & El-Rayes, 2007; Perrucci & Baroud, 2018). After Hurricane Ike in 2008, expansions of this model considered various social, economic, and environmental aspects which enabled cost reductions, family locational preference, and identification of the optimal housing type; however, the approach was not computationally efficient (Chen et al., 2012; El-anwar et al., 2010; Omar El-Anwar et al., 2009; Perrucci & Baroud, 2018).

Shortly after Irene struck the north-eastern section of the United States in 2011, an updated iteration of the model provided a housing assignment based on a specific displaced family's needs, while still minimizing federal expenditure. This temporary housing optimization system is web-based and utilizes a customized Hungarian Algorithm, a combination enabling a reduced run-time (Chen et al., 2012; Perrucci & Baroud, 2018). In the aftermath of Hurricane Sandy in 2012, temporary housing optimization models considered equivalent total displacement distances, socioeconomic benefit, and a larger range of temporary housing alternatives. These added complexities required a prolonged run-time and revealed that socioeconomic benefit needed further study. One of the latest studies presents a model which minimizes the distance to family preferred location and support services, all while analyzing life-cycle costs and accounting for computational requirements. However, the model relies on housing providers to manually enter and routinely update their available units. This method can have detrimental consequences if housing providers fail to keep an accurate unit availability, causing inefficiencies in temporary housing units, either shortfalls or excess, due to the calculated demand based on incorrect availabilities (Omar El-Anwar & Chen, 2016; Perrucci & Baroud, 2018).

Each one of these studies has separately addressed different aspects of the dilemma in post-disaster temporary housing management. Current models do not consider the trade-off between pre- and post-disaster investment in temporary housing (Chen et al., 2012; Perrucci & Baroud, 2018; Rakes et al., 2014). This research proposes to model temporary housing allocation from an inventory management standpoint and aims to address the trade-off in pre-and post-disaster investment for the United States. Preliminary work employs the newsvendor model and a data-driven forecast of disaster severity to inform inventory for temporary housing in the case of Hurricane Harvey (Perrucci & Baroud, 2018). This paper builds on that hurricane Harvey case model by considering a range of possible scenarios and uses Monte Carlo simulation to account for the variability in the event intensity and temporary housing demands. The integration of inventory management and simulation approaches allows for a consideration of the spatial variability in hazard intensity and demographic distribution across multiple regions. Therefore, the model is used to draw insights on several states along the Gulf and Atlantic Coasts. The new model accounts for the uncertainty of disasters, social vulnerability of communities, available rental property alternatives, and upkeep, maintenance, and salvage costs/profits.

The outcome of the model answers the trade-off in disaster spending and recommends an optimal pre-disaster investment that improves resource management within the supply chain through proactive planning and price/design negotiation of temporary housing units (Perrucci & Baroud, 2018). Therefore, the research confronts the dual challenge behind excessive expenditure and uncertainty in demand by adopting a simulation-based demand forecasting method and a newsvendor inventory management optimization model to identify the most cost-effective stocking inventory for temporary housing.

4.3 Case Study

4.3.1 Hazards and geographic areas

The United States post-disaster temporary housing efforts are the focus of this research. The types of hazards are limited to those which most commonly require temporary housing in the United States, specifically, hurricanes and tropical storms. The scope is reduced by analyzing nine states from the Gulf Coast states and the South Atlantic states up to North Carolina. These states are selected as a case study due to their significantly larger risk of experiencing impacts that cause prolonged housing displacement from hurricanes and tropical storms (NOAA, 2020; Perrucci & Baroud, 2018). A one-year span, where multiple hazards can occur and cause a population displacement is considered for the analysis to enable annual inventory stocking amount adjustments. This outlined case study approach is modifiable to fit other contexts, including but not limited to, types of disasters, geographic areas (additional states or countries), and social and economic factors.

4.3.2 Data description

This section describes the variables included in the modeling approach and the corresponding source of data used to estimate their values.

Table 9: Data Description

Variable	Description	Resolution	Unit	Source
Property Damage (PD)	Property damage from past hurricanes and tropical storms	County	$	[34]
Median Housing Price (MH)	The median housing prices of the specified area	County	$	[35]
Population Urban (PU)	Percentage of the population in an urban area	County	%	[36]
Social Vulnerability Index (SVI)	Uses 15 variables to estimate level of required support	County	-	[37]
Homelessness (H)	Annual and point-in-time homelessness rates for 2018	State	%	[38], [39]
Rental Properties (R)	Available rental properties in the specified area	State	-	[40]
Wholesale Cost (WC)	Price to purchase manufactured unit before hazard	Nationwide	$	[41]
Emergency Purchase Cost (PC)	Price to purchase manufactured unit after hazard	Nationwide	$	[42]
Upkeep Cost (UpC)	Price to maintain unused manufactured	Nationwide	$	[43]
Salvage Profit (SP)	Profit from salvaging manufactured unit after hazard	Nationwide	$	-

This model utilizes data at multiple resolutions (e.g. county, state, and nationwide) depending on the stage of the analysis.

During the simulation stage, county-level property damage, median housing prices, percentage of urban population, and social vulnerability are utilized. The property damage data is obtained from the Center for Emergency Management and Homeland Security and represents county-level property damage in U.S. dollars for a specified hazard type. The median housing prices (MH) for each county are published in U.S. dollars by Zillow Research's in the Zillow Home Value Index (ZHVI). The population urban (PU) percentages for each county are sourced from the 2010 United States Census 2010 urban and rural classification. For the datasets with monetary units, the dollar has adjusted to the U.S. 2018-dollar value. The Social Vulnerability Index (SVI) is produced by the Center for Disease Control and Prevention (CDC). The CDC's SVI evaluation system is updated every two years for each county and utilizes evaluation variables from four themes, including Socioeconomic Status, Household Composition & Disability, Minority Status & Language, and Housing Type & Transportation.

In the next stage of the model, these county-level SVI values are factored into the temporary housing demand using state homelessness rates (H). These homelessness rates (H) are based on the annual estimates for sheltered homelessness from the 2018 Annual Homeless Assessment Report (AHAR) Part 2 and the point-in-time estimates of both sheltered and unsheltered homelessness from 2019 AHAR Part 1, created by the Department of Housing and Urban Development (HUD) (Deveoplment, 2018; The U.S. Department of Housing and Urban Development, 2019). The 2018 Annual Homeless Assessment Report (AHAR) Part 2 provides a nationwide estimate of 1,446,159 people who experienced sheltered homelessness (e.g. emergency shelter, safe haven, or housing program) between September 30, 2017 and September 30, 2018 (Deveoplment, 2018). This estimate is divided by US Census estimates for 2018 to determine a sheltered homelessness rate of 0.44%. The 2019 Annual Homeless Assessment Report (AHAR) to Congress provides state-level point-in-time (PIT) estimates of unsheltered people on a single night in January 2019 (The U.S. Department of Housing and Urban Development, 2019). These state-level PIT estimated were divided by the US Census estimates for 2019 to determine the unsheltered homelessness rate for each of the nine states considered in this research. The sheltered homelessness rate then adds half of the unsheltered homelessness rate, to provide a unique homelessness rate for each state that includes sheltered and unsheltered estimates.

Once the temporary housing demand includes social vulnerability considerations, the states' available rental properties are subtracted. The rental properties (R) are collected from Zillow.com at the time of this publication in 2021. These rental availability values are expected to actively change and require updating during implementation.

In the final step, national wholesale purchase and emergency purchase costs were estimated by quoting professionals from each field. A study by the MIT Center for Transportation and Logistics estimates an average of $110,000 to $129,000 per unit, and up to as much as $229,000 per unit, for this research the lower bound of $110,000 is considered the emergency purchase and is expected to include installation, transportation, and time-demand pricing considerations (Windle et al., 2019). A manufactured housing industry professional provided an estimated wholesale cost of a FEMA manufactured home at approximately $25,000, however, for this research, the wholesale cost is considered to be $40,000 to effectively account for fees and transportation cost (Allen, 2016). Following the sustainability guidelines of "Reduce, Reuse, and Recycle", the manufactured housing can be maintained in storage for $1,000 per year (upkeep price) until the next disaster strikes or auctioned at a salvage price, which can dramatically differ between auctions, of an estimated lower bound of $5,000 (Brien, 1999; Mica, 2009).

4.4 Methodology

This research proposes a comprehensive and integrated approach founded in the newsvendor model to manage the stocking inventory of temporary housing units and address the allocation delays, increased financial impact, and trade-off between pre- and post-disaster investment.

Figure 11 is a diagram of the research approach comprised of a simulation optimization model to calculate corresponding expected losses and identify the optimal stocking inventory.

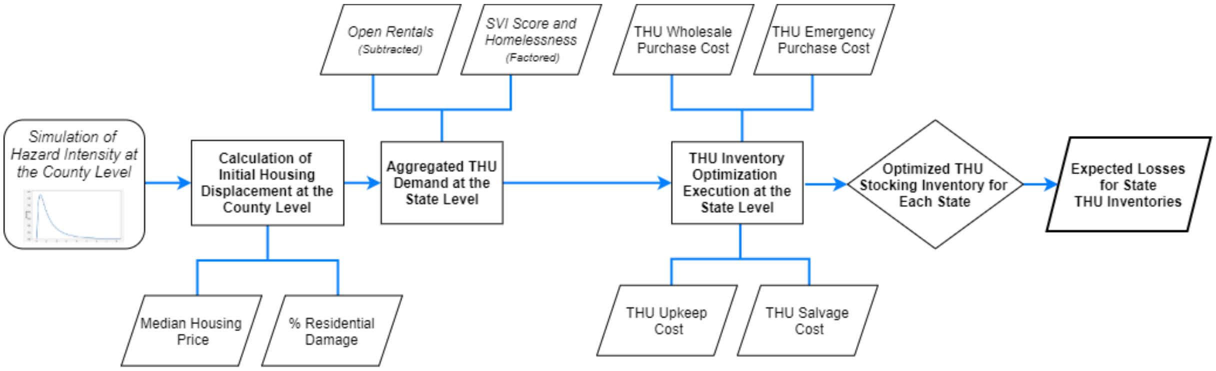


Figure 11: Model Flow Chart of THU Inventory Optimization at the State Level

This flow chart begins with a rounded square representing the starting process, a property damage simulation. Each parallelogram represents fixed inputs except for the final output of expected losses from the inventories. The rectangles are processes or calculations in the model, and the final stocking inventory decision is a diamond. This diagram describes the state level inventory optimization, the national THU inventory demand is starts by aggregating the state level demand and the THU inventory optimization execution remains the same.

Due to the rare occurrence of disasters requiring post-disaster temporary housing, historical data is lacking and a simulation approach is used to model the demand variability of temporary housing given the intensity of the disaster (Perrucci & Baroud, 2020). The model provides an optimal inventory that minimizes expected losses with inputs that include:

- **Damages:** simulated property damage
- **Demographics:** social vulnerability, homelessness
- **Housing:** available rental properties, median housing price
- **THU Costs:** Upkeep cost, wholesale purchase cost, emergency purchase cost, and salvage price.

We first provide an overview of the proposed approach and then explain in more details the demand simulation and inventory management models.

Algorithm 1: Algorithm to find the optimal stocking inventory

```
Data: PD, PU, PR, MH, R, SVI, H, WC, EC, UpC, SP
Results: $THU_D$, WL, EL, SP, ExL
begin
    Set X = 1000
        MA = 0.60
        RDA = 0.075
        UDA = 0.15

  Fit lognormal distributions for each county's historical property damage
    for m = 1: length (PD)
        C.PD = Makedist ('Lognormal', dist_mu(i), dist_sigma(i))
        Establish $C.PD$ bounds as $0 < C.PD \geq M.PD$
        C.PD = Ø
  Sample counties' distributions from the range of C.PD
```

```
        PD (:,i) = random (C.PD, X, 1)
    end

Estimate the THU demand
    for k = 1: length (PD)
    for z = 1: width (PD)
        URD (k,z) = PD (k,z) * PU * UDA
        RRD (k,z) = PD (k,z)  * PR * RDA
        RD (k,z) = URD (k,z) + RRD (k,z)
        MD (z) = MH * MA
        ICHD (k,z) = RD (k,z) / MD (z)
        CHD (k,z) = ICHD(k,z)  * (1+((1+SVI(z))*H))
    end
    end
        SD = sum(CHD,2)
        THU_D = SD – R

Optimize the THU Inventory
     for i = 1: size (a,2)
        Ď = maximum (THU_D, 0)
        WPC = WI(i) * WC
        UC = minimum (Ď, WI(i)) * WC
        MC = maximum (0, WI(i) - Ď) ∗ UpC
        WL (:,i) = WPC -UC+MC
        EL = maximum (0, Ď − WI(i)) * EC
        SP = maximum (0, Ď)*SC
        ExL = EL + WL +SP
     end

     Store the ExL(:,i), EL(:,i), WL(:,i), and SP(:,i)
```

For each state, the manufactured temporary housing demand is assessed based on its property damage (PD) which is modeled as a vector containing the county level property damage from hurricanes and tropical storms (C.PD) simulated using a lognormal distribution. The lognormal distribution is chosen for its superior fit of various county data and its natural ability to describe natural hazard events, where there are higher frequencies of low-level property damage and lower frequencies of severe property damage. The C.PD is split between rural versus urban and multiplied by adjustment factors to account for the percentage of residential damage (RD), rather than including various other types of damages including most notably public property damages.

The percentage of housing damage for prolonged displacement (MA) is set to 60% and represents the average amount of damage required to cause prolonged displacement. The 60% represents a safe estimation of damage that would cause prolonged displacements, 3 months to 3 years, independent of housing attributes (e.g., size, location, design). The MA varies between disasters and therefore, a sensitivity analysis is conducted to determine its influence on the model. This adjustment percentage is multiplied by the median housing price (MH) of each county to determine the median of required housing damage (MD).

The initial county housing demand (ICHD), from the quotient of RD and MD, factors in the CDC's social vulnerability index and state homelessness rates to estimate county housing demand (CHD), before aggregating for state housing demands (SD).

The temporary housing demands (THU_D) are the state housing demands (SD) with other available temporary housing methods subtracted (i.e., available rental properties obtained from Zillow.com at the time of this paper in 2021). To ensure non-negativity in demand, Ď takes the maximum of either THU_D or zero. This set of temporary housing demands (Ď) is utilized to evaluate each potential wholesale stocking inventory (WI). The WI ranges between 0 and a state demand-specific upper limit of units, in 500-unit increments.

The newsvendor optimization model runs for each Ď (i.e., each potential stocking inventory is solved for each demand in the set of Ď), solving for the expected losses for the specified WI. The set of expected losses for each stocking inventory are then averaged together to create a singular expected loss for each evaluated inventory. This methodology is applied to the set of Ď to solve for the overall optimal stocking inventory, therefore, reducing the expected losses associated with temporary housing unit (THU) allocation and establishing a strategic and resilient supply chain with less manufacturing uncertainty in post-disaster situations due to the increase in stocked units.

4.4.1 Demand Simulation

4.4.1.1 Property Damage

The first step in simulating the required amount of manufactured temporary housing units consists of simulating the property damage for future events. In this research, a Monte Carlo simulation of 1,000 iterations utilizes log-normal distributions from the counties in Alabama, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Texas, to provide the estimates for future hurricane and tropical storm events.

The log-normal distributions were fitted using historical data on property damage during hurricanes and tropical storms from 1960 to 2018 with 7,044 damage observations from the selected states, where counties with fewer than two historical events are not considered. In addition, the distributions were truncated to $50 million above the historical state maximum property damage (M.PD). This truncation ensures realistic property damage estimations based on historical events.

These guidelines create considerations for the increasing frequency and severity of natural disasters since the late 1900s and current century. By considering the increasing trends in damages and displaced peoples, we minimize inaccuracies within the simulation results that create the potential for hindered success in hedging for overstocks and shortages (Beutel & Minner, 2012). For temporary housing, these inventory overstocks are a financial loss, while the shortages cause financial losses and have the potential to debilitate the overall recovery.

The outcome from these simulations is a set of 1,000 simulated property damages for each county (C.PD) which are aggregated into one set of 1,000 simulated property damages for each state (PD).

These property damage values are then used to calculate the manufactured temporary housing demand.

4.4.1.2 Demand for Manufactured THUs

In the estimation of THU demand from the simulated property damages, varying demand levels are captured by including considerations for home values, urban density, social vulnerability, and homelessness. The simulated property damage (PD) can include damage from agriculture, public properties, etc., making it inappropriate to utilize the raw damage values. To calculate the THU demand, the amount of residential damage (RD) must be identified from the PD. The approach to calculate RD requires the percent urban (PU) vs. percent rural of each county (PR), and urban residential damage adjustment (UDA) and rural residential damage adjustment (RDA).

The approach first calculates the Urban Residential Damage (URD) using the property damage (PD), percent of county urban (PU), and the urban residential damage adjustment (UDA). Similarly, the Rural Residential Damage (RRD) is calculated using the property damage (PD), percent of county rural (PR), and the rural residential damage adjustment (RDA). The total Residential Damage (RD) is a sum of the URD and the RRD, Equation 1.

$$\mathrm{RD} = (\ \mathrm{PD} * \mathrm{PU} * \mathrm{UDA}) + (\mathrm{PD} * \mathrm{PR} * \mathrm{RDA}) \tag{1}$$

There is uncertainty in the UDA and RDA, these adjustments would vary based on the location and severity of the event, however, for this research UDA is set as 15% and RDA is set as 7.5%. These UDA and RDA values represents an estimation of the percentage of property damage being residential damage and the ratio between urban vs. rural (i.e., it is expected for a more urban area to experience more housing damage). Due to this uncertainty in the UDA and RDA values, a sensitivity analysis is conducted to determine and discuss its influence on the model output.

Once the amount of residential damage is determined from the simulated data, the expected initial housing displacement can be calculated. The county level residential damage (RD) is divided by the county's median required damage per household for displacement (MD). This approach using MD ensures that the calculation is estimating the number of homes which will require prolonged displacement from the overall RD. The median damage consists of the median housing price (MH) multiplied by the percentage of housing damage for prolonged displacement (MA), Equation 2.

$$\mathrm{ICHD} = \frac{\mathrm{RD}}{\mathrm{MH} * \mathrm{MA}} \tag{2}$$

These initial estimates for housing demand then account for the county's social vulnerability. The county hazard demand is calculated by multiplying the initial demand by one plus the social vulnerability index percentile multiplied by the combined homelessness rate, Equation 3.

$$\mathrm{CHD} = \mathrm{ICHD} * (1 + \big((1 + \mathrm{SVI}) * \mathrm{H}\big)\big) \tag{3}$$

The final temporary housing demand is evaluated by summing all counties' housing demand and subtracting the available rental properties. To ensure non-negativity in demand, the minimum considered is zero. As seen in Equation 4.

$$\check{D} = \max((\text{sum}(\text{CHD}) - \text{R}), 0) \tag{4}$$

This calculated demand for manufactured THU is based off the simulated property damage for each county.

4.4.1.3 Qualitative Verification of PD and THU Estimation

In any given year there is uncertainty for disaster devastation, and hurricane seasons fluctuate with severity and frequency of events (e.g., one year may only have minimal hurricanes, and another year may have several extreme hurricanes). The purpose of this verification is to ensure the practicality of the simulated property damage data and the corresponding THU estimations, for a series of different disaster potentials. This verification utilizes three scenarios, worst-case, average case, and best-case are selected to represent the uncertainty in different years and disasters. The definition of each scenario is as follows:

- worst-case is the maximum amount of simulated property damage
- standard case is the average amount of simulated property damage
- best-case is the least amount of simulated property damage.

The results for the simulation (e.g., property damage and THU estimation) are in Table 10.

Table 10: Results for Simulated Property Damage and THU Estimation

Type	Property Damage ($ Billion)	THUs
Worst-Case Scenario	92.5	165,680
Standard Case Scenario	16.9	14,621
Best-Case Scenario	1.46	247

The simulated property damage ranges from $1.46 billion to $92.5 billion and the THU requirement ranges from 165,680 to 247 units.

The simulation methodology is verified by comparing the three scenarios with the historical property damage to ensure rationality of the simulation. Then, the THU estimation methodology is validated by comparing the three scenarios to historical THU usage from events with similar property damage levels (e.g., worst-case compared with Katrina, standard case compared with Wilma, and best-case compared with Matthew). The historical values are in

Table 11 (Avila & Cangialosi, 2011; Cooper, 2017; FEMA.gov, 2009b, 2009a; Gibbens, 2019; Kleinberg, 2009; Lindsay, 2017; NOAA, 2019, 2020; Stewart, 2017; U.S. Department of Homeland Security, 2013).

Table 11: Summary of Historical Data with Simulated Demand Forecast

Hurricane	Year	Rank	Category	Property Damage ($ Billion)	THUs
Katrina, Rita	2005	1	3	95	+200,000*
Sandy	2012	4	1	70	118
Ivan, Charley, Frances, Jeanne	2004	3	4	45	17,000
Ike	2008	5	2	19.3	3,692
Wilma	2005	6	3	16.8	1,182
Irene	2011	7	1	15.8	784
Matthew	2016	8	4	10	161

*Although there was a 200,000-unit demand during Katrina and Rita, only around 120,000 were manufactured in time.

This comparison between simulated and historical data (i.e., Table 3 and Table 4) shows that the property damage simulation does simulate events of reasonable size, with a maximum property damage similar to Hurricane Katrina, the standard property damage similar to Ike, Wilma, and Irene, and the best-case scenario representing the less severe events.

With regards to the THU estimation, the validity of the simulated values are qualitatively, not quantitatively due to insufficient data, confirmed upon comparison to the historical THU usage in

Table 11. For the worst-case and best-case scenarios of the results (i.e., 165,000 units for $92.5 billion in property damage and 247 units for $1.5 billion in property damage), the THU requirement has the greatest similarities to the historical events. The standard case scenario has a larger THU requirement than expected for the corresponding property damage, however, this can be partly accounted for in the variability of disaster locations (from the validating events) and the nonlinear relationship between the THU requirement and increases in property damage.

These results are desired due to the influence that a projection has on the overall optimization of the inventory model and corresponding supply chain (i.e., if the forecasting model is wrong, the optimization suffers). The comparison between THU estimation and historical usage for large property damages reduces the chances of an overestimation of temporary housing demand that leads to an inflated optimized inventory and inaccurate expected loss calculations. High losses and slow recovery due to an underestimation of THU demand does not apply, since the THUs forecast is larger than the 4,000 unit FEMA baseline inventory (Fugate, 2011).

4.4.2 Inventory Management Model

In supply chain management, the main objective is to reduce the supply chain disturbances that can occur due to material shortage, transportation malfunctions, disasters, among others. These disruptive events cause a lack of symbiosis in the supply chain that ultimately ends with a delay or lack of materials or products (Chopra & Sodhi, 2004; Perrucci & Baroud, 2018). In order to mitigate the risk within these supply chain disruptions and the toll on the inventory quantity, the newsvendor model is a proven method of inventory management and control. Criticisms of the newsvendor methodology revolve around supporting insufficient stocking inventories for peak demand. If stocking quantities were too low that would potentially cause adverse side effects, such as a tarnished reputation and reduced profitability; however, these criticisms are profit-minded and do not apply to disaster situations where the objective is to reduce losses (Perrucci & Baroud, 2018; J. Wu et al., 2008).

The objective of a newsvendor model is to either maximize the expected profit or minimize the expected loss. In disaster management situations, the desire is to minimize the expected loss. First, the emergency, wholesale, and preservation losses, which make up the expected losses, are calculated according to Equation 3 through Equation 7.

The wholesale purchase cost (WPC) is the initial investment required by the response agencies calculated by multiplying the wholesale cost (WC) (price per unit) by the wholesale inventory (WI).

$$\mathrm{WPC} = \mathrm{WI} * \mathrm{WC} \tag{3}$$

The wholesale cost is then used to calculate the utilized cost according to Equation 4. The utilized cost (UC) is the total money spent on the wholesale inventory utilized during the relief and recovery. The utilized cost is calculated by taking the smaller of either the actual demand (Ď) or the wholesale inventory, which would then be multiplied by the wholesale cost (WC) (price per unit).

$$\mathrm{UC} = \min\left(\check{\mathrm{D}}, \mathrm{WI}\right) * \mathrm{WC} \tag{4}$$

The final component of the wholesale loss is the maintenance cost, described in Equation 5. The maintenance cost (MC) encompasses the cost to keep the investment if the wholesale inventory is not required; it includes storage and maintenance of unused units. This maintenance cost is calculated by finding the maximum of either zero or the surplus wholesale inventory and multiplying it by the upkeep cost (UpC) per THU, which includes the prices for maintenance and storage.

$$\mathrm{MC} = \max\left(0\,, \mathrm{WI} - \check{\mathrm{D}}\right) * \mathrm{UpC} \tag{5}$$

The wholesale loss is then calculated according to Equation 6. The wholesale loss (WL) represents the amount of the initial investment which went underutilized. This wholesale loss is calculated by subtracting the utilized cost from the wholesale purchase cost.

$$\mathrm{WL} = \mathrm{WPC} - \mathrm{UC} \tag{6}$$

Once the wholesale loss is calculated, the emergency loss is calculated using Equation 7. The emergency loss (EL) is the cost to purchase the additional inventory of manufactured temporary housing once the wholesale inventory fails to support the demand. Emergency loss is calculated by taking the maximum of either zero or the demand still required after utilization of the full wholesale inventory (actual demand – wholesale inventory), where the maximum is then multiplied by the emergency cost (EC) (price per unit).

$$\mathrm{EL} = \max(0\,, \check{\mathrm{D}} - \mathrm{WI}) * \mathrm{EC} \tag{7}$$

After these disaster expenses are calculated, the salvage profit from units is calculated using Equation 8. The salvage profit (SP) is the cost to profit from auctioning the previously utilized inventory of manufactured temporary housing. Salvage profit is calculated by taking the maximum of either zero or the temporary housing demand, where the maximum is then multiplied by the salvage price (SPr) (price per unit).

$$\mathrm{SP} = \max(0\,,\,\check{\mathrm{D}}) * \mathrm{SPr} \tag{8}$$

Using these wholesale and emergency losses, the quoted price estimates from professionals, and the salvage profits, the expected loss (ExL) is calculated using Equation 9.

$$\mathrm{ExL} = \mathrm{EL} + \mathrm{WL} + \mathrm{MC} - \mathrm{SP} \tag{9}$$

Expected losses are calculated by simply adding the emergency losses, wholesale losses, maintenance costs, and salvage profit. To optimize the wholesale inventory, the objective is to minimize the expected loss.

4.5 Results

4.5.1 State Level Inventory Optimization

In this research, the optimization considers a different range of wholesale stocking inventories for each state, providing a more relevant state-by-state analysis that accounts for spatial variability and the varying THU demand from the simulated property damages. The disaster intensity is modeled using property damage where 1,000 scenarios are simulated from a lognormal distribution of the property damage for each county in the selected states. A portion of these property damage values are considered residential damage. The modeled property damage at the county level, which represents multiple households, is then divided by the damaged proportion of the median housing price, to provide initial housing demand at the county level. By dividing the modeled property damage for a county by the median housing price, we can estimate the number of homes that are significantly damaged to cause displacement and require THUs. Once the initial housing demand is obtained, it is multiplied by the SVI-homelessness adjustment. The SVI-homelessness adjustment is calculated for each county by multiplying one plus SVI percentile of the county by the state homelessness rates (county-level homelessness rates were unavailable). Thus, the initial housing demand is adjusted to consider those likely to suffer homelessness (and increase demand) due to the increased disruption of the event. These county-level housing demands are then aggregated to state-level housing demands. These state housing demands have available rentals subtracted to reach temporary housing unit demands. The results from the simulation methodology are utilized to produce a distribution of the expected loss under each potential wholesale stocking inventory at increments of 500 units.

Figure 12 organizes the average simulated state property damage to examine the underlying reasoning for temporary housing risk.

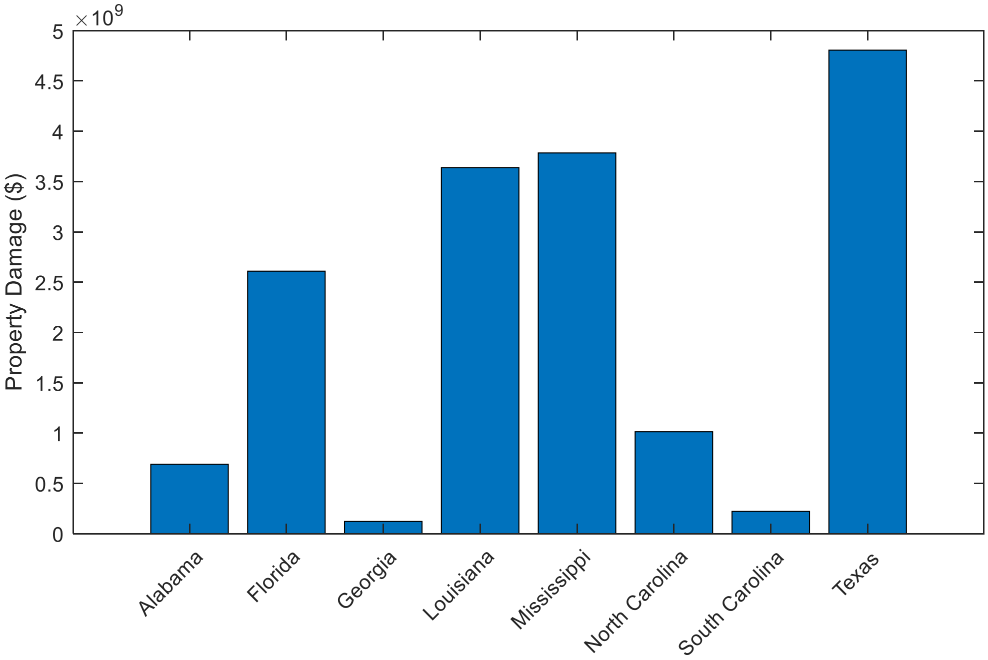


Figure 12: Simulated Property Damage by State

The underlying state risk for temporary housing is determined by the average levels of simulated property damage. From these simulations, Texas is most at risk for increased property damage with Mississippi, Louisiana, and Florida showing increased potential. Property damage directly relates to THU demand, however, there are other factors (e.g., available rentals and social vulnerability) which can influence housing risk and demand for THUs. The factors influencing temporary housing demand are broken down for each state in Figure 13.

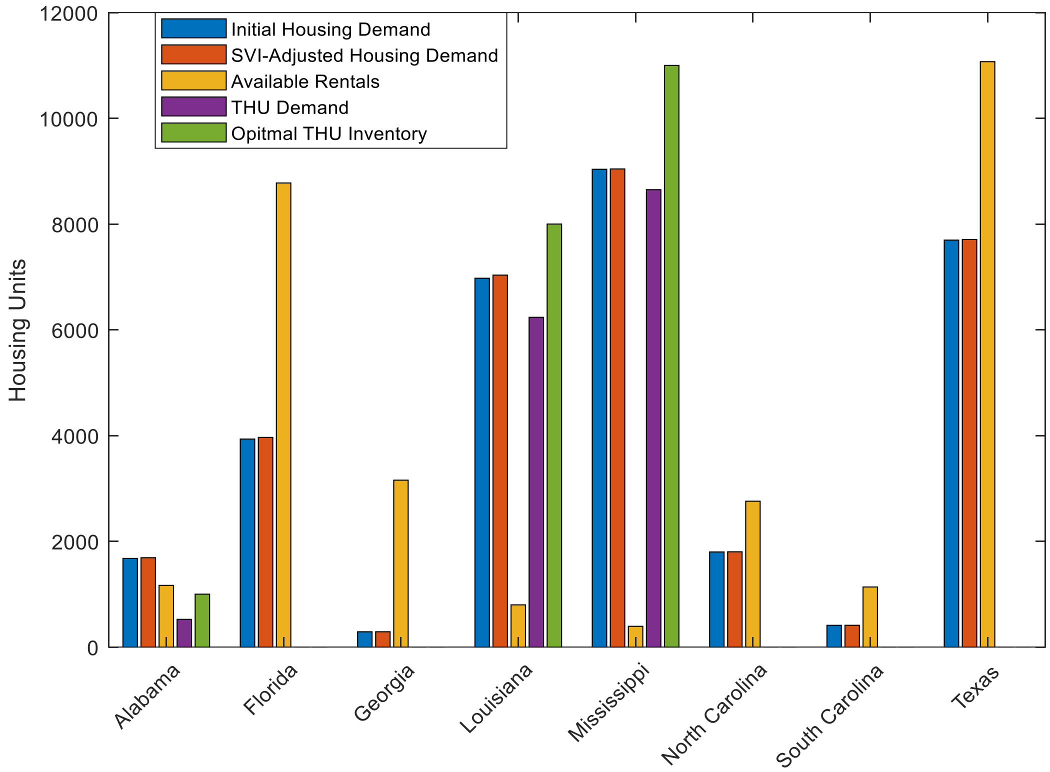


Figure 13: Breakdown of factors influencing temporary housing demand for each state

The expected property damage and resulting displaced population in Texas is mitigated by the availability of rental properties, whereas the lack of rental properties in Louisiana and Mississippi caused an increased requirement for temporary housing. Florida and Georgia are also largely mitigated by available rental properties, whereas Alabama, North Carolina, and South Carolina are more at risk.

As one of the most at risk for THU demand, Louisiana is detailed to show the reduction in financial risk with stocking inventory adjustments in Figure 14.

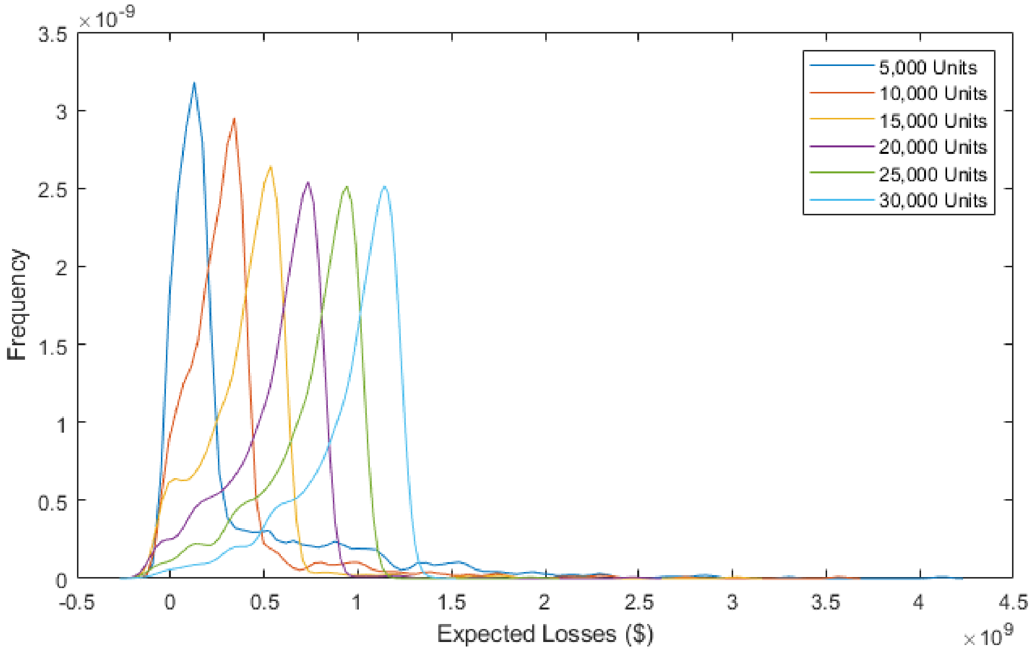


Figure 14: Louisiana Overlay of Expected Losses by Stocking Inventory

The largest drop in frequency of extreme expected losses occurs between 5,000 units and 10,000 units, with a less drastic shift of the overall distribution compared to the other inventory amounts. These results signify that the optimal stocking inventory will be within that stocking inventory range and is confirmed in Figure 15.

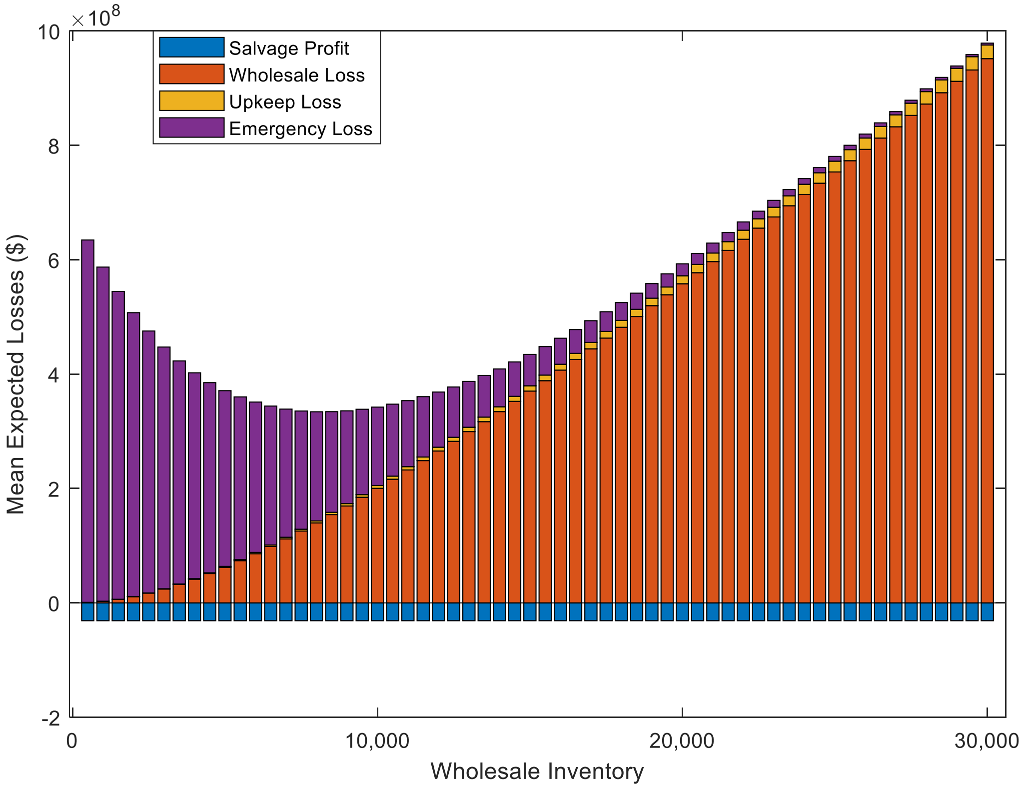


Figure 15: Breakdown of Mean Expected Losses for Wholesale Inventories in Louisiana

The breakdown of mean expected losses provides perspective on the maintenance costs associated with the upkeep loss. At a lower wholesale stocking inventory, the upkeep loss can be argued negligible compared to other losses. In addition, the average THU demand for Louisiana would provide a salvage profit from utilized units that effectively covers the upkeep losses for stocking inventories up to 30,000 units. Unlike the traditional newsvendor model where the salvage cost is associated with unused inventory, this model considers the salvage profit from utilized housing units due to U.S. policies which limit reuse and support auctioning of utilized units. This definition of the salvage profit is dependent on THU demand and the profit remains constant in figure 7, independent of stocking inventory, due to the averaged demand it represents. These loss and profit conclusions cannot be made for other states until referencing their breakdown of mean expected losses. The remaining state-level analysis results for Alabama, Florida, Georgia, Mississippi, North Carolina, South Carolina, and Texas are organized in the Appendix B.

4.5.2 Nationwide Inventory Optimization

These state temporary housing demands for Alabama, Florida, Georgia, Louisiana, Mississippi, North Carolina, South Carolina, and Texas, are aggregated into one representative nationwide temporary housing demand, resulting in 1,000 scenarios of national demand. The demand for these states is considered representative of the United States demand due to the increased regularity of hurricane and tropical storm events which warrant temporary housing. The nationwide demand utilizes the same newsvendor methodology as the state-specific analysis to create an overall optimized inventory. The distribution of potential expected losses is shown in Figure 16.

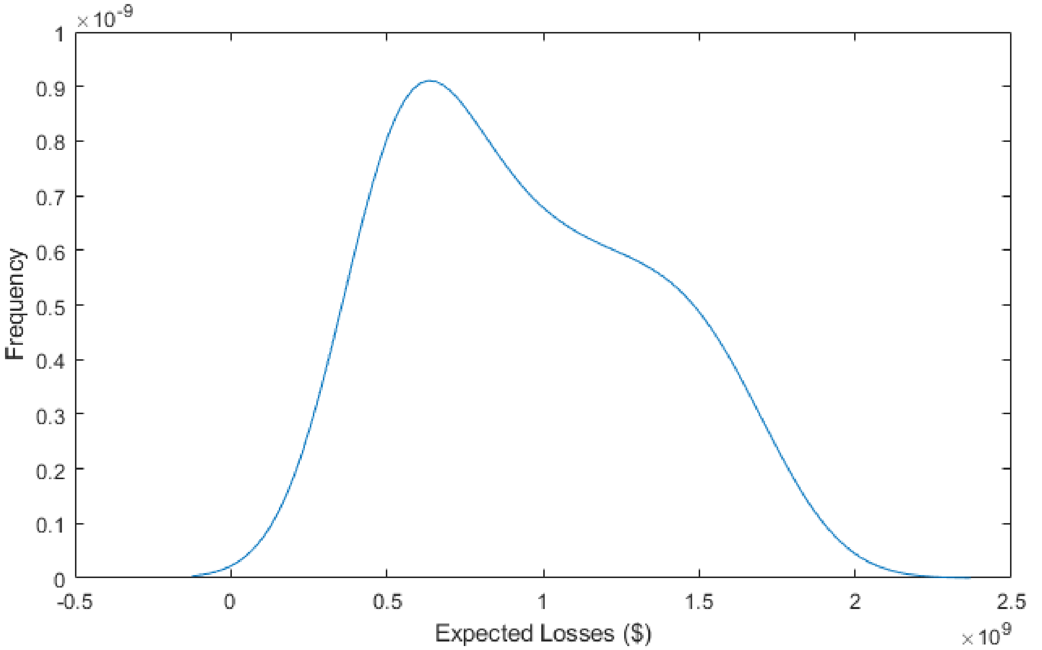


Figure 16: Nationwide Density Overlay of Expected Losses

The nationwide financial risk from expected losses based on the aggregated state THU demands range from $0 to $2.5 billion. The distributions of expected losses for a subset of stocking inventory are shown in Figure 17.

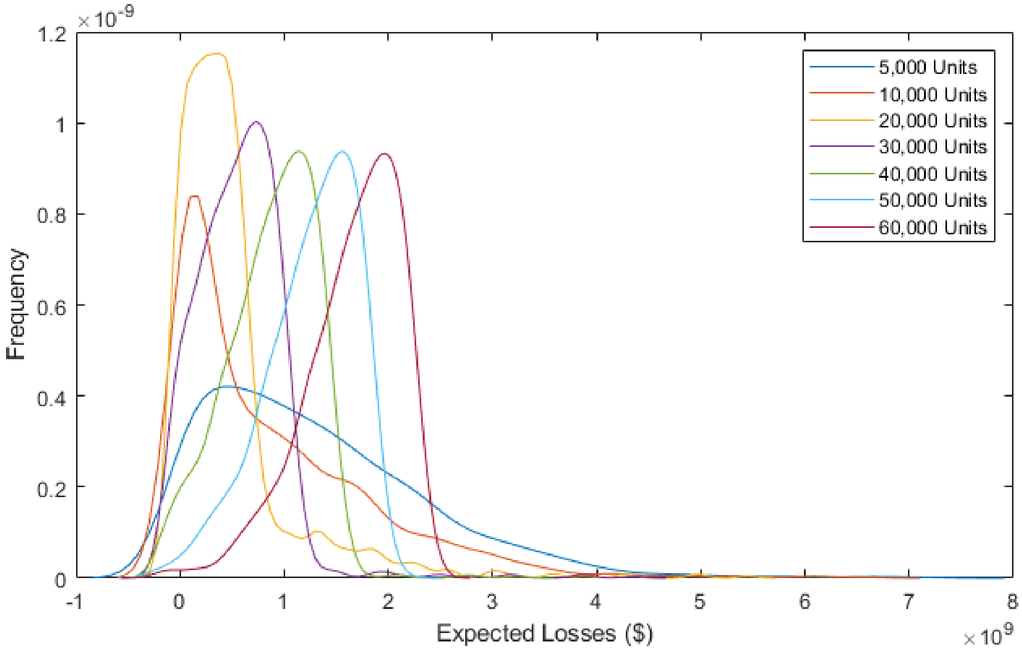


Figure 17: Nationwide Overlay of Expected Losses by Stocking Inventory

The lowest inventory considered is 5,000 wholesale units which results in a wide distribution of losses reaching up to $8 billion. Larger inventories of 10,000 and 20,000 units' raise the probability of experiencing an extreme expected loss and shrink the span of expected losses; ultimately, reducing the probability of the high-cost, low-risk events. Then for each of the increasing inventories after 20,000 wholesale units, the distributions shift to the right, with higher average expected losses, but less variance on the range of possible losses.

As such, a higher inventory will require a larger investment; however, it will decrease the frequency of stockouts and emergency purchases. This information from the density overlay can be applied to the overall minimization of expected losses and the optimization using wholesale inventory as the constraint variable. The convexity of the optimized solution is seen in Figure 18.

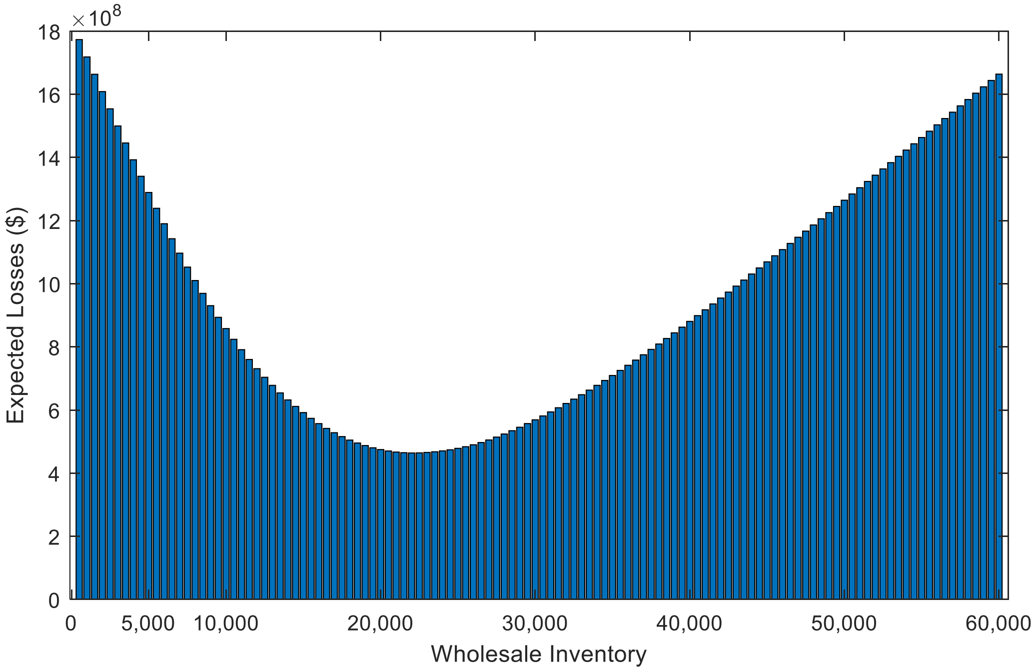


Figure 18: Nationwide Expected Losses for Wholesale Inventories

The inventory optimization calculates that a wholesale inventory of 22,000 manufactured temporary housing units is the optimal stocking inventory for the national financial temporary housing risk management, containing a mean expected loss of $464 million. In comparison, the model shows that with a baseline stocking inventory of 4,000 there is a mean expected loss of $1.4 billion, or nearly a $936 million-dollar increase in expected losses. Therefore, the model achieves the desired reduction of expected losses, while creating a temporary housing supply chain that is more resilient and time efficient. This increase in allocation time efficiency and reduction in housing delay due to the increased baseline inventory minimizes the duration of family displacement and, as a result, minimizes the potential for psychological effects while also increasing the community resilience through a shortened recovery period.

In this research, the demand pooling value (i.e., optimal nationwide stocking inventory) is the same as the number of units required if each state were to hold its own inventory due to the fundamental assumption that negative demand would not be considered. Negative demands are from a surplus of rental units and if these surpluses of rental units (i.e., the negative demands) were combined, then those displaced in one state could theoretically be housed in another state, an instance that occurred during hurricane Katrina and caused severe delays to recovery (Campanella, 2006; Perrucci & Baroud, 2018).

4.5.3 Sensitivity Analysis

Several model inputs are uncertain and estimated based on various assumptions. A sensitivity analysis is conducted for each uncertain variable in the model to effectively quantify and evaluate the potential impacts. This section presents Louisiana's results with the remaining state-level sensitivity analysis results for Alabama, Florida, Georgia, Mississippi, North Carolina, South Carolina, and Texas are organized in the Appendix B.

4.5.3.1 Percentage Housing Damage for Prolonged Displacement (MA)

The first sensitivity analysis, Figure 19, investigates the impact of required percentage of housing damage that will lead to prolonged displacement and require temporary housing (6 months to 3 years).

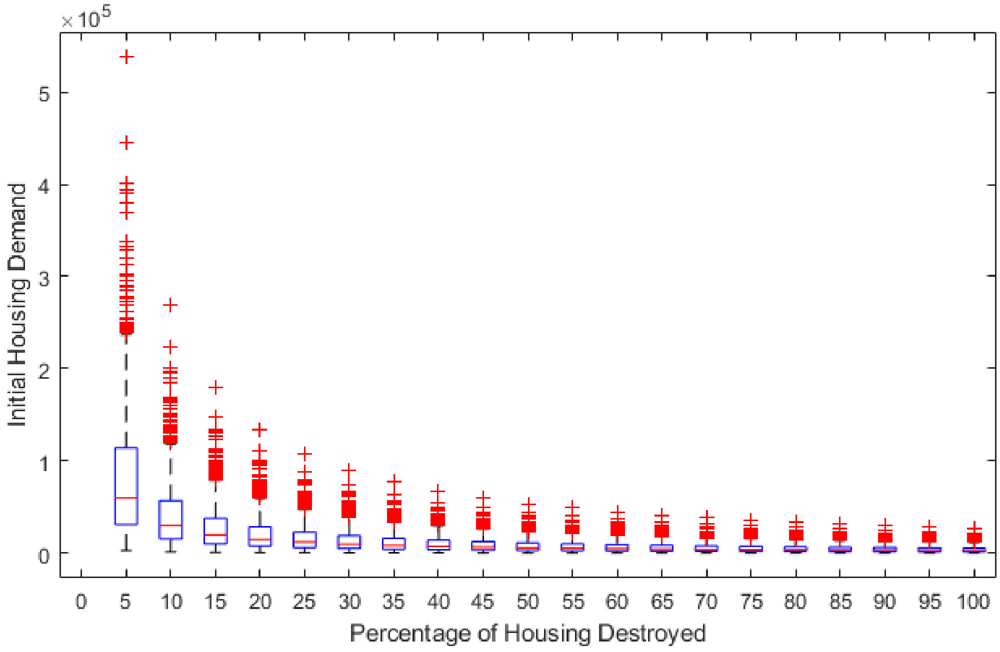
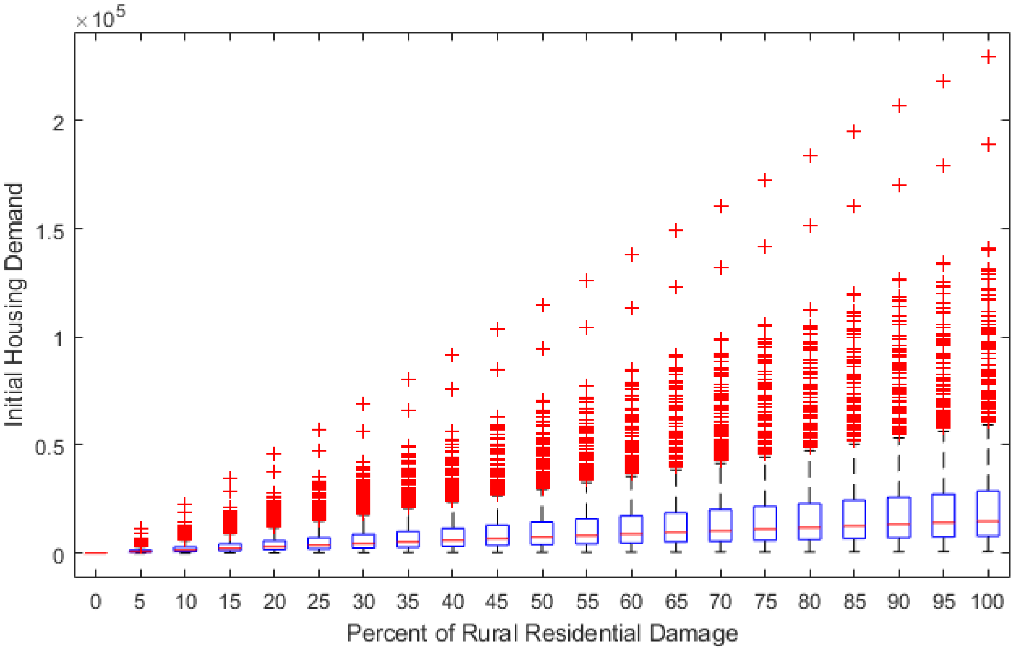


Figure 19: Louisiana Sensitivity Analysis on Amount of Housing Damage to Require Temporary Housing

This sensitivity analysis reveals that at lower damage requirements there is significant variability in the initial housing demand (y-axis). On the contrary, the variability on the y-axis reduces as the housing damage increases on the x-axis, from 35% to 100% of housing destruction there is reduced variability between the calculated initial housing demand (y-axis). For this research, 60% of housing damage is required for prolonged displacement from pre-disaster housing.

4.5.3.2 Rural and Urban Residential Damage Adjustment (RDA) and (UDA)

A sensitivity analysis is conducted on the percentage of housing damage included in the property damage values in both rural and urban communities. This percentage can vary drastically between communities (e.g., a city may have more public properties and a rural area may have more farmland) and can impact the demand drastically, this analysis determines the potential range of impacts in Figure 20 and Figure 21.



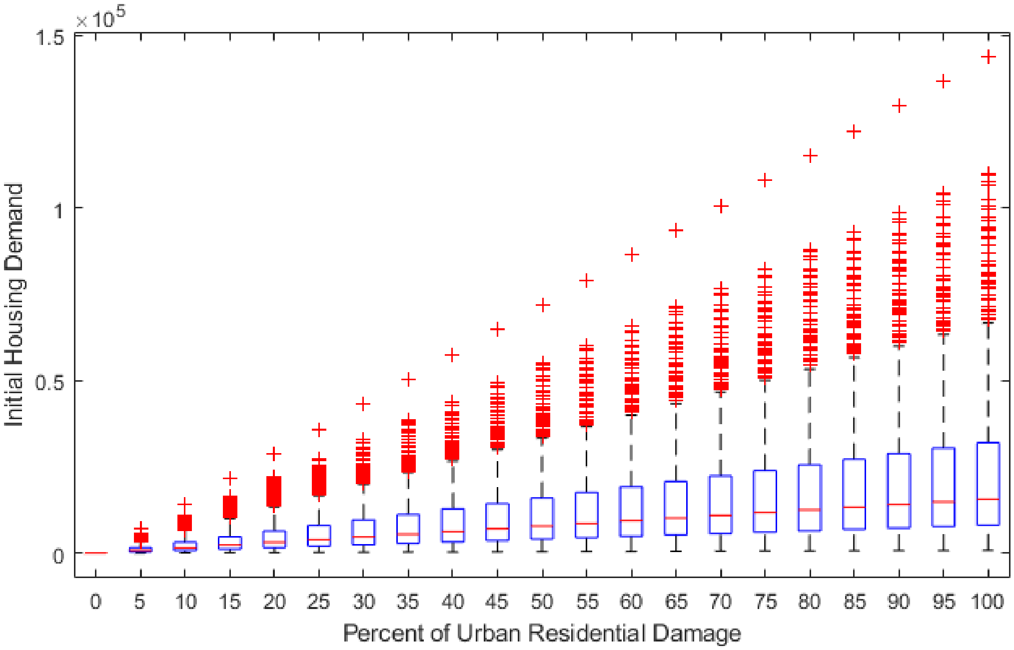


Figure 20: Louisiana Sensitivity Analysis on Rural Residential Damage

Figure 21: Louisiana Sensitivity Analysis on Urban Residential

These sensitivity plots show that for Louisiana there is more uncertainty in rural residential damage. Overall, the percentage of residential damage can be volatile to the initial housing demand in both cases, causing a range from 0 and up to 250,000 in initial housing demand. These results stress caution when determining percentages of residential damage in property damage values; where median housing prices, amount of rural vs. urban land, and the damage required for displacement can contribute towards the volatility.

4.5.3.3 Social Vulnerability Index (SVI) and Homelessness

The final sensitivity analyses are conducted on the social vulnerability and homelessness rates in the communities. A sensitivity analysis of social vulnerability was conducted by ranging the SVI percentile incrementally by 20% from 0% to 100%. The analysis reveals that the distribution of expected losses does not change as the social vulnerability varies. The expected losses are not sensitive to the value of the social vulnerability. However, this does not signify a lack of importance for social vulnerability in temporary housing decisions because the SVI's influence is hindered by the availability of, and uncertainty in, statewide homelessness rates. It is important to adjust these statewide homelessness rates using SVI because the base homelessness rates do not represent the disaster driven homelessness. The inclusion of the social vulnerability index enables the transition from non-disaster homelessness values to potential post-disaster values using recognized vulnerability of communities. Figure 22 represents the sensitivity of the housing demand, and impact of SVI, to these homelessness rates.

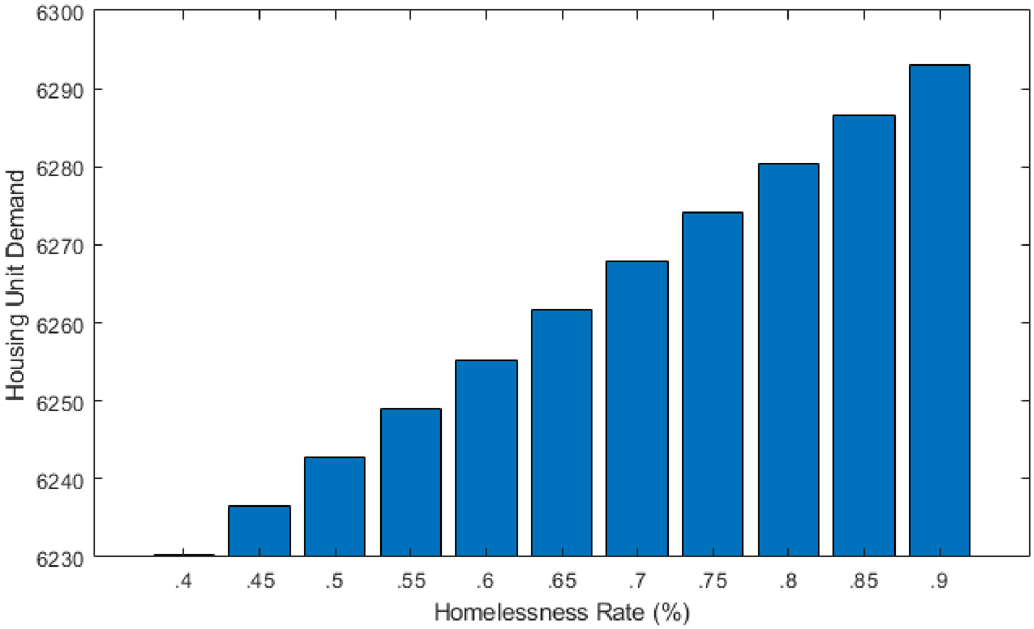


Figure 22: Louisiana Sensitivity of Housing Demand from Homelessness Rate

This analysis on the impact of homelessness rate on housing demand does show a mild increasing relationship. In this model, a combination of annual sheltered and unsheltered point-in-time homelessness rates are considered the baseline estimates that increase dependent on the corresponding social vulnerability percentiles. Therefore, the impacts of social vulnerability of the community are constrained by the homelessness rates to an influence range of 0-60 units on THU demand.

4.6 Discussion

The simulated methodology is comprehensive and representative of hurricanes and tropical storms for property damage, and corresponding temporary housing needs, in the United States.

The accuracy is qualitatively confirmed to ensure that large-inventory forecasts do not cause over purchasing and wasted upfront investment.

This model made a series of assumptions that will require further research to reduce uncertainties and potential inaccuracies. Each one of the model's assumptions were subjected to a sensitivity analysis to determine the potential severity of the impacts. The assumption on the percentage of housing damage for prolonged displacement (MA) is shown to contain reduced risk with a housing damage percentage of 20% and above. This reduced risk makes helps mitigate the assumptions potential impacts; however, the model would benefit from further research and exactness for the variable.

The assumptions with the largest potential impacts on the model are the Urban Residential Damage Adjustment (UDA) and Rural Residential Damage Adjustment (RDA). In this research, a UDA of 15% and RDA of 7.5% were set iteratively and utilized after verification of property damage values (qualitative comparison of Table 3 and Table 4). The sensitivity analyses done on UDA and RDA reveal severe potential impacts on initial housing demand and the overall appropriateness of the stocking inventory suggestions. Moving forward, these variables must be accurately quantified or directly documented during post-disaster scenarios to ensure the appropriateness of stocking inventory proposals and reduce the potential for unnecessary investments.

In addition, this model may have suffered from the lack of information on the impacts of social vulnerability during disaster scenarios. A greater understanding of how social vulnerability impacts temporary housing demand is required to determine the best methodology for incorporation in future post-disaster housing models. For instance, the sensitivity analysis of SVI and homelessness for Louisiana reveal that the impact of SVI on expected losses is negligible and only increases unit demand by up to 60 units in the most severe scenario. Future research is required in two areas. First, this research utilizes pre-disaster homelessness rates as a baseline which is increased based on the county-level SVI. To better characterize homelessness, an investigation on how pre-disaster homelessness rates fluctuate during disaster events is required. Second,, the CDC's SVI which is utilized in this research ranks census tracks based on 15 social factors, while the Social Vulnerability Index for the United States (SoVI) from the Hazards & Vulnerability Research Institute syntheses 29 socioeconomic variables (Hazards & Vulnerability Research Institute, n.d.; Prevention, 2018). Future research is required to determine which vulnerability metric is more applicable to disaster scenarios and which set of variables (i.e., 15 social or 29 socioeconomic) relates more accurately to homelessness potential. Relevant studies have implemented a factor analysis approach to identify the most important variables for measuring community vulnerability and resilience (P. Johnson et al., 2020). Benefits from optimizing the inventory support further research to successfully store and re-use manufactured units in the magnitude of 20,000 units or more. The current temporary housing design would be problematic in meeting storage demands and new temporary housing designs must be considered. One innovation would be the re-use of recycled shipping containers as temporary housing. Prior research acknowledged benefits of reusing shipping containers such as modern, human-based designs and less expensive construction costs due to the rigidity and excess of containers worldwide (Perrucci et al., 2016). In addition to these benefits, a shipping container's rigid design would enable the stacking of manufactured temporary housing units, therefore, enabling magnitudes higher storage capacity than currently possible for the United States' response agencies. A shipping container design is one of many potential designs and the best alternative would require an in-depth analysis, nonetheless, the re-consideration is initially well supported by the increased stocking inventory results from this research.

The outcomes from this model, reduced financial risk and decreased allocation periods due to increased availability of units, can be re-evaluated for the United States based on novel temporary housing designs, and any change in wholesale purchase price, emergency purchase price, upkeep costs, and salvage profits. Furthermore, this model can be impactful on a worldwide scale, by evaluating temporary housing stocking inventories globally with the additional location-specific historical demand and property damage information.

4.7 Conclusion

Post-disaster displaced people are expected to increase as coastal densities grow, and natural disasters become more frequent and extreme. These increases within displaced people will create unmanageable levels of temporary housing demand, that will drive over expenditure in response efforts and enable the devastating impacts from response delays. This research proposed an integrated simulation optimization method to manage the inventory of temporary housing units and balance resource allocation before and after a disaster. The model results in risk-informed temporary housing unit allocation across multiple states and at the national level. The property damage simulation and corresponding housing unit demand suggest an optimized stocking inventory of 22,000 units and can potentially provide savings of over $900 million, compared to the previous United States' baseline stocking inventory of 4,000 units (Fugate, 2011).

While the research focuses on minimizing the financial risk associated with temporary housing management, the model has the potential to improve outcomes of disaster management such as psychological impacts and community resilience by providing a readily available amount of temporary housing units that will be sufficient for most displacements. An opportunity for expansion of this research would be in the redesign of manufactured temporary housing units to increase storage capacities of units, in order to successfully prepare for the next Hurricane Katrina-sized storm.

A required area of future investigation is the evaluation of current, and application of novel, property damage estimation methodologies. This model required a series of property damage assumptions and the uncertainty in property damage values may undesirably influence the models' outcome and success. In Chapter 5 this research proposes an exploratory methodology to evaluate residential property damage levels using drone imagery, enable dynamic relief appropriations (i.e., temporary housing types, need-based funding, etc.), and discusses its potential to add a layer of transparency/efficiency if updated into FEMA's current Preliminary Damage Assessment Guide.

CHAPTER 5, AN EXPLORATORY ANALYSIS OF THE USE OF DRONE IMAGERY TO SUPPORT DYNAMIC AND EQUITABLE DISASTER RELIEF

5.1 Motivation

The evaluation of current, and application of novel, property damage estimation methodologies is required to reduce the uncertainty in property damage values and number of assumptions necessary to successfully implement an inventory management model such as the newsvendor model in Chapter 5. This research proposes an exploratory methodology using drone imagery to evaluate residential property damage levels caused by disasters with extreme winds (e.g., hurricanes, typhoons, cyclones, tornadoes, etc.) and enable dynamic relief appropriations (i.e., temporary housing types, and need-based funding, among others). The climate-driven severities of these types of disaster events can increase damages and population displacement, one example of this climate driven severity is the 2020 Middle Tennessee tornado event which was the most devastating tornado in Tennessee for the last decade (Weather.gov, 2020). The proposed methodology utilizes the 2020 Middle Tennessee tornado as case study to represent an applicable evaluation of exterior disaster damages (i.e., damages caused by wind, water, earth) for various disaster types and ignores potential internal flood related losses during these high-wind events due to the drone inability to capture internal damages (i.e., flood damages cause significant structural damages and personal property damages inside of the structure which are not visible with drone imagery). In addition, the potential increases in population displacement and the duration of displacements caused by the climate-driven devastation will depend on the levels of community resilience (i.e., communities ability to bounce back to a pre-disaster lifestyle) (Norris et al., 2008; Opricovic & Tzeng, 2002; Perrucci et al., 2016). For a community to achieve resilience, social equity must be promoted through public policy and resource allocations. In this research the National Academy of Public Administration's definition of social equity is accepted and defined as:

> "The fair, just and equitable management of all institutions serving the public directly or by contract; the fair, just and equitable distribution of public services and implementation of public policy; and the commitment to promote fairness, justice, and equity in the formation of public policy." (Berry-James et al., 2021)

To achieve levels of community resilience to reduce displacements and duration, the desired social equity between impacted communities is achievable through dynamic disaster plans and programs to efficiently allocate resources based on updated need and add transparency to the process to ensure accessible communication pathways between stakeholders in disaster scenario (Ahmed, 2015; Norris et al., 2008; Walsh, 2007). The absence of social equity during Hurricane Katrina, due to conflicting policy goals for rapid recovery, safety, betterment, and equity, led to an estimated decade long recovery for certain communities (Kates et al., 2006).

This research presents the inclusion of drone imagery capturing visual damage and recovery to achieve the desired social equity levels through dynamic relief funding which is updated on a time-series collection of imagery. The use of drone imagery (i.e., UAV imagery) has shown potential for damage mapping and assessment, however, research has failed to solve coordination and scalability issues and reference decision makers for applicability of the imagery

(Greenwood et al., 2020; N. Kerle et al., 2019; Norman Kerle et al., 2019). There are also areas of drone implementation which are understudied including, but not limited to, the recovery evaluation and the assessment of social equity between communities. Overall these gaps within past research combine to create a significant absence in the usefulness and applicability of drone imagery in legislative/policy maker context (Calantropio, 2019; Estrada & Ndoma, 2019; Ghaffarian & Kerle, 2019). This research proposes, and supports with stakeholder perspectives, that an initial damage evaluation using visual cues, including but not limited to structural damage (i.e., cracks or broken components), missing roofing/housing materials, scattered debris, and condition of yard/property enables the potential prioritization of neighborhoods based on devastation level. Similarly, the survey analysis shows potential for using drone images to enable iteratively updated recovery progress estimations using visual cues of recovery, including but not limited to number of blue tarped roofs, progress of debris clean-up/street cleaning, activity in the area (Civilians, laborers, and volunteers), and condition of yard/property that will enable the prioritization of current methods (expert visitation and written reports) or increased (or decreased) resource allocation due to estimated levels of recovery.

This research suggests a novel solution using drone imagery for evaluating residential property damage and estimating recovery progress which can reduce uncertainties in risk management models such as the ones described in Chapters 3 and 4 of this dissertation. The image evaluation methodology utilizes visual aspects of damage and recovery in drone imagery which is grounded by the perspective of key organizational stake holders. The initial images of damages and the iterative images of recovery progress have their effectiveness demonstrated with a designed survey with key stakeholders from the case study. A case study of the United States’ 2020 Middle Tennessee tornado is selected to illustrate the methodology and validate the approach with stakeholder participation from government and non-government organization (NGO) decision makers.

The outcome of this research presents a framework to collect the drone imagery, identifies the useful visual aspects of devastation and recovery, presents a methodology to evaluate property damage and recovery rates during disaster scenarios using the drone imagery, and supports the theoretical methodology with survey data. The proposed methodology provides United States’ federal and state governments a groundwork for expansion of drone image analysis of disasters and the ability to adopt a transparent and dynamic relief/response resource allocation that can assist in ensuring the social equity between communities. The remainder of this chapter is organized as follows: a review of background literature on traditional disaster evaluation methods and historical usage of drone imagery in evaluation in section 5.2, section 5.3 presents the proposed methodology, section 5.4 details the case study and validation methodology, section 5.5 organizes the results from the analysis, with the discussion and conclusion in sections 5.6 and 5.7, respectively.

5.2 Background

5.2.1 Drone Imagery as an Evaluation Tool

Prior research for visual based post-disaster evaluation evolved with, and is constrained by, technology availability, however, the overarching goal is always to create a rapid evaluation method.

During large-scale disasters such as riverine, coastal, or tsunami driven flooding, satellite imagery has proven efficient and effective in identifying regions impacted (Brown et al., 2008; YAMAZAKI & MATSUOKA, 2007). The effectiveness of satellite imagery becomes limited for structural and property damage assessments, with even high-resolution satellites failing to provide the required level of detail (Bendea et al., 2008; Norman Kerle et al., 2005). In response to the insufficient detail in satellite imagery, airborne visuals were being investigated as early as 2005 for their potential utilization for rapid, near-real time, post-disaster damage assessment. A notable study presents a novel assessment methodology which utilizes uncalibrated oblique airborne imagery (i.e., imagery commonly first available and captured by law enforcement or news agencies) and three case study examples, to effectively show the potential of texture-based segmentation for the identification of damage levels and groupings (Norman Kerle et al., 2005).

With fixed-wing unmanned ariel vehicle (UAV) technology becoming more common in the early 2000s, researchers began developing methodologies for post-disaster assessment using the low-cost, higher resolution, imagery and mappings from fixed-winged UAVs. In 2008, a study utilizes early UAV technology combined with satellite imagery for post-disaster assessment, however, the implementation suffered due to reduced positioning accuracy with the automated navigation (Bendea et al., 2008). As time progressed, UAV imagery was overlayed or combined (i.e., structure-from-motion method) to create 3-D visuals to compete with the Light Detection and Ranging (LIDAR) and 3-D Geographical Information System (GIS) mapping technologies which struggle with feasibility (e.g., difficult to implement and costly) for rural areas; however, studies from 2014 show fixed-wing UAVs were unable to identify or estimate building damage and suffered from insufficient details which can be partly attributed to poor accuracy (Park & Jung, 2014; Sui et al., 2014; Yamazaki et al., 2017).

Modern UAVs (i.e., quadcopter drones and updated fixed-wing) paired with contemporary image analysis techniques re-establishes the potential of UAV imagery for post-disaster damage assessment. Studies in 2015 acknowledge a gap within research, being the absence of detailed images from quadcopter UAVs in post-disaster assessment, and presents support for the effectiveness of building's façade and roofing damage assessment and evaluating response efforts (e.g., logistics, transportation of goods, timeliness of relief) (Boccardo et al., 2015; Fernandez Galarreta et al., 2015). These studies in 2015 make progress in making drone imagery applicable to disaster assessment with computerized methods, however, they vaulted a necessary step and left a significant gap within research regarding the applicability and opinion of stakeholders/decision makers (i.e., the ones utilizing the drone imagery to make decisions) on the potential usefulness of the imagery. The most recent studies also fail to fill this gap within research and instead explore how to automate the analysis of the imagery within the High-Resolution UAV Dataset (HRUD), however, the researchers acknowledge that a UAV's top-view image style may hide a significant portion of the building's damage and applicability scenarios (Chowdhury et al., 2020; Chowdhury & Rahnemoonfar, 2021). This research aims to fill this gap regarding the potential applicability of drone imagery with regards to disaster decision-making by directly eliciting stakeholder/decision maker perspectives to determine applicability and ability of the imagery to capture ranging situations and efforts (i.e., damage, recovery, equity).

Another gap in the research for UAV imaging during disasters is the scalability of the methodology, which includes these key aspects of disaster type, altitude, area, UAV type, and geographic location. All five of these aspects uniquely impact the scalability of UAV imaging and they also intercorrelate. For example, a reservoir collapse is documented using UAV imagery and requires a significant altitude of approximately 100m to 250m for an area of 900 km^2. At this altitude and for that size area analysis, a fixed-wing UAV would be the best option for implementation and the type of analysis would be flood damages (e.g., flooded farmland, levee leakage, collapse distance) (Pellicani et al., 2019). When documenting a smaller area using UAV imagery for higher building detail, for example an area size of 6.85 km^2, the optimal altitude is noted to be 80m. To cover this region at a smaller altitude, a network of UAVs is required and fast deployable UAV launching systems are one solution.(Castellanos et al., 2019). One study proposes a mutli-UAV system which consists of fixed-wing and/or quad-copter drones that can be launched from a fixed (i.e., ground or building attached launching platform or mobile deployment center (i.e., a pickup truck with design launching center on back) by a single individual and self-navigate with the global positioning system (GPS) (Erdelj et al., 2017). This research aims to solve this gap and reduce the ambiguity regarding drone deployment with a general framework detailing iterative drone (i.e., quad-copter UAVs) image collection from an altitude of 60 meters for multiple impacted communities by a single individual. The iterative collection will enable a time-series comparison for initial damage evaluations, recovery progress estimations, and evaluation of social equity. By utilizing this framework, the scalability issues for drone image collection are reduced by providing guidance for selecting the focus area, recommending a universal altitude, requiring a quad-copter drone, and suggesting site visit frequency.

The final gap this work attempts to fill is the identified lack of coordination/communication in post-disaster UAV image collection and disagreement between organizations over the implementation of UAV data (Greenwood et al., 2020; N. Kerle et al., 2019; Norman Kerle et al., 2019). This research aims to solve this lack of coordination and disagreement on implementation of the imagery with an established post-disaster data collection framework and consensus from key government and non-government organizations on the applicability of the collected imagery for analysis. This research explores initial damage evaluation, recovery estimation, dynamic relief appropriation, and social equity (i.e., the fair, just and equitable distribution of public services) between different communities; ultimately, suggesting drone image collection to be added to FEMA training courses and alterations to the current FEMA Preliminary Damage Assessment Guide which is required to declare a federal disaster declaration in the United States.

5.2.2 FEMA Preliminary Damage Assessment Guide

The Preliminary Damage Assessment Guide (PDA Guide) became effective in June of 2020 and details how emergency management officials must conduct the preliminary damage assessments in the United States following a disaster (FEMA, 2021b). The PDA Guide is utilized by FEMA and any state, local, tribal, and territorial (SLTT) government organizations to evaluate the post-disaster impact and damage magnitudes with the goal of verifying/supporting the need for a disaster declaration. During this process, the government organization estimates the corresponding unmet needs to individuals, the public sector, and communities from the impact and damage evaluation (FEMA, 2020a).

The timeline for the PDA Guides assessment period varies depending on scenario and a one-size-fits-all approach is acknowledged to be unrealistic, instead the guide recommends a standard process which can be adjusted based on an events requirement. The standard procedure ensures efficient federal assistance and sets the following steps for a successful disaster declaration:

1. Disaster occurs
2. Local or tribal government identifies damage
3. State, local, or territory verifies damage
4. State, tribal, or territorial government requests a joint PDA with FEMA
5. FEMA and state/tribe/territory validate damage
6. Validated damage informs request and recommendation for disaster declaration.

When attempting to include continued/additional relief funding from FEMA's Individual Assistance (IA) or Public Assistance (PA) program, SLTT government organizations need to conduct an "Initial Damage Assessment" (IDA). When SLTT organizations IDAs use multiple documentation methods and may request technical assistance (i.e., GIS analysts, program specialists, etc.) from FEMA. The resulting IDA must include visual confirmation of damage for validation of estimated damage magnitudes and communal impacts. During this process site visits and assessments are conducted to view actual damages, collecting data and photographs for prioritizing the most significant damage first (FEMA, 2020b).

5.3 Methodology

This research proposes a novel and holistic approach for evaluating visual property damage and estimating progress towards recovery in communities using iterative collections of drone imagery and decision maker perspectives. The utilization of drone imagery as pictorial evidence during various dates and stages of the disaster enables this approach to address the efficiency and transparency of damage evaluation, iterative updating for dynamic need-based relief, and ensures equity in resource allocation between communities. An elicitation of key stakeholders then occurs to verify the findings, ensuring the images applicability and accuracy of the conclusions (i.e., drone imagery enabled dynamic relief and helps to ensure social equity). Figure 23 is a diagram of the research approach comprised of iterative site visits for data collection, image organization and composition, and image analysis and review for evaluation of damage and recovery progress.

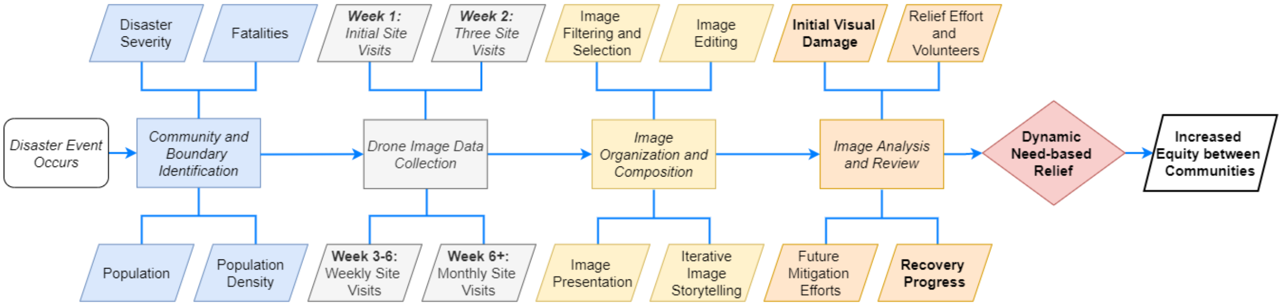


Figure 23: Methodology Flow Chart of Drone Imagery Evaluation

This flow chart begins with a rounded square representing the starting process, an occurrence of a disaster event. Each parallelogram represents a consideration or commitment to realize the final output of increased social equity. The rectangles are processes in the methodology, and the outcome of dynamic need-based relief decisions is a diamond. This diagram describes the methodology's implementation for this case study; however, the method would remain the same when applied to unique disaster scenarios.

The first step of this methodology is to identify communities of interest for comparison. The process for identification of these communities will vary from location and event; however, certain attribute consideration ensures comparability between selected location, including, but not limited to, aspects of the disaster (severity, damage, etc.), similarities between population/population density, and geographic location.

Once the event occurs and the locations are identified, the most important step of this methodology, the drone image collection, begins. An iterative collection schedule must be established and will require adjustment depending on disaster and location. This research suggests one initial site visit at each location within the first week of the event and a constant altitude of 60 meters for all residential imagery. These initial site visits require the most substantial commitment of time and help determine the transportation logistics in the disaster area, establish a preliminary analysis of the scale of devastation, and setup the drone take-off locations and the focus areas of the images. These drone take-off locations and focus areas will be utilized throughout the entirety of this research; therefore, if chosen incorrectly or hastily the entire analysis is jeopardized. The iterative collection continues from these determined take-off locations for 6 months (this will vary based on disaster, where transitions to recovery can range in duration) after the event to capture the preliminary damage, relief efforts, and recovery progress. The frequency of site visits and drone image collection are expected to reduce as time passes from the disaster event occurrence due to a decrease in relief activity and time-consuming recovery projects which do not deem frequent visits necessary, this reduction and site visit schedule is detailed in Figure 23.

These steps and methodological framework were applied to the 2020 Tennessee Tornado; however, the steps are universal for evaluating external disaster damages in future disaster events. Minor changes can be required to the framework depending on the disaster event (i.e., severe events like Hurricane Katrina may benefit from an image collection period longer then 6-months due to the extended access to relief funding), but this is a generalized framework which will be applicable for average severity events. The framework's image analysis portion will also vary in scope depending on the number of relevant stakeholders, preferred elicitation method (e.g., survey, interview, etc.) and is left generalized for future adjustment or automation. This research utilized a survey methodology for stakeholders in the surrounding area of the disaster event for the image analysis. This exploratory analysis uses the cross-comparisons between locations as the basis of the image analysis and verifies its functionality/effectiveness in a case study using stakeholder opinions of the imagery. Finally, the potential for dynamic need-based relief and identification of social equity concerns based on the image analysis is commented on by the stakeholders.

5.4 Case Study Verification

5.4.1 Hazard and Geographic Areas

The United States' post-disaster damage and recovery evaluations are the focus of this research. The types of applicable hazards are limited to those which most commonly cause visual damage to property including, but not limited to, tornadoes and hurricanes (i.e., this method evaluates visual wind damages, therefore, other types of disasters (e.g., flood, fire, chemical, etc.) would require an updated methodology due to differences in visual damages). In this research, the methodology is demonstrated by analyzing the damage and recovery from the 2020 Middle Tennessee, the two selected site locations of East Nashville and Mt. Juliet are detailed in Table 12.

Table 12: Justification for Case Study Locations

	East Nashville	Mt. Juliet	Source
County	Davidson	Wilson	(East Nashville Neighborhood in Nashville, Tennessee (TN), n.d.; Quick Facts: Mount Juliet, TN, n.d.)
Population Density	Urban	Suburban	
Approximate Population	60,000	37,000	
Category Tornado	EF-3	EF-3	(Bliss et al., 2020)
Fatalities	2	2	(WKRN, 2020)

For this research, the selected two locations, located in different counties, experienced similar tornado strengths. These similarities, and differences in geographical location and political management, enable a cross-comparison between the resource allocation and relief/recovery processes. In addition, the varying population density allows for an investigation into the historical dilemma fewer resources in rural communities and faltering equity between more rural and more urban communities (Jerolleman, 2020).

A 6-month span of relief and recovery processes in the aftermath of the event is considered for the analysis to provide an iterative and representative view of the efforts. This research limits the analysis to the first 6 months after a disaster occurs because funding for assistance and relief is most readily available to the recovering communities (Olshansky, 2005). For a more extensive approach, this window of evaluation can be expanded to the entire recovery period (i.e., a range of months to years depending on disaster) but to do so, requires a significant investment of resources. In addition, this outlined case study approach is modifiable to fit other contexts, including but not limited to, types of disasters (if they cause visual damage to structures or property), geographic areas, and social and economic factors between locations.

5.4.2 Stakeholder Elicitation

This research utilizes stakeholders' perspective to verify the effectiveness of the methodology at evaluating initial property damage and estimating recovery progress for each location, and implicitly identifying discrepancies between the two case study locations. The key stakeholders elicited are those with potential influence on impacted populations during disaster scenarios and are specifically from government agencies or NGOs. The survey is built around the collected, compiled, and composed imagery of the March 2020 Tornado, specifically, the case study locations of East Nashville and Mt. Juliet.

The survey analysis focuses on images depicting the initial impact from the tornado and the subsequent weeks/months. After presenting relevant background information, the survey questions serve to evaluate the success of the imagery at documenting property damage and recovery progress estimation, while identifying any potential social equity disparities. The survey is designed to require approximately 15 minutes to answer the 15 multiple choice questions and 1 short answer response. The objective of the survey is to answer the following research question and sub-questions:

- How effective is the imagery at evaluating the recovery progress and estimating the overall recovery with visual housing/property damage?
  - Does the imagery enable **dynamic**, continually updated based on need, relief appropriation?
  - Does the imagery reveal **social equity** concerns in/between neighborhoods?

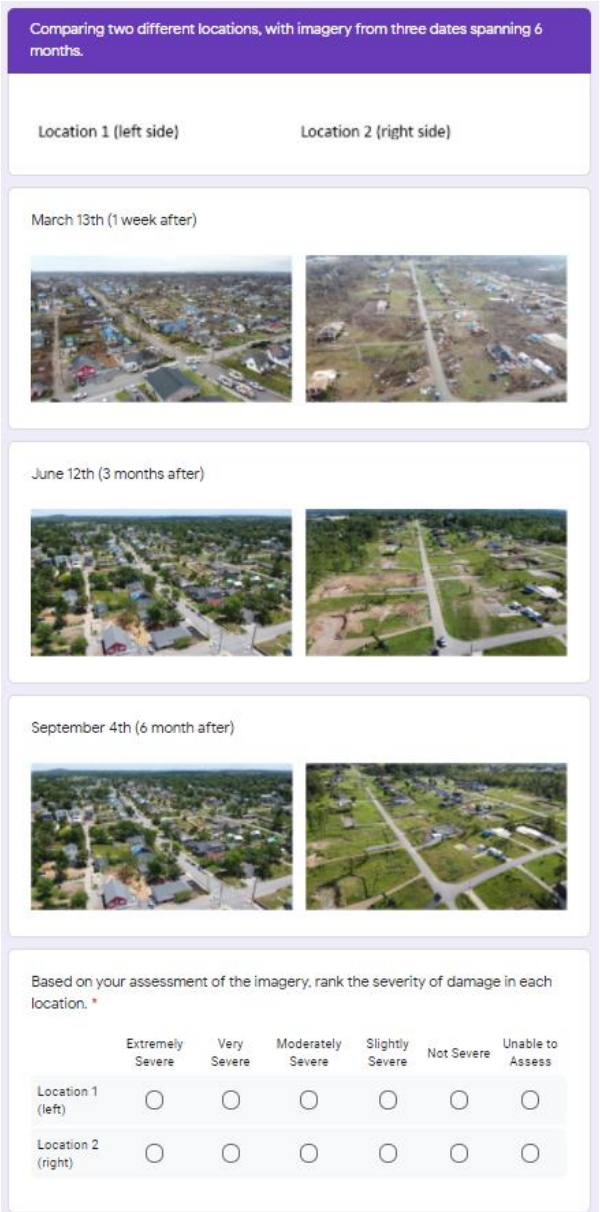
Figure 24 presents a sample question from the survey which includes wording, format, and style of the questions. This example question presents a multiple-choice question for the respondent to rank the severity of damage in each location. If the results from this question show consensus among stakeholders, it would be a successful first step towards enabling dynamic relief. In addition, the figure shows an example of the survey's iterative organization of the images and setup of the corresponding questions. The iterative structure of the images as seen in Figure 24 enables a direct cross-comparison of the timeframes from the two locations; this comparison is limited to two locations but can be extended with more locations in future studies using the same iterative collection schedule.

The elicitation for the survey focuses on government organizations and non-government organizations (NGOs) stakeholders from the middle Tennessee Region. Table 13 details the number of targeted elicitations and response rate for each stakeholder group.

Table 13: Survey Elicitations and Response Rate

Stakeholder	Number Targeted	Response Rate
Government	26	38%
NGO	26	27%

There was a total of 52 targeted middle Tennessee stakeholders and 17 responses, resulting in a combined response rate of 33%. For this research, the focused scope on the singular event consideration and focus on middle Tennessee region stakeholders confirms that the number of respondents and response rates of approximately 30% are sufficient for each stakeholder category.



Comparing two different locations, with imagery from three dates spanning 6 months.

Location 1 (left side)

Location 2 (right side)

March 13th (1 week after)

June 12th (3 months after)

September 4th (6 month after)

Based on your assessment of the imagery, rank the severity of damage in each location. *

	Extremely Severe	Very Severe	Moderately Severe	Slightly Severe	Not Severe	Unable to Assess
Location 1 (left)	○	○	○	○	○	○
Location 2 (right)	○	○	○	○	○	○

Figure 24: Example Image Analysis Question and Setup

5.5 Results

The elicited responses are organized and analyzed in three unique thematic categories to support the main goals of this research; these thematic categories include Property Damage Evaluation, Recovery Progress Estimation, and Social Equity in Relief.

5.5.1 Property Damage Evaluation

An initial damage evaluation is the first priority when evaluating a post-disaster scenario. The initial damage evaluation helps determine the first phases of disaster management including, but not limited to, emergency funding, service allocation, and volunteer's focus. Figure 25 presents the damage estimations for each location, organized by stakeholder type, on a 1 (not severe) to 5 (extremely severe) scale.

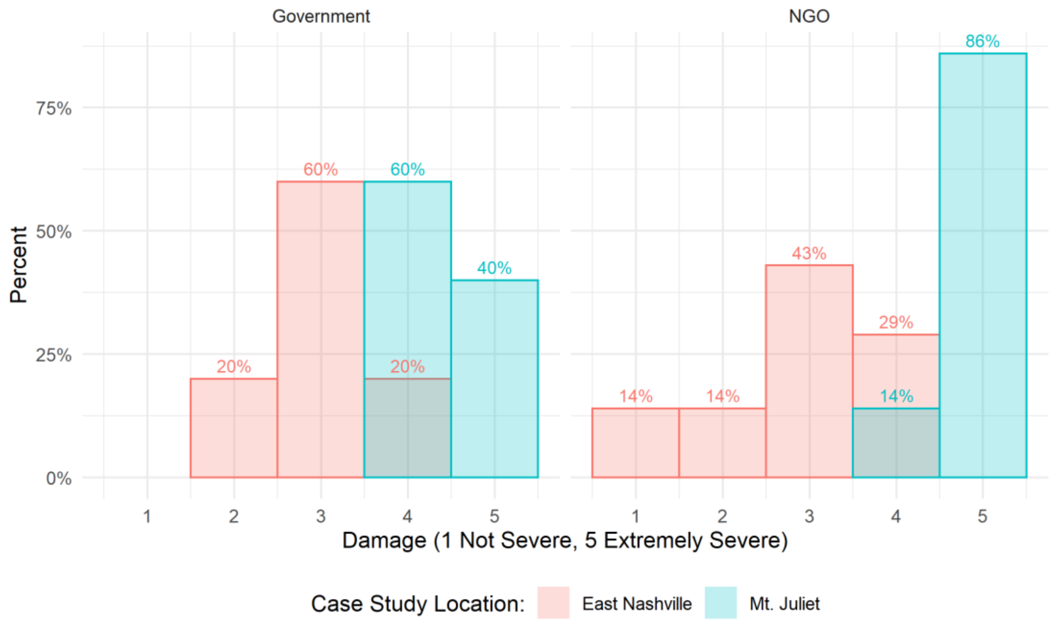


Figure 25: Initial Property Damage for Location by Stakeholder Type

There is a clear consensus between both government and NGO stakeholders that Mt. Juliet experienced a greater level of damage compared to East Nashville; however, there is slight disagreement by NGO stakeholders regarding the amount of damage existing in East Nashville. One possible explanation for this slightly larger disagreement for East Nashville can be contributed to the higher population density in the region adding uncertainty with a quick evaluation. The speed of the initial damage evaluation is further investigated in Figure 26.

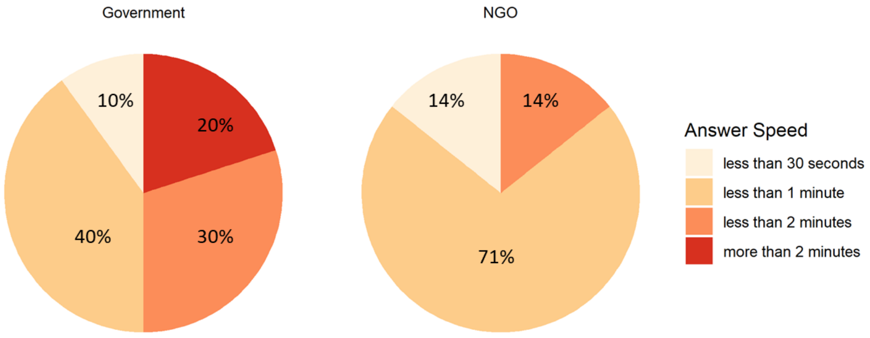


Figure 26: Time Commitment for Initial Property Damage Evaluation by Stakeholder Type

These pie charts organize the percentage of stakeholders which fit into each time increment (i.e., answer speed) which ranges from less than thirty seconds to greater than two minutes. The upper bound for answer speed is set to two minutes to encourage the stakeholder's quick evaluation and to ensure the method's applicability for large scale implementations which require efficiency. The time breakdown by stakeholder reveals that 100% NGO stakeholders took less than one minute to conduct the initial damage evaluations, compared to only 50% of the government stakeholders. This difference in speed, paired with the level of agreement in the stakeholder groups, suggests greater agreement will be achieved with a mandated two-minute evaluation period.

5.5.2 Recovery Progress Estimation

After the initial damage evaluation and the immediate relief provided to the impact areas, the recovery estimation is the most informative metric for determining continued relief funding. A significant portion of recovery level is determined by the progress in repairs (e.g., blue roof installation, roof re-shingling, siding repair, etc.). Figure 27 compiles the progress in visual repairs for each location.

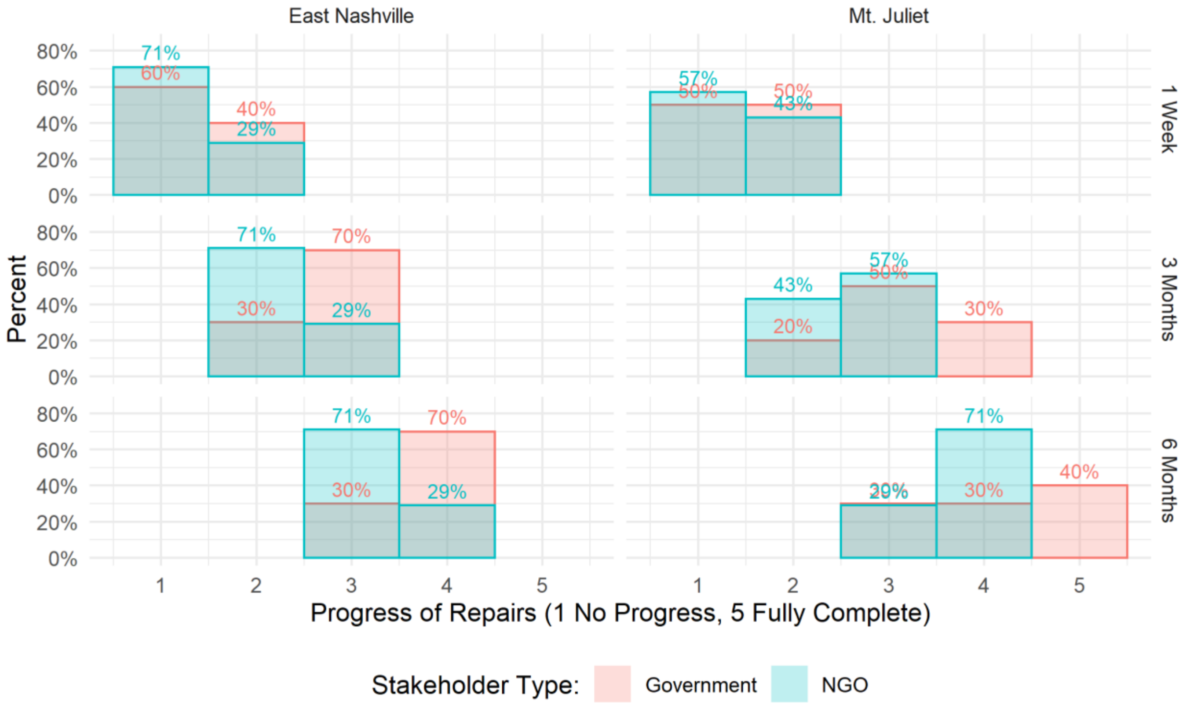


Figure 27: Progress of Visual Repairs in Each Location for a Set of Months

This figure compiles the elicited responses from stakeholders regarding the progress of repairs for three unique increments (i.e., 1 week, 3 months, and 6 months). On the y-axis and directly labelled above the bars are the percentages of stakeholder perspective for the specified increment of repair progress. In the first week, the progress of repairs at each case study location is indistinguishable. As the recovery enters its third month, Mt. Juliet takes a clear lead in repair progress according to the stakeholders and this same trend continues into the final six-month evaluation period. These results confirm stakeholders are confident and agree on their evaluations of repair progress for each case study location, however, the progress of repairs is only a singular metric for recovery progress so further investigation is required. Figure 28 presents a comparison in recovery progress between the two case study locations (i.e., which location, East Nashville or Mt. Juliet, is recovering faster).

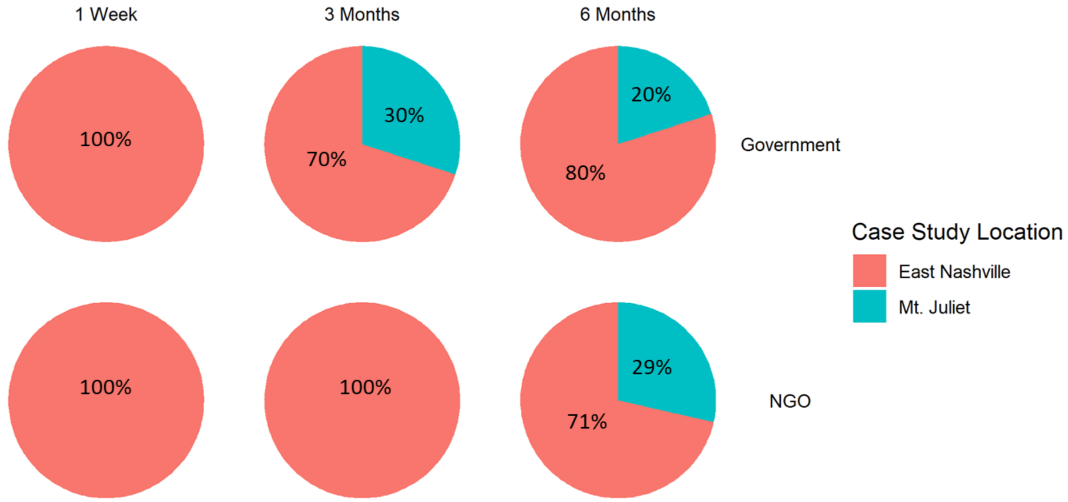


Figure 28: Percentage of Stakeholder Agreement on which Case Study Location is Most Recovered

In the first week after the tornado, all stakeholders agreed that East Nashville made the most progress in recovery; however, this may be attributed to the lesser damage in East Nashville as determined in Figure 25. At the three-month period Mt. Juliet's recovery begins to rebound. More specifically, this location makes significant progress in roofing repairs, yard maintenance, and other visible property restorations which convinces 30% of government stakeholders that it is experiencing a more rapid recovery. More stakeholders begin to acknowledge the progress Mt. Juliet is making at the 6-month mark (i.e., 20% of government and 29% of NGOs believe Mt. Juliet is recovering faster), however, there is still a majority consensus that East Nashville is closer to fully recovering (i.e., 80% of government and 71% of NGOs believe East Nashville is recovering faster). The recovery progress at the six-month mark is further broken down in Figure 29.

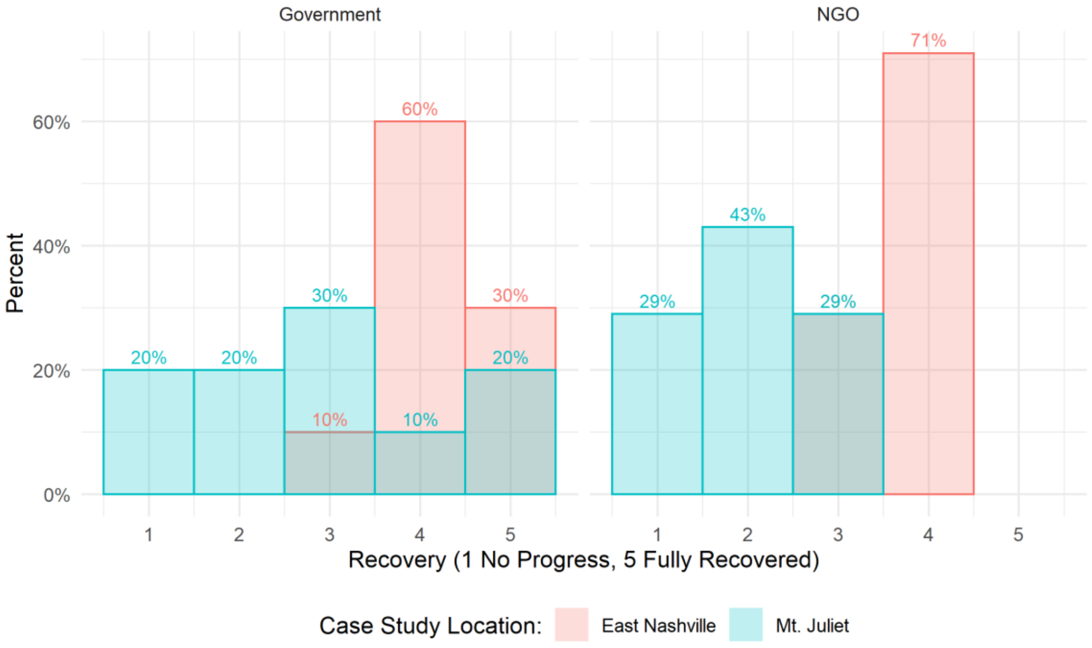


Figure 29: Six-month Recovery Progress Breakdown

The breakdown in recovery progress at the six-month period for each case study location shows that there is larger variation in the progress towards recovering in Mt. Juliet. One explanation for this disagreement in recovery progress for Mt. Juliet is the number of properties demolished and the lack of a definition in the survey regarding how demolished properties impacts recovery levels (i.e., help or hurt recover progress).

5.5.3 Social Equity in Disaster Management

5.5.3.1 Dynamic Relief Assistance

In support for dynamic, iteratively updated, disaster relief, this research breakdowns images (i.e., separates into four quadrants) from East Nashville and Mt. Juliet during the post-disaster recovery period and requests the stakeholders to identify the regions which require greater assistance. To do so, an image from East Nashville and Mt. Juliet is broken down into four regions (i.e., the four Cartesian quadrants) to identify which quadrant of the community in the image requires greater assistance. Figure 30 presents the percentage of stakeholders who identified each quadrant of East Nashville as requiring greater assistance.

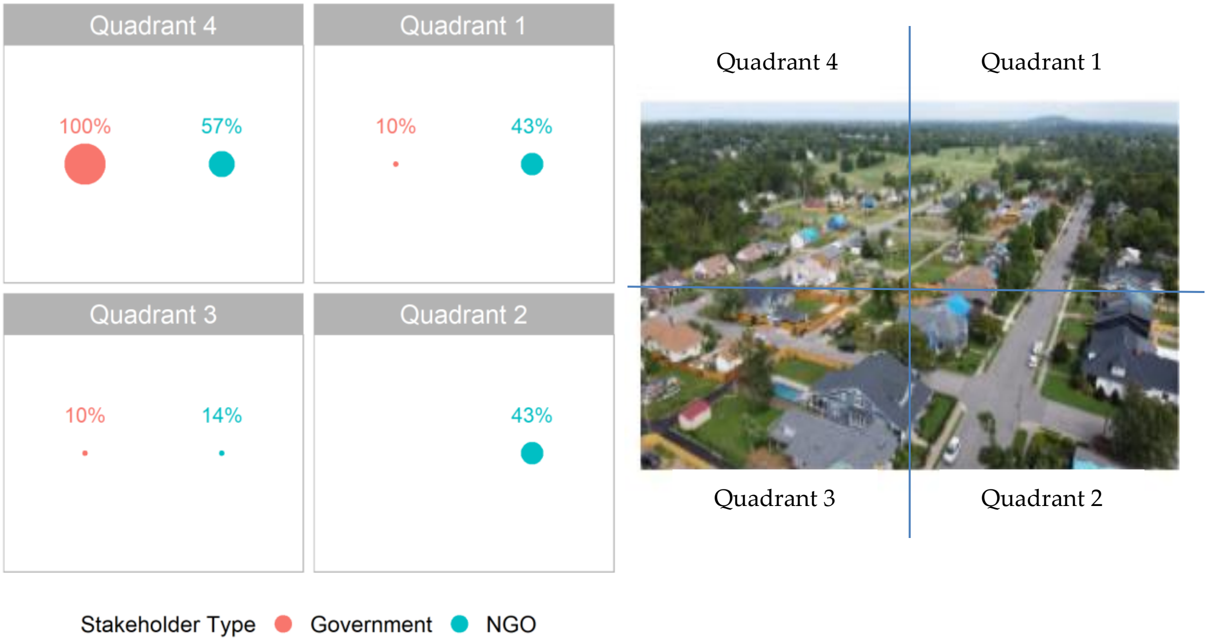


Figure 30: East Nashville - Which Quadrants Require More Assistance
On the right is the image which is broken down into four quadrants for the stakeholders, and on the left is the plot showing the percentage of stakeholders which believe the quadrant needs greater assistance in recovering.

The stakeholders most confidently agreed that quadrant four required greater assistance, and there is no conclusive agreement or significant assistance required in any other quadrant of the imaged portion of East Nashville. The identified quadrant is expected and is the desired outcome for this survey question, as it still contains various type of visual property damages, while the other quadrants are fully recovered or contain only minor roofing damages. This same process and style of figure is present in Figure 31 for Mt. Juliet and represents the percentage of stakeholders who identified which quadrants require greater assistance.

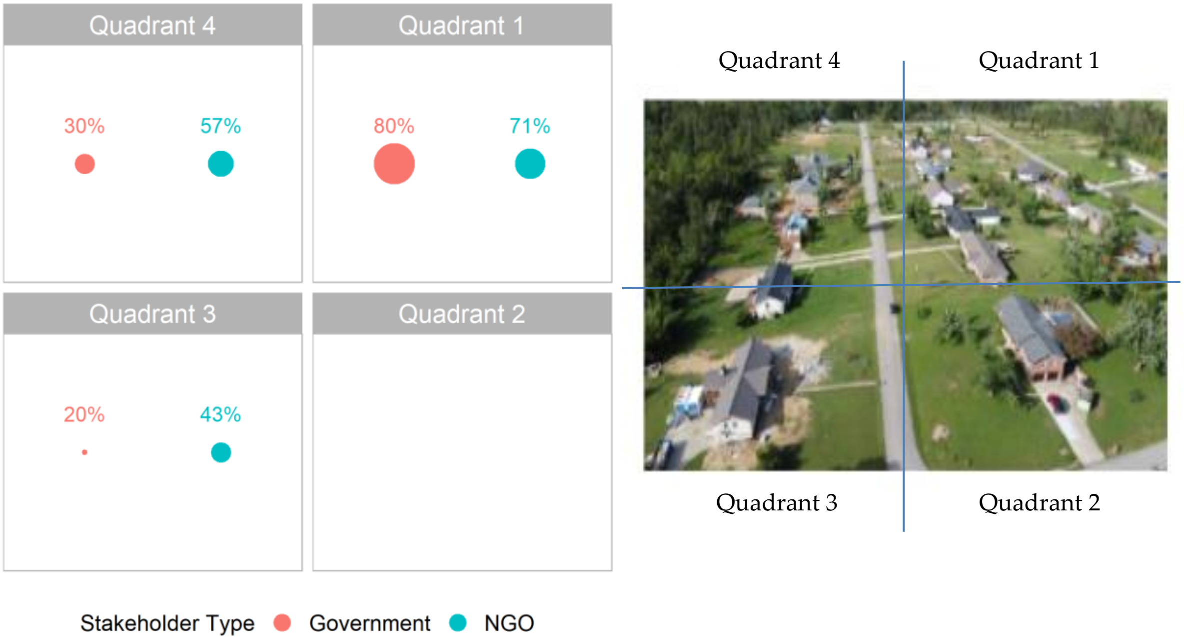


Figure 31: Mt. Juliet - Which Quadrants Require More Assistance
On the right is the image which is broken down into four quadrants for the stakeholders, and on the left is the plot showing the percentage of stakeholders which believe the quadrant needs greater assistance in recovering.

For Mt. Juliet, the stakeholders most confidently agreed that quadrant one required greater assistance with potential agreement for greater assistance in quadrant three and minimal agreement in four. In addition, the stakeholders can identify and agree that quadrant two does not require greater assistance. These results are the desired and expected outcome from this survey question because quadrant one of this Mt. Juliet neighbourhood experienced extensive damage and required the demolition of numerous properties; while quadrant four is able to rebound faster with new construction but several properties still struggle to rebuild or were required to demolish the structure due to the extensive damage. To evaluate the efficiency of the survey method used for Figure 30 and Figure 31, the time commitment for evaluating the total of eight quadrants is presented in Figure 32.

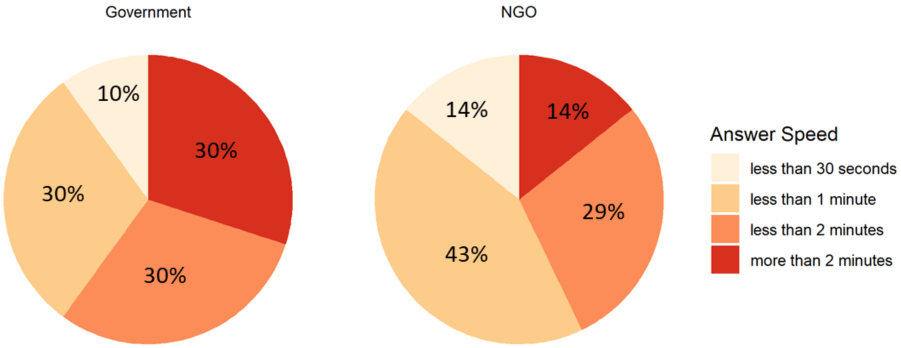


Figure 32: Time Commitment for Evaluating Regions for More Assistance by Stakeholder Type

Overall, 76.5% of stakeholders required less than two minutes to evaluate the two location's four quadrants, with only 23.5% of stakeholders requiring more than two minutes. Government stakeholder required more time than NGOs, with 60% of government stakeholders requiring more than one minute in comparison to only 43% of NGO stakeholders.

5.5.3.2 Economic and Social Impacts

Quantifying the level of social and economic impacts is one method, outside of evaluating future amount of disaster assistance, which can ensure the social equity of recovering communities. The holistic and accurate representation of impacts caused by disasters, especially social impacts, has proven difficult in prior studies on aspects of disaster management (Andres & Valencia, 2016; Omar El-Anwar, 2013; Huang & Hosoe, 2017). Figure 33 represents the stakeholder's perspective of these impacts.

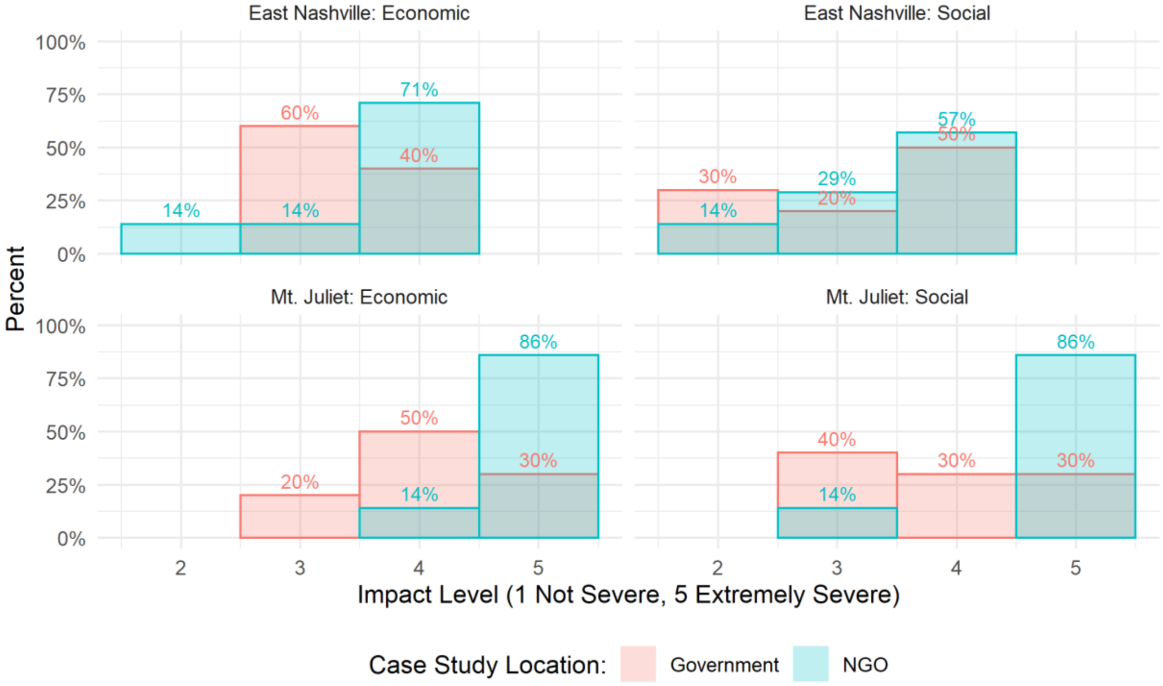


Figure 33: Economic and Social Impacts from the Tornado in Each Case Study Location

The consensus, regardless of the variation in responses in each stakeholder group, suggests that Mt. Juliet experienced larger economic and social impacts. Non-government organization stakeholders show more agreement regarding the impacts compared to government stakeholders; however, the variance between responses hinders the conclusiveness of any assessments.

5.6 Discussion

The proposed methodology using drone technology and recent technological advances solve various scalability issues (e.g., focus area, altitude, drone type, visit frequency, cost, etc.) which enables local, state, and federal government agencies or NGOs to effectively utilize drone imagery for holistic disaster evaluation with minimal resources.

This study demonstrates with Figure 28, Figure 29, and Figure 33 how to revolutionize disaster management with iterative drone imagery for recovery progress evaluations and corresponding dynamic relief. The dynamic relief can be implemented during each phase of the disaster scenario and at multiple levels including, but not limited to, NGOs determining and iteratively updating where volunteering/donations will be most effective and phased federal or state funding allocation decisions rather than larger sum appropriation. Furthermore, the responses from NGO and government stakeholders in Figure 30 and Figure 31 indicates the potential to pinpoint quadrants of need (rather than macro scale community need) to assist local governments in allocating federal and state funds. These macro- and micro-scale aspects of dynamic relief will ensure social equity between recovering communities by providing additional resources based on the communities/areas updated need and progress towards fully recovering. To ensure the success of dynamic relief and depending on disaster type, this study recommends a minimum of weekly site visits for the first six weeks before transitioning to monthly site visits. Future research is required to determine how site visit frequency should fluctuate with disaster severity to ensure optimal utilization of resources during implementation (i.e., too many site visits waste human and financial resources, while too few site visits can be detrimental to the success of the methodology). The methodology also proves to be time efficient, with damage evaluation between the two case study locations requiring approximately 88% of stakeholders less than 2 minutes to identify Mt. Juliet as having more severe damage. Although, determining regions of communities needing additional assistance took longer with approximately 76% of stakeholder requiring less than 2 minutes. These time commitments do suggest that the methodology is implementable for large-scale disaster and image collections; however, automation of the image analysis would benefit the methodology's efficiency, and potentially, accuracy due to the reduction of human error in evaluation.

A limitation which may impact the stakeholder supported utilization of this methodology for multiphase disaster evaluations (e.g., the evaluation of damage, recovery progress, and verification of social equity at various timelines) is the ability of drone imagery to only capture external damages. This limitation in UAV technology has restricted UAV imagery to damage mapping for decades, however, this research suggests broader potential for UAV technology (i.e., drone imagery) with its incorporation into FEMA's Preliminary Damage Assessment guide. If this research's proposed methodology is combined with FEMA's PDA guide, it would assist local, state and federal government agencies in identifying, verifying, and validating the damage when seeking relief funding and a federal disaster declaration. By utilizing drone imagery in the FEMA guided assessment, the process would be streamlined and require less resources to obtain photographic evidence (i.e., one person can quickly document damages at multiple impact locations in a single day using low-cost drone technology) and the same set of imagery can be utilized to verify and validate the identified/reported damage.

In addition to dynamic appropriation, this study explores the estimated social/economic impacts as a metric to evaluate and ensure social equity during disaster recoveries. The social and economic impacts from the disaster are estimated by the stakeholders using only drone imagery which suggests that Mt. Juliet compared to East Nashville has experienced larger social and economic impacts due to the Tornado. These perspectives on social and economic impacts do include discrepancies in responses which require further investigation for reduction. Initial pathways of investigation to achieve this desired reduction can be specialized training in evaluating impacts with drone imagery, computerized evaluation, inclusion of supplementary information (e.g., resident statements, interviews, on-ground photography), or elicited stakeholder restrictions (e.g., a minimum required work experience, education, and disaster involvement). Nonetheless, the initial success of the imagery at transcribing these impacts visually does support future research to determine the applicability/effectiveness of iteratively updated social and economic impact evaluation (whereas this research only investigates initial impacts).

5.7 Conclusion

This research shows the potential of UAV imagery's positive impact on current disaster management methods (i.e., integration with current FEMA PDAs) and exposes future beneficial policy implementations (e.g., dynamic relief and ensuring social equity). The results compile responses from key stakeholders involved during the 2020 Middle Tennessee Tornado and presents a synthesis of the responses for analysis. The survey results suggest UAV/drone imagery is an effective solution for residential property damage evaluation, recovery period assessment, relief requirement estimation. In addition, the results suggest more information is required to ensure accuracy in quantification of economic and social impacts, however, these occupant impacts do not affect uncertainty for initial housing displacement which is based on property damages and only in-directly impacts duration of displacement through community resilience (i.e., reduced economic and social impacts enable a faster resume of pre-disaster daily activities which are essential to higher levels of resilience). Therefore, this methodology can successfully reduce the uncertainty and minimize the assumptions for inventory management models.

While the research focuses on determining UAV imagery's applicability in disaster management for a case study, the results are relevant for other disaster types and scenarios. An opportunity for expansion of this research would be a redesign of the methodology for social and economic impact evaluation, due to the increase in response variance between stakeholders from using a majority of high-altitude imagery which lacks appropriate ground level detail. Further research will also be required to automate the applicable image analyses, which are validated by this research through the survey analysis, to reduce the methodologies reliance on human evaluation. Once the methodology is automated, the initial property damage values can be quantified immediately for inventory management modeling.

CHAPTER 6, SYNTHESIS AND CONCLUSIONS

As the world population continues to grow and disasters become more frequent and devastating, temporary housing will increasingly be a critical aspect of disaster response and recovery (Opricovic & Tzeng, 2002; Perrucci et al., 2016). The increased frequency and the enlarged number of displaced peoples will require pro-active management of temporary housing through a series of novel designs, decision-making methodologies, and optimization models for temporary housing to ensure the safety, wellbeing, and ability to recover. This research makes progress by first identifying a main gap in the literature regarding the pro-active management of temporary housing units (e.g., unit selection/design considerations and pre-stock/inventory capacities) through an extensive literature review and presents a synthesis of methodologies to fill the gap.

A first step of proactively managing temporary housing implementation is to re-evaluate the temporary housing unit design to be implemented. A multi-criteria decision model using stakeholder input is created to evaluate various temporary housing unit designs for a set of disaster scenarios. This type of multiple criteria modeling enables a re-evaluation of current housing methods (i.e., evaluate the range of pros and cons between designs and unit types) and a further consideration of cultural requirements due to the stakeholder participation. In a case study where experts from the United States were elicited, the stakeholder opinions are consistent with MCDA results and recommend the Manufactured Home (i.e., Katrina Cottage) for all U.S. based allocation (i.e., States and territories) and the HHI Shelter for humanitarian efforts. These multi-criteria decision model results enable preemptive planning in the United States that reduces supply chain ambiguity in advance of a disaster and is applicable for countries worldwide with updated stakeholder participation.

Once the government or disaster response agency determines the type of temporary housing unit design which best satisfies their displaced population needs, the authoritative organization must then determine purchasing processes and potential demand. This dissertation presents a newsvendor model which is classically utilized in retail/industrial inventory management situations as the next step to achieve pro-active management of temporary housing. Utilizing the THU design determined to be the most preferred by United States' stakeholders and MCDA, the Monte-Carlo driven newsvendor model first simulates property damages for the states most prone to disaster displacements and temporary housing unit demand (i.e., an integrated simulation optimization method to manage the inventory of temporary housing units and balance resource allocation before and after a disaster). After making relevant adjustments to the simulated property damage values, estimates for THU requirements are modeled for each State and compiled for a nationwide demand. Finally, the expected losses from each option of potential stocking inventory are calculated and minimized to determine the optimal stocking inventory to hedge for the simulated future disaster events.

The largest source of uncertainty within this synthesis of methodologies (i.e., MCDA to newsvendor) is the utilization of property damages for estimating the THU requirement. Due to a lack of available data, this research utilized property damage which did not specify between type of property (e.g., residential, commercial, etc.) or ownership of property (e.g., public, private, etc.) and required assumptions regarding the amount of damage to be residential in rural/urban counties. These assumptions, if made incorrectly, can cause inaccuracies in the MCDA selected unit (i.e., property damage will determine displacement duration and alter the disaster scenario which stakeholders' reference) and eliminate the financial hedging ability of stocked inventories (i.e., inaccuracies of property damage led to inaccurate demands and under/over stocking of temporary housing units). To address this uncertainty, this dissertation explores a methodology for quantifying residential damages, estimating recovery progress/length, and ensuring equity if relief appropriation. The methodology consists of collecting iteratively updated drone imagery and focuses on two United States' case studies which experienced similar levels of devastation. A survey investigated the applicability of this methodology (i.e., iteratively update compilations of drone imagery) and elicited key stakeholders from the areas surrounding the case study communities. The survey results present a synthesis of the responses for analysis and suggest UAV/drone imagery is an effective solution for residential property damage evaluation, recovery period assessment, relief requirement estimation, and economic and social impact quantification; therefore, the methodology can reduce the uncertainty and minimize the assumptions for inventory management models.

Overall, this dissertation presents a synthesis of methodologies to enable the pro-active management of temporary housing and provides a novel solution to reducing the uncertainty which can hinder the contribution of this work if unresolved.

6.1 Areas for Future Work

Disasters occur and nations worldwide continue to struggle with temporary housing. The most evident area for future work is the expansion of the current analyses to a series of countries past this United States' case study. To expand these analyses, a more extensive list of global THU options (i.e., housing designed in the region to occupancy amount, quality of living, etc.) and relevant social vulnerability metric are required to ensure applicability for various nations. In addition, an expansion is required in cultural/social objectives for wide implication as novel temporary housing designs become more culturally specialized as seen in Japan after the Tōhoku earthquake. Also, an interesting analysis of value would between the different social vulnerability metrics in the United States (e.g., SOVI, SVI, etc.), where SOVI may capture more social aspects of vulnerability and alter the results from this current research which utilizes the CDC's SVI.

The next step in reducing the uncertainty in residential property damages for the newsvendor model is to automate the methodology using drone imagery and eliminate the reliance on key stakeholders (i.e., the human requirement). An automated methodology would enable rapid quantification and storage of residential property damages, of which will require calibration and validation, for inventory management modeling.

Outside the scope of this dissertation entirely but still relevant to the results, a redesign of manufactured temporary housing units is required to increase storage capacities of units and reduce maintenance costs to enable the larger stocking inventories suggested in this research at a lower cost.

6.2 Outlook and Closing Remarks

Housing is a universal requirement for all humans and the importance dates to our earliest cave dwelling existences. As natural disasters become more common and their severity increases, the impact on human life and housing will be amplified. A global collaboration in research and humanitarian efforts are required to mitigate the future housing impacts from the impending climate change.

REFERENCES

Abreu, M. C. S. de, & Ceglia, D. (2018). On the implementation of a circular economy: The role of institutional capacity-building through industrial symbiosis. *Resources, Conservation and Recycling*, *138*(June), 99–109. https://doi.org/10.1016/j.resconrec.2018.07.001

Ahmed, R. (2015). Discerning community resilience in disadvantaged communities in the context of violence and injury prevention. *Southern African Journal of Psychology*, *34*(3), 386–408.

Akdede, N. (2018). *EVALUATION OF TEMPORARY HOUSING UNITS WITH MULTI-CRITERIA DECISION MAKING METHODS* (Issue June) [MIDDLE EAST TECHNICAL UNIVERSITY]. https://movisa.org.mx/images/NoBS_Report.pdf

Allen, R. (2016). It's Idiotic': FEMA Mobile Homes' 6-Figure Price Tags Are Outrageous, Officials Say. *The Advocate*.

Amin Hosseini, S. M., De La Fuente, A., & Pons, O. (2016). Multi-criteria decision-making method for assessing the sustainability of post-disaster temporary housing units technologies: A case study in Bam, 2003. *Sustainable Cities and Society*, *20*, 38–51. https://doi.org/10.1016/j.scs.2015.09.012

Anandan, V., & Uthra, G. (2017). A modification of fuzzy TOPSIS based on distance measure. *International Journal of Pure and Applied Mathematics*, *116*(23 Special Issue), 109–114.

Andres, B., & Valencia, J. (2016). *Social and Economic Impacts of Natural Disasters*.

Arslan, H. (2007). Re-design, re-use and recycle of temporary houses. *Building and Environment*, *42*(1), 400–406. https://doi.org/10.1016/j.buildenv.2005.07.032

Arslan, H., & Cosgun, N. (2008). Reuse and recycle potentials of the temporary houses after occupancy: Example of Duzce, Turkey. *Building and Environment*, *43*(5), 702–709. https://doi.org/10.1016/j.buildenv.2007.01.051

Atmaca, N. (2017). Life-cycle assessment of post-disaster temporary housing. *Building Research and Information*, *45*(5), 524–538. https://doi.org/10.1080/09613218.2015.1127116

Avila, L., & Cangialosi, J. (2011). *Tropical Cyclone Report Hurricane Irene* (Issue October 2010).

Azhar, S., Carlton, W. A., Olsen, D., & Ahmad, I. (2011). Automation in Construction Building information modeling for sustainable design and LEED ® rating analysis. *Automation in Construction*, *20*(2), 217–224. https://doi.org/10.1016/j.autcon.2010.09.019

Bain, A., Shenoy, M., Ashton, W., & Chertow, M. (2010). Industrial symbiosis and waste recovery in an Indian industrial area. *Resources, Conservation and Recycling*, *54*(12), 1278–1287. https://doi.org/10.1016/j.resconrec.2010.04.007

Barakat, S. (2003). Network Paper Housing reconstruction after conflict and disaster.

Humanitarian Practice Network, *44*(43).

Bashawri, A., Garrity, S., & Moodley, K. (2014a). AN OVERVIEW OF THE DESIGN OF DISASTER RELIEF. *Procedia Economics and Finance*, *18*(September), 924–931. https://doi.org/10.1016/S2212-5671(14)01019-3

Bashawri, A., Garrity, S., & Moodley, K. (2014b). An Overview of the Design of Disaster Relief Shelters. *Procedia Economics and Finance*, *18*, 924–931. https://doi.org/10.1016/S2212-5671(14)01019-3

Bastian, N. D., Griffin, P. M., Spero, E., & Fulton, L. V. (2016). Multi-criteria logistics modeling for military humanitarian assistance and disaster relief aerial delivery operations. In *Optimization Letters* (Vol. 10, Issue 5). https://doi.org/10.1007/s11590-015-0888-1

Bendea, H., Boccardo, P., Dequal, S., Tonolo, F. G., Marenchino, D., & Piras, M. (2008). Low cost UAV for post-disaster assessment. *Proceedings of The XXI Congress of the International Society for Photogrammetry and Remote Sensing Beijing China 311 July 2008*, *XXXVII*, 1373–1380. http://www.isprs.org/congresses/beijing2008/proceedings/8_pdf/14_ThS-20/37.pdf

Berry-James, R. J. M., Blessett, B., Emas, R., McCandless, S., Nickels, A. E., Norman-Major, K., & Vinzant, P. (2021). Stepping up to the plate: Making social equity a priority in public administration's troubled times. *Journal of Public Affairs Education*, *27*(1), 5–15. https://doi.org/10.1080/15236803.2020.1820289

Beutel, A., & Minner, S. (2012). Safety stock planning under causal demand forecasting. *Intern. Journal of Production Economics*, *140*(2), 637–645. https://doi.org/10.1016/j.ijpe.2011.04.017

Birkland, T., & Waterman, S. (2008). Is Federalism the Reason for Policy Failure in Hurricane Katrina ? *The Journal of Federalism*, *38*(4), 692–714. https://doi.org/10.1093/publius/pjn020

Biswas, A. (2019). Exploring Indian post-disaster temporary housing strategy through a comparative review. *International Journal of Disaster Resilience in the Built Environment*, *10*(1), 14–35. https://doi.org/10.1108/IJDRBE-09-2018-0037

Blake, E., Jarrell, J., Rappaport, E., & Landsea, C. (n.d.). *U.S. Mainland Hurricane Strikes by State, 1851-2004*. NOAA. https://www.nhc.noaa.gov/paststate.shtml

Bliss, J., Thorson, M., & Padilla, R. (2020). *Tennessee tornadoes' path of terror*. Tennessean. https://www.tennessean.com/pages/interactives/news/graphics/march-2020-tornado-path-nashville-cookeville-putnam-tennessee/

Boccardo, P., Chiabrando, F., Dutto, F., Tonolo, F. G., & Lingua, A. (2015). UAV deployment exercise for mapping purposes: Evaluation of emergency response applications. *Sensors (Switzerland)*, *15*(7), 15717–15737. https://doi.org/10.3390/s150715717

Bolin, R., & Stanford, L. (1998). The Northridge Earthquake: Community-based Approaches to Unmet Recovery Needs. *Disasters*, *22*, 21–38.

Bostick, T. P., Holzer, T. H., & Sarkani, S. (2017). Enabling Stakeholder Involvement in Coastal Disaster Resilience Planning. *Risk Analysis*, *37*(6), 1181–1200. https://doi.org/10.1111/risa.12737

Brien, C. O. (1999). *Sustainable production — a new paradigm for a new millennium*. *61*, 1–7.

Bris, P., & Bendito, F. (2019). Impact of Japanese post-disaster temporary housing areas' (THAs) design on mental and social health. *International Journal of Environmental Research and Public Health*, *16*(23). https://doi.org/10.3390/ijerph16234757

Brown, D., Saito, K., Spence, R., Chenvidyakarn, T., Adams, B., Mcmillan, A., Platt, S., & Platt, S. (2008). Indicators for measuring, monitoring and evaluating post-disaster recovery. 6th International workshop on Remote Sensing for disaster applications. *6th International Workshop on Remote Sensing for Disaster Applications*, *March*.

Browne, K. E. (2015). *Standing in The Need: Culture, Comfort, and Coming Home after Katrina*.

Bucci, Steven P. Inserra, David. Lesser, Jonathan. Mayer, Matt A. Slattery, Brian. Spencer, Jack. Tubb, K. (2013). After Hurricane Sandy: Time to Learn and Implement the Lessons in Preparedness, Response, and Resilience from THE HERITAGE FOUNDATION EMERGENCY PREPAREDNESS WORKING GROUP. *The Heritage Foundation*, *Special Re*(No.144). http://thf_media.s3.amazonaws.com/2013/pdf/SR144.pdf

Calantropio, A. (2019). The use of UAVs for performing safety-related tasks at post-disaster and non-critical construction sites. *Safety*, *5*(4). https://doi.org/10.3390/safety5040064

Campanella, T. J. (2006). Urban Resilience and the Recovery of New Orleans. *American Planning Association*, *72*(2), 141–147.

Cascone, S. M., Caruso, C., Russo, G., Cascone, S. M., & Russo, G. (2019). Sustainability and innovation in constructions intended for emergency housing. *Technologies, Engineering, Materials, Architecture (TEMA)*, *5*(2).

Casey, S. R. P. (2012). *Casey Urges FEMA To Consider Giving Unused Trailers from Irene and Lee to States Impacted by Sandy*.

Castellanos, G., Deruyck, M., Martens, L., & Joseph, W. (2019). Performance evaluation of direct-link backhaul for UAV-aided emergency networks. *Sensors (Switzerland)*, *19*(15), 1–16. https://doi.org/10.3390/s19153342

Castro-lacouture, D., Sefair, J. A., & Flo, L. (2009). Optimization model for the selection of materials using a LEED-based green building rating system in Colombia. *Building and Environment*, *44*, 1162–1170. https://doi.org/10.1016/j.buildenv.2008.08.009

Chamlee-Wright, E. (2010). The cultural and political economy of recovery: Social learning in a post-disaster environment. In *The Cultural and Political Economy of Recovery: Social Learning in a Post-Disaster Environment*. https://doi.org/10.4324/9780203855928

Chamlee-wright, E., & Storr, V. H. (2011). Social capital as collective narratives and post-disaster community recovery. *The Sociological Review*, *2*.

Chamlee-Wright, E., & Storr, V. H. (2009). Club goods and post-disaster community return. *Rationality and Society*. https://doi.org/10.1177/1043463109337097

Chen, L., El-anwar, O., Heim, J. A., & Chen, L. (2012). *A Web-based System for Optimizing Post Disaster Temporary Housing Allocation*. 54.

Chopra, S., & Sodhi, M. S. (2004). Managing Risk To Avoid Supply-Chain Breakdown. *MIT Sloan Management Review*. https://doi.org/10.1108/IJOPM-10-2012-0449

Chowdhury, T., & Rahnemoonfar, M. (2021). *Attention Based Semantic Segmentation on UAV Dataset for Natural Disaster Damage Assessment*. 2–5. http://arxiv.org/abs/2105.14540

Chowdhury, T., Rahnemoonfar, M., Murphy, R., & Fernandes, O. (2020). Comprehensive Semantic Segmentation on High Resolution UAV Imagery for Natural Disaster Damage Assessment. *Proceedings - 2020 IEEE International Conference on Big Data, Big Data 2020*, 3904–3913. https://doi.org/10.1109/BigData50022.2020.9377916

Chu, J., & Su, Y. (2012). The Application of TOPSIS Method in Selecting Fixed Seismic Shelter for Evacuation in Cities. *Systems Engineering Procedia*, *3*(2011), 391–397. https://doi.org/10.1016/j.sepro.2011.10.061

Cinelli, M., Coles, S. R., & Kirwan, K. (2014). Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. *Ecological Indicators*, *46*, 138–148. https://doi.org/10.1016/j.ecolind.2014.06.011

Comerio, M. C. (1997). Housing issues after disasters. *Journal of Contingencies and Crisis Management*, *5*(3), 166–178. https://doi.org/10.1111/1468-5973.00052

Container Weight. (n.d.). https://www.containercontainer.com/shipping-container-dimensions%0A

Cooper, R. (2017). *NC Gov. Cooper: One Year Later: North Carolina Continues Recovering from Hurricane Matthew*.

Cutter, S., Barnes, L., Berry, M., Burton, C., Evans, E., Tate, E., & Webb, J. (2008). *A place-based model for understanding community resilience to natural disasters*. *18*, 598–606. https://doi.org/10.1016/j.gloenvcha.2008.07.013

Deveoplment, U. S. D. of H. and. (2018). *The 2018 Annual Homeless Assessment Report to Congress* (Issue September).

Dombi, J. (2011). Temporary Housing — Permanent Impressions. *The Military Engineer, Emergency and Humanitarian Outreach*.

East Nashville neighborhood in Nashville, Tennessee (TN). (n.d.). City-Data.Com. Retrieved January

7, 2020, from https://www.city-data.com/neighborhood/East-Nashville-Nashville-TN.html

El-anwar, O., Kandil, A., El-rayes, K., & El-anwar, O. (2010). Optimization Research : Enhancing the Robustness of Large-Scale Multiobjective Optimization in Construction. *Construction Engineering and Management*, *January*. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000140

El-Anwar, O, El-Rayes, K., & Elnashai, A. (2009). Optimizing Large-Scale Temporary Housing Arrangements after Natural Disasters. *Journal of Computing in Civil Engineering*, *23*(2), 110–118. https://doi.org/10.1061/(ASCE)0887-3801(2009)23:2(110)

El-Anwar, Omar. (2012). Advancing Optimization of Hybrid Housing Development Plans Following Disasters : Achieving Computational Robustness , Effectiveness , and Efficiency. *Journal of Computing in Civil Engineering*, *27*(4), 358–369.

El-Anwar, Omar. (2013). Advancing optimization of hybrid housing development plans following disasters: Achieving computational robustness, effectiveness, and efficiency. *Journal of Computing in Civil Engineering*, *27*(4), 358–369. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000234

El-Anwar, Omar, & Chen, L. (2012). Computing a Displacement Distance Equivalent to Optimize Plans for Postdisaster Temporary Housing Projects. *ASCE*, *139*(2), 174–184.

El-Anwar, Omar, & Chen, L. (2016). Automated Community-Based Housing Response: Offering Temporary Housing Solutions Tailored to Displaced Populations Needs. *Journal of Computing in Civil Engineering*. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000588

El-Anwar, Omar, & El-Rayes, K. (2007). Post-Disaster Optimization of Temporary Housing Efforts. *ASCE Construction Research Congress*.

El-Anwar, Omar, El-Rayes, K., & Elnashai, A. (2009). An automated system for optimizing post-disaster temporary housing allocation. *Automation in Construction*, *18*(7), 983–993. https://doi.org/10.1016/j.autcon.2009.05.003

El-Anwar, Omar, El-Rayes, K., & Elnashai, A. (2010a). Maximizing Temporary Housing Safety after Natural Disasters. *Journal of Infrastructure Systems*, *16*(2), 138. https://doi.org/10.1061/(ASCE)IS.1943-555X.0000018

El-Anwar, Omar, El-Rayes, K., & Elnashai, A. S. (2010b). Maximizing the Sustainability of Integrated Housing Recovery Efforts. *Journal of Construction Engineering and Management*, *136*(7), 794–802. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000185

El Amine, M., Pailhes, J., & Perry, N. (2014). Critical review of multi-criteria decision aid methods in conceptual design phases: Application to the development of a solar collector structure. *Procedia CIRP*, *21*, 497–502. https://doi.org/10.1016/j.procir.2014.03.134

Erdelj, M., Król, M., & Natalizio, E. (2017). Wireless Sensor Networks and Multi-UAV systems for natural disaster management. *Computer Networks*, *124*, 72–86.

https://doi.org/10.1016/j.comnet.2017.05.021

Estrada, M. A. R., & Ndoma, A. (2019). The uses of unmanned aerial vehicles -UAV's- (or drones) in social logistic: Natural disasters response and humanitarian relief aid. *Procedia Computer Science*, *149*, 375–383. https://doi.org/10.1016/j.procs.2019.01.151

EX-CONTAINER PROJECT. (n.d.). Yasutaka Yoshimura Architects. http://exc.ysmr.com/container_e/

Facilities, C. P., & Paper, I. (n.d.). *TEMPORARY HOUSING AND CRITICAL PUBLIC FACILITIES*. 1–2.

Faure, J. C., Faust, K. M., & Kaminsky, J. (2020). Stakeholder Legitimization of the Provision of Emergency Centralized Accommodations to Displaced Persons. *Sustainability*, *12*(1), 284. https://doi.org/10.3390/su12010284

Félix, D., Branco, J. M., & Feio, A. (2013). Temporary housing after disasters : A state of the art survey. *Habitat International*, *40*, 136–141. https://doi.org/10.1016/j.habitatint.2013.03.006

FEMA.gov. (2009a). *Federal Assistance In Hurricane Ike Disaster Tops $2.5 Billion*.

FEMA.gov. (2009b). *Five Years of Hurricane Jeanne Recovery - By the Numbers*.

FEMA. (2005). Disaster Assistance: A Guide to Recovery Programs. *FEMA 229*, *September*.

FEMA. (2018). *Hurricane Harvey 6 Months Later Texas Hurricane Harvey Recovery Guide* (Vol. 3362, Issue February). https://gov.texas.gov/hurricane

FEMA. (2020a). *Fact Sheet: Preliminary Damage Assessment Guide 2020*. 1–2.

FEMA. (2020b). *Preliminary Damage Assessment Guide*. https://www.fema.gov/disasters/how-declared/preliminary-damage-assessments/guide

FEMA. (2021a). *Housing Resources for Residents of Puerto Rico Displaced by Hurricanes Irma and Maria*. https://www.fema.gov/press-release/20210318/housing-resources-residents-puerto-rico-displaced-hurricanes-irma-and-maria

FEMA. (2021b). *Preliminary Damage Assessment Guide*. https://www.fema.gov/disasters/how-declared/preliminary-damage-assessments/guide

FEMA. (2021c). *You've Been Approved for a Temporary Housing Unit. Now What?* https://www.fema.gov/fact-sheet/youve-been-approved-temporary-housing-unit-now-what

FEMA, U. S. D. of H. S. (2008). *Draft Environmental Assessment Alternative Housing Pilot Program Jackson Barracks Site*.

Fernandez Galarreta, J., Kerle, N., & Gerke, M. (2015). UAV-based urban structural damage assessment using object-based image analysis and semantic reasoning. *Natural Hazards and Earth System Sciences*, *15*(6), 1087–1101. https://doi.org/10.5194/nhess-15-1087-2015

Fessler, P. (NPR). (2017). *At Least 100 , 000 Homes Were Affected By Harvey . Moving Back In Won ' t Be Easy*. NPR.

Force, H. S. R. T. (2013). Hurricane Sandy Rebuilding Strategy. *Pre-Publication Addition*, *August*.

Ford, G., Ahn, Y. H., & Choi, D. M. (2014). Modular Building for Urban Disaster Housing: Case Study of Urban Post-Disaster Housing Prototype in New York. *Fire Science and Engineering*, *28*(6), 82–89. https://doi.org/10.7731/KIFSE.2014.28.6.082

Fugate, C. (2011). *Catastrophic Preparedness: How Ready Is FEMA for the Next Big Disaster?* FEMA.

Fugate, C. (2013). ONE YEAR LATER: EXAMINING THE ONGOING RECOVERY FROM HURRICANE SANDY. *U.S. Department of Homeland Security*, 1–15.

Fussell, E., & Lowe, S. R. (2014). Social Science & Medicine The impact of housing displacement on the mental health of low-income parents after Hurricane Katrina. *Social Science & Medicine*, *113*, 137–144. https://doi.org/10.1016/j.socscimed.2014.05.025

Geng, S., Hou, H., & Zhang, S. (2020). Multi-Criteria Location Model of Emergency Shelters in Humanitarian Logistics. *Sustainability*, *12*(5), 1759. https://doi.org/10.3390/su12051759

Ghaffarian, S., & Kerle, N. (2019). Towards post-disaster debris identification for precise damage and recovery assessments from uav and satellite images. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *42*(2/W13), 297–302. https://doi.org/10.5194/isprs-archives-XLII-2-W13-297-2019

Gheytanchi, A., Joseph, L., Gierlach, E., Kimpara, S., Housley, J., Franco, Z. E., & Beutler, L. E. (2007). The Dirty Dozen. *American Psychologist*, *62*(2), 118–130. https://doi.org/10.1037/0003-066X.62.2.118

Gibbens, S. (2019). Hurricane Sandy, explained. *The National Geographic*, 1–6.

Gibbs, D. (2003). Trust and Networking in Inter-firm relations: the Case of Eco-Industrial Development. *Local Economy*, *18*(3), 222–236. https://doi.org/10.1080/0269094032000114595

Gillespie-Marthaler, L., Nelson, K., Baroud, H., & Abkowitz, M. (2019). Selecting Indicators for Assessing Community Sustainable Resilience. *Risk Analysis*, *39*(11), 2479–2498. https://doi.org/10.1111/risa.13344

Government Auctions and Sales Government Sales of Seized and Surplus Property. (2019). USA.Gov. https://www.usa.gov/auctions-and-sales#item-36772

Greenwood, F., Nelson, E. L., & Gregg Greenough, P. (2020). Flying into the hurricane: A case study of UAV use in damage assessment during the 2017 hurricanes in Texas and Florida. *PLoS ONE*, *15*(2), 1–30. https://doi.org/10.1371/journal.pone.0227808

Groen, J. a., & Polivka, a. E. (2008). Hurricane Katrina evacuees: Who they are, where they are, and how they are faring. *Monthly Lab. Rev.*, *131*(October 2005), 32–51. http://heinonlinebackup.com/hol-cgi-bin/get_pdf.cgi?handle=hein.journals/month131&section=27

Hany Abulnour, A. (2013). The post-disaster temporary dwelling: Fundamentals of provision, design and construction. *HBRC Journal*, *10*(1), 10–24. https://doi.org/10.1016/j.hbrcj.2013.06.001

Harriss, L., Parrack, C., & Jordan, Z. (2020). Building safety in humanitarian programmes that support post-disaster shelter self-recovery: an evidence review. *Disasters*, *44*(2), 307–335. https://doi.org/10.1111/disa.12397

Hazards & Vulnerability Research Institute. (n.d.). *SoVI*. http://artsandsciences.sc.edu/geog/hvri/sovi®-0

He, J., Feng, C., Hu, D., & Liang, L. (2017). A Decision Model for Emergency Warehouse Location Based on a Novel Stochastic MCDA Method: Evidence from China. *Mathematical Problems in Engineering*, *2017*. https://doi.org/10.1155/2017/7804781

Heerwagen, J. H., Ph, D., & Heerwagen, J. H. (2006). *Investing In People : The Social Benefits of Sustainable Design*. 1–17.

Hidayat, B., & Egbu, C. (2010). *A LITERATURE REVIEW OF THE ROLE OF PROJECT MANAGEMENT IN POST-DISASTER RECONSTRUCTION*. *September*, 1269–1278.

Hong, Y. (2017). A study on the condition of temporary housing following disasters: Focus on container housing. *Frontiers of Architectural Research*, *6*(3), 374–383. https://doi.org/10.1016/j.foar.2017.04.005

Hosseini, S. M. A., de la Fuente, A., & Pons, O. (2016). Multicriteria Decision-Making Method for Sustainable Site Location of Post-Disaster Temporary Housing in Urban Areas. *Journal of Construction Engineering and Management*, *142*(9), 04016036. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001137

Hosseini, S. M. A., Yazdani, R., & De, A. (2020). Multi-objective interior design optimization method based on sustainability concepts for post-disaster temporary housing units. *Building and Environment*, *173*, 106742. https://doi.org/10.1016/j.buildenv.2020.106742

Huang, M. C., & Hosoe, N. (2017). Fiscal and social costs of recovery programs for an earthquake disaster in northern Taiwan. *Journal of Asian Economics*, *53*, 1–17. https://doi.org/10.1016/j.asieco.2017.10.001

Hurricane Sandy FEMA After-Action Report. (2013). In *FEMA*.

Jacquet-Lagreze, E., & Siskos, J. (1982). Assessing a set of additive utility functions for multicriteria decision-making, the UTA method. *European Journal of Operational Research*, *10*(2), 151–164. https://doi.org/10.1016/0377-2217(82)90155-2

Jerolleman, A. (2020). Louisiana ' s Response to Extreme Weather. In S. Laska, W. Sprigg, & S. Steignberg (Eds.), *Louisiana ' s Response to Extreme Weather* (Exetreme W, pp. 285–310). https://doi.org/10.1007/978-3-030-27205-0

Johnson, C. (2004). *Strategies for the Reuse of Temporary Housing*. 323–331.

Johnson, C. (2007a). Impacts of prefabricated temporary housing after disasters: 1999 earthquakes in Turkey. *Habitat International*, *31*(1), 36–52. https://doi.org/10.1016/j.habitatint.2006.03.002

Johnson, C. (2007b). Strategic planning for post-disaster temporary housing. *Disasters*, *31*(4), 435–458. https://doi.org/10.1111/j.1467-7717.2007.01018.x

Johnson, P., Brady, C., Philip, C., Baroud, H., Camp, J., & Abkowitz, M. (2020). A Factor Analysis Approach Toward Reconciling Community Vulnerability and Resilience Indices for Natural Hazards. *Risk Analysis*, *40*. https://doi.org/10.1111/risa.13508

Kar, B., & Hodgson, M. E. (2008). A GIS-based model to determine site suitability of emergency evacuation shelters. *Transactions in GIS*, *12*(2), 227–248. https://doi.org/10.1111/j.1467-9671.2008.01097.x

Kates, R. W., Colten, C. E., Laska, S., & Leatherman, S. P. (2006). Reconstruction of New Orleans after Hurricane Katrina: a research perspective. *Proceedings of the National Academy of Sciences of the United States of America*, *103*(40), 14653–14660. https://doi.org/10.1073/pnas.0605726103

Kerle, N., Nex, F., Duarte, D., & Vetrivel, A. (2019). Uav-based structural damage mapping-results from 6 years of research in two european projects. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *42*(3/W8), 187–194. https://doi.org/10.5194/isprs-archives-XLII-3-W8-187-2019

Kerle, Norman, Nex, F., Gerke, M., Duarte, D., & Vetrivel, A. (2019). UAV-based structural damage mapping: A review. *ISPRS International Journal of Geo-Information*, *9*(1), 1–23. https://doi.org/10.3390/ijgi9010014

Kerle, Norman, Stekelenburg, R., Van Den Heuvel, F., & Gorte, B. (2005). Near-real time post-disaster damage assessment with airborne oblique video data. *Geo-Information for Disaster Management*, 337–353. https://doi.org/10.1007/3-540-27468-5_24

Kessler, R. C., Galea, S., Gruber, M. J., Sampson, N. A., Ursano, R. J., & Wessely, S. (2008). Trends in mental illness and suicidality after Hurricane Katrina. *Molecular Psychiatry*, *13*(4), 374–384. https://doi.org/10.1038/sj.mp.4002119

Kleinberg, E. (2009). Hurricane Wilma Victim Is Still Waiting for FEMA Aid. *Miami Herald*.

Koyama, S., Aida, J., Kawachi, I., Kondo, N., Subramanian, S. V, Ito, K., Kobashi, G., Masuno, K., Kondo, K., & Osaka, K. (2014). Social Support Improves Mental Health among the Victims Relocated to Temporary Housing following the Great East Japan Earthquake and Tsunami. *The Tohoku Journal of Experimental Medicine*, *234*(3), 241–247. https://doi.org/10.1620/tjem.234.241

Kreimer, A., Arnold, M., & Carlin, A. (2003). Building safer cities: the future of disaster risk. In *Disaster Risk Management Series No. 3* (Issue 3).

Kreimer, Alcira. (1979). Emergency, temporary and permanent housing after disasters in developing countries. *Ekistics*, *279*(279), 361–365.

Lakshmi, T. M., Vetriselvi, K., Anand, A. J., & Venkatesan, P. (2016). A study on different types of normalization methods in adaptive Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). *International Journal of Engineering Research & Technology (IJERT)*, *4*(05), 1–7.

Levine, J. N., Esnard, a.-M., & Sapat, a. (2007). Population Displacement and Housing Dilemmas Due to Catastrophic Disasters. *Journal of Planning Literature*, *22*(1), 3–15. https://doi.org/10.1177/0885412207302277

Lindsay, B. R. (2017). FEMA Disaster Housing : The Individuals and Households Program — Implementation and Potential Issues for Congress. *Congressional Research Service*, 18.

Liu, Q., Ruan, X., & Shi, P. (2011). Selection of emergency shelter sites for seismic disasters in mountainous regions: Lessons from the 2008 Wenchuan Ms 8.0 Earthquake, China. *Journal of Asian Earth Sciences*, *40*(4), 926–934. https://doi.org/10.1016/j.jseaes.2010.07.014

Maddalena, R., Russell, M., Sullivan, D. P., & Apte, M. G. (2009). Formaldehyde and Other Volatile Organic Chemical Emissions in Four FEMA Temporary Housing Units. *Enviromental Science Technology*, *43*(15), 5626–5632.

Masozera, M., Bailey, M., & Kerchner, C. (2006). Distribution of impacts of natural disasters across income groups: A case study of New Orleans. *Ecological Economics*, *63*(2–3), 299–306. https://doi.org/10.1016/j.ecolecon.2006.06.013

McCarthy, F. X. (2010). FEMA disaster housing: From sheltering to permanent housing. *Disaster Assistance and Recovery Programs: Types and Policies*, 49–78.

Mcintosh, J. (2013). The Implications of Post Disaster Recovery for Affordable Housing. *Intech*. https://doi.org/10.5772/55273

Merdjanoff, A. A. (2013). There ' s no place like home : Examining the emotional consequences of Hurricane Katrina on the displaced residents of New Orleans. *Social Science Research*, *42*(5), 1222–1235. https://doi.org/10.1016/j.ssresearch.2013.04.004

Mica, J. L. (2009). Ranking Member Staff Analysis of FEMA ' s Temporary Housing : Four Years

After Katrina Thousands of Trailers Remain In Storage. *U . S . House of Representatives Committee on Transportation and Infrastructure, October*.

Mickelson, S., Patton, N., Gordon, A., & Rammler, D. (2019). *Fixing America's Broken Disaster Housing Recovery System*.

Mirata, M., & Emtairah, T. (2005). Industrial symbiosis networks and the contribution to environmental innovation: The case of the Landskrona industrial symbiosis programme. *Journal of Cleaner Production*, *13*(10–11), 993–1002. https://doi.org/10.1016/j.jclepro.2004.12.010

Montis, A. De, Toro, P. De, Droste-franke, B., Omann, I., & Stagl, S. (2000). Criteria for quality assessment of MCDA methods. *3rd Biennial Conference of the European Society for Ecological Economics,* 30.

Mora, M., & Akinci, B. (2018). Measuring the Social Impact of Innovation in the Fabrication and Delivery of Post-Disaster Temporary Housing—2017 Fire in Chile Case Study. *Proceeding of Construction Research Congress 2018*, 429–438. https://doi.org/10.1088/1751-8113/44/8/085201

Mosier, R., & Gransberg, D. D. (2013). A Framework to Reconcile Green Goals with Budget Reality. *ISRN Construction Engineering*, *2013*, 1–10. https://doi.org/10.1155/2013/656742

Murphy, B. L. (2007). Locating social capital in resilient community-level emergency management. *Natural Hazards*. https://doi.org/10.1007/s11069-006-9037-6

Nigg, J. M., Barnshaw, J., & Torres, M. R. (2006). Hurricane Katrina and the Flooding of New Orleans: Emergent Issues in Sheltering and Temporary Housing. *The ANNALS of the American Academy of Political and Social Science*, *604*(1), 113–128. https://doi.org/10.1177/0002716205285889

NOAA. (2019). *Hurricanes in History*. National Hurricane Center and Central Pacific Hurricane Center. https://www.nhc.noaa.gov/data/tcr/index.php?season=1995&basin=atl

NOAA. (2020). *U.S. 2020 Billion-Dollar Weather and Climate Disasters*. https://www.ncdc.noaa.gov/billions/

Norris, F. H., Stevens, Æ. S. P., Pfefferbaum, B., Wyche, Æ. K. F., & Pfefferbaum, R. L. (2008). Community Resilience as a Metaphor , Theory , Set of Capacities , and Strategy for Disaster Readiness. *American Journal of Community Psychology*, 127–150. https://doi.org/10.1007/s10464-007-9156-6

Ohlson, S. (2014). Designing and Developing Sustainable Housing for Refugee and Disaster Communities. *IEEE*.

Olshansky, R. B. (2005). How do Communities Recover from Disaster? A Review of Current Knowledge and an Agenda for Future Research. *46th Annual Conference of the Association of Collegiate Schools of Planning*, *1974*.

http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.492.1231&rep=rep1&type=pdf

Opricovic, S., & Tzeng, G. H. (2002). Multicriteria planning of post-earthquake sustainable reconstruction. *Computer-Aided Civil and Infrastructure Engineering*, *17*(3), 211–220. https://doi.org/10.1111/1467-8667.00269

Park, Y. J., & Jung, K. Y. (2014). Availability Evaluation for Generation of Geospatial Information using Fixed Wing UAV. *Journal of Korean Society for Geospatial Information System*, *22*(4), 159–164. https://doi.org/10.7319/kogsis.2014.22.4.159

Paton, D. (2007). Preparing for natural hazards: The role of community trust. *Disaster Prevention and Management: An International Journal*. https://doi.org/10.1108/09653560710758323

Paxson, C., Fussell, E., Rhodes, J., & Waters, M. (2011). Five years later : Recovery from post traumatic stress and psychological distress among low-income mothers affected by Hurricane Katrina. *Social Science & Medicine*, *74*(2), 150–157. https://doi.org/10.1016/j.socscimed.2011.10.004

Pellicani, R., Argentiero, I., Manzari, P., Spilotro, G., Marzo, C., Ermini, R., & Apollonio, C. (2019). UAV and airborne LiDAR data for interpreting kinematic evolution of landslide movements: The case study of the montescaglioso landslide (Southern Italy). *Geosciences (Switzerland)*, *9*(6). https://doi.org/10.3390/geosciences9060248

Pelling, M. (1998). Participation, social capital and vulnerability to urban flooding. *International Development*. https://doi.org/10.1002/(SICI)1099-1328(199806)10:4<469::AID-JID539>3.0.CO;2-4

Pelling, M., & High, C. (2005). Understanding adaptation: What can social capital offer assessments of adaptive capacity? In *Global Environmental Change*. https://doi.org/10.1016/j.gloenvcha.2005.02.001

Perrucci, D., & Baroud, H. (2020). A review of temporary housing management modeling: Trends in design strategies, optimization models, and decision-making methods. *Sustainability (Switzerland)*, *12*(24), 1–20. https://doi.org/10.3390/su122410388

Perrucci, D. V., & Baroud, H. (2018). Improving Community Resilience through Post-Disaster Temporary Housing Optimization. *Probabilistic Safety Assessment and Management PSAM 14*.

Perrucci, D. V., & Baroud, H. (2021). Temporary housing operations: A simulation-based inventory management approach using the newsvendor model. *International Journal of Disaster Risk Reduction*, *65*(April), 102512. https://doi.org/10.1016/j.ijdrr.2021.102512

Perrucci, D. V., Vazquez, B. A., & Aktas, C. B. (2016). Sustainable Temporary Housing: Global Trends and Outlook. *Procedia Engineering*, *145*(Integrating Data Science Construction and Sustainability), 327–332. https://doi.org/10.1016/j.proeng.2016.04.082

Peters, C. N., Baroud, H., & Hornberger, G. M. (2019). Multicriteria decision analysis of drinking water source selection in southwestern Bangladesh. *Journal of Water Resources Planning and Management*, *145*(4), 1–14. https://doi.org/10.1061/(ASCE)WR.1943- 5452.0001029

Pierre, J. K., Stephenson, G. S., Pierre, J. K., & Stephenson, G. S. (2008). *After Katrina : A Critical Look at FEMA ' s Failure to Provide Housing for Victims of Natural Disasters Provide Housing for Victims of Natural Disasters*. *68*(2).

Prevention, C. for D. C. and. (2018). *CDC Social Vulnerability Index (SVI)*. https://data.cdc.gov/Health-Statistics/CDC-Social-Vulnerability-Index-SVI-/u6k2-rtt3

Quarantelli, E. L. (1982). General and particular observations on sheltering and housing in American disasters. *Disasters*, *6*(4), 277–281. https://doi.org/10.1111/j.1467-7717.1982.tb00550.x

Quarantelli, E. L. (1991). Disaster planning for transportation accidents involving hazardous materials. *Journal of Hazardous Materials*. https://doi.org/10.1016/0304-3894(91)80020-O

Quick Facts: Mount Juliet, TN. (n.d.). U.S. Census Bureau. Retrieved January 7, 2021, from https://www.census.gov/quickfacts/mountjulietcitytennessee

Rakes, T. R., Deane, J. K., Rees, L. P., & Fetter, G. M. (2014). A decision support system for post-disaster interim housing. *Decision Support Systems*, *66*, 160–169. https://doi.org/10.1016/j.dss.2014.06.012

Ram, C., Montibeller, G., & Morton, A. (2011). Extending the use of scenario planning and MCDA for the evaluation of strategic options. *Journal of the Operational Research Society*, *62*(5), 817–829. https://doi.org/10.1057/jors.2010.90

Rebuilding Stronger and Faster After Natural Disasters In the aftermath of hurricanes. (2019). In *U.S. Department of Housing and Urban Development*. https://www.huduser.gov/portal/pdredge/pdr-edge-featd-article-111819.html

Ritchie, L. A., & Tierney, K. (2011). Temporary housing planning and early implementation in the 12 January 2010 haiti earthquake. *Earthquake Spectra*, *27*(SUPPL. 1). https://doi.org/10.1193/1.3637637

Rudolph, J. W., Repenning, N., Rudolph, J. W., & Repenning, N. P. (2002). Disaster Dynamics : Understanding the Role of Quantity in Organizational Collapse. *Administrative Science Quarterly*, *August 2014*. https://doi.org/10.2307/3094889

Sagiroglu, M. (2018). Learning from the Experiences of Using Different Types of Temporary Housing Systems. *42nd IAHS World Congress*. https://doi.org/10.4324/9780203360835_chapter_19

Samanta, S., Koloa, C., Pal, D. K., & Palsamanta, B. (2016). Flood risk analysis in lower part of Markham river based on multi-criteria decision approach (MCDA). *Hydrology*, *3*(3), 1–13.

https://doi.org/10.3390/hydrology3030029

Schmeltz, M. T., González, S. K., Fuentes, L., Kwan, A., Ortega-williams, A., & Cowan, L. P. (2013). *Lessons from Hurricane Sandy : a Community Response in Brooklyn , New York*. *90*(5). https://doi.org/10.1007/s11524-013-9832-9

Seike, T., Kim, Y., Hosaka, Y., Ida, S., & Masuda, T. (2018). Intraregional reuse of emergency temporary housing in Japan. *Sustainable Cities and Society*, *42*(July 2017), 650–662. https://doi.org/10.1016/j.scs.2017.11.001

Sener, S. M., & Altun, M. C. (2009). Design of a post disaster temporary shelter unit. *A|Z ITU Journal of Faculty of Architecture*, *6*(2), 58–74. https://doi.org/10.1016/0047-259X(90)90089-Z

Severino, K. (2018). *Post-Hurricane Maria: Transitional Shelter Assistance (TSA) & Other Housing Assistance* (Issue April).

Sewell, A. (2012). *FEMA has up to 1000 trailers — why not give to Sandy victims?* Digital Journal.

Shaw, R., & Goda, K. (2004). From disaster to sustainable civil society: the Kobe experience. *Disasters*, *28*(1), 16–40. https://doi.org/10.1111/j.0361-3666.2004.00241.x

Shelter Box: Providing Shelter, Supporting Recovery. (n.d.). https://www.shelterboxusa.org/home-page/aid/

Siskos, Y., Grigoroudis, E., & Matsatsinis, N. F. (2016). UTA methods. In *International Series in Operations Research and Management Science* (Vol. 233, Issue May 2014). https://doi.org/10.1007/978-1-4939-3094-4_9

Song, Y., Mithraratne, N., & Zhang, H. (2016). Life-time performance of post-disaster temporary housing : A case study in Nanjing. *Energy & Buildings*, *128*, 394–404. https://doi.org/10.1016/j.enbuild.2016.07.019

Stanley, S. (2018). *U.S. Green Building Council Releases Annual Top 10 Countries and Regions for LEED*. https://www.usgbc.org/articles/us-green-building-council-releases-annual-top-10-countries-and-regions-leed

Stewart, S. R. (2017). Hurricane Matthew. *National Hurricane Center*, *October 2016*, 1–96. http://www.nhc.noaa.gov/data/tcr/AL142016_Matthew.pdf

Sui, H., Tu, J., Song, Z., Chen, G., & Li, Q. (2014). A novel 3D building damage detection method using multiple overlapping UAV images. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives*, *40*(7), 173–179. https://doi.org/10.5194/isprsarchives-XL-7-173-2014

Szibbo, N. A. (2015). Assessing Neighborhood Livability: Evidence from LEED® for Neighborhood Development and New Urbanist Communities. *Journal of Urban Research*, *14*. https://doi.org/10.4000/articulo.3120

Talbot, J., Poleacovschi, C., Hamideh, S., & Santos-Rivera, C. (2020). Informality in Postdisaster Reconstruction: The Role of Social Capital in Reconstruction Management in Post–Hurricane Maria Puerto Rico. *Journal of Management in Engineering*, *36*(6), 04020074. https://doi.org/10.1061/(asce)me.1943-5479.0000833

The U.S. Department of Housing and Urban Development. (2019). *The 2019 Annual Homeless Assessment Report (AHAR) to Congress* (Issue January). https://files.hudexchange.info/resources/documents/2019-AHAR-Part-1.pdf

Tsai, M. K. (2015). Designing Postdisaster Temporary Housing Facilities: Case Study in Indonesia. *Natural Hazards Review*, *16*(3), 1–9. https://doi.org/10.1061/(ASCE)NH.1527-6996.0000163

U.S. Department of Homeland Security. (2013). *Unless Modified, FEMA's Temporary Housing Plans Will Increase Costs by an Estimated $76 Million Annually*.

Ueda, Y., & Shaw, R. (2015). Managing and bridging communities in temporary housing: case of the Great East Japan Earthquake and Tsunami in Kesennuma City, Japan. *Natural Hazards*, *80*(1), 567–587. https://doi.org/10.1007/s11069-015-1984-3

Vafaei, N., Ribeiro, R. A., & Camarinha-Matos, L. M. (2018). Selection of normalization technique for weighted average multi-criteria decision making. *IFIP Advances in Information and Communication Technology*, *521*(May), 43–52. https://doi.org/10.1007/978-3-319-78574-5_4

Veleva, V., Todorova, S., Lowitt, P., Angus, N., & Neely, D. (2015). Understanding and addressing business needs and sustainability challenges: Lessons from Devens eco-industrial park. *Journal of Cleaner Production*, *87*(1), 375–384. https://doi.org/10.1016/j.jclepro.2014.09.014

Venable, C., Javernick-Will, A., & Liel, A. B. (2020). Perceptions of Post-Disaster Housing Safety in Future Typhoons and Earthquakes. *Sustainability*, *12*(9), 3837. https://doi.org/10.3390/su12093837

Verderber, S. (2008). Emergency housing in the aftermath of Hurricane Katrina: An assessment of the FEMA travel trailer program. *Journal of Housing and the Built Environment*, *23*(4), 367–381. https://doi.org/10.1007/s10901-008-9124-y

Vitoriano, B., Ortuño, M. T., Tirado, G., & Montero, J. (2011). A multi-criteria optimization model for humanitarian aid distribution. *Journal of Global Optimization*, *51*(2), 189–208. https://doi.org/10.1007/s10898-010-9603-z

Walsh, F. (2007). Traumatic Loss and Major Disasters: Strengthening Family and Community Resilience. *Family Processes*, *46*(2), 207–228.

Waugh, W. L. (2006). The Political Costs of Failure in the Katrina and Rita Disasters. *The ANNALS of the American Academy of Political and Social Science*, *604*(1), 10–25.

https://doi.org/10.1177/0002716205284916

Weather.gov. (2020). *March 2-3, 2020 Tornadoes and Severe Weather*. https://www.weather.gov/ohx/20200303

Windle, M., Quraishi, S., & Goentzel, J. (2019). *DISASTER HOUSING CONSTRUCTION CHALLENGES Exploring the Role of Factory-Built Housing* (Issue October).

WKRN. (2020). *Interactive Map: 2020 Nashville Tornado Outbreak damage*. https://www.wkrn.com/news/nashville-tornado/interactive-map-2020-nashville-tornado-outbreak-damage/

Womack, M. (2015). *Louisiana — Hurricanes Katrina & Rita*.

Wu, J., Li, J., Wang, S., & Cheng, T. C. E. (2008). *A Note on Mean-variance Analysis of the Newsvendor Model with Stockout Cost*. *852*, 1–15.

Wu, J. Y., & Lindell, M. K. (2004). Housing reconstruction after two major earthquakes: The 1994 northridge earthquake in the United States and the 1999 Chi-chi earthquake in Taiwan. *Disasters*. https://doi.org/10.1111/j.0361-3666.2004.00243.x

Yamazaki, F., Kubo, K., Tanabe, R., & Liu, W. (2017). Damage Assessment and 3D Modeling By Uav Flights After the 2016. *International Geoscience and Remote Sensing Symposium*, *V*, 3182–3185.

YAMAZAKI, F., & MATSUOKA, M. (2007). Remote Sensing Technologies in Post-Disaster Damage Assessment. *Journal of Earthquake and Tsunami*, *01*(03), 193–210. https://doi.org/10.1142/s1793431107000122

Yi, H., & Yang, J. (2014). Research trends of post disaster reconstruction : The past and the future. *Habitat International*, *42*, 21–29. https://doi.org/10.1016/j.habitatint.2013.10.005

Zhang, G., Setunge, S., & van Elmpt, S. (2014). Using Shipping Containers to Provide Temporary Housing in Post-disaster Recovery: Social Case Studies. *Procedia Economics and Finance*, *18*(September), 618–625. https://doi.org/10.1016/S2212-5671(14)00983-6

Zhao, X., Du, P., Chen, J., Yu, D., Xu, W., Lou, S., Yuan, H., & Ip, K. P. (2020). A typhoon shelter selection and evacuee allocation model: A case study of macao (SAR), China. *Sustainability (Switzerland)*, *12*(8). https://doi.org/10.3390/SU12083308

APPENDIX A, PLANNING FOR TEMPORARY HOUSING THROUGH MULTI-CRITERIA DECISION ANALYSIS

Table 14: Temporary Housing Design Data

THU Design	c1	c2	c3	c4	c5	c6	c7	c8	c9	c10	c11	c12	c13	c14	c15	c16
Prefabricated Modular Units	5	3	3	2	36000	20	9520	1360	6	60	5	4	4	4	4	1
	5	3	3	2	48000	20	9520	1360	6	60	5	4	4	4	4	1
	5	3	3	2	60000	20	9520	1360	6	118	5	5	4	4	4	1
Manufactured Temporary Housing Units	4.5	1	2	1	42000	20	18000	2000	12	66	5	5	5	5	5	1
	4.5	1	2	1	65000	20	18000	2560	12	68	5	4	5	4	5	1
Prefabricated Kit Supplies	4	10	4	4	2500	5	250	100	12	46	2	5	1	3	3	50
	8	10	5	4	2000	20	1200	74	3	22	2	3	2	4	4	40
	3	16	5	5	1000	20	50	2	3	127	3	4	4	3	4	32
Tents	8	1	4	4	500	3	25	2	1	9	2	2	3	2	2	50

Table 15: Unit Security Scoring Metric Breakdown

Unit Security	1	2	3	4	5
	None	Privacy	Rigid Structure	Lockable Door	Flood Lighting

Table 16: Fire Safety Scoring Metric Breakdown

Fire Safety	1	2	3	4	5
	None	Fire retardant materials	Rigid Structure	Multiple Exits	Fire Sprinkler

Table 17: Sustainability Scoring Metric Breakdown

Sustainability	1	2	3	4	5
	None	Re-useable	Sustainable Material Construction	Local Construction	Transitional

Table 18: Methods of Transport Scoring Metric Breakdown

Methods of Transport	1	2	3	4	5
	Trucking or Rail Required	Trucking, Rail, Boat	Trucking, Rail, Boat, Plane	Trucking, Rail, Boat, Plane, Helicopter	Local Materials And Construction

Table 19: Lavatory Type Scoring Metric Breakdown

Lavatory Type	1	2	3	4	5
	Outhouse	Portable Bathrooms	Shared Bathroom	Private Bathroom w/ shared shower	Private Bathroom w/ shower

Table 20: Cooking Area Scoring Metric Breakdown

Cooking Area	1	2	3	4	5
	Fire Cooking	Portable Stove	Shared outdoor kitchen	Shared Kitchen	Private Kitchen

Table 21: Natural Lighting Scoring Metric Breakdown

Natural Lighting	1	2	3	4	5
	No windows or door with window	A door with window	A door and window	Multiple windows and door	Skylight or outdoor sitting area

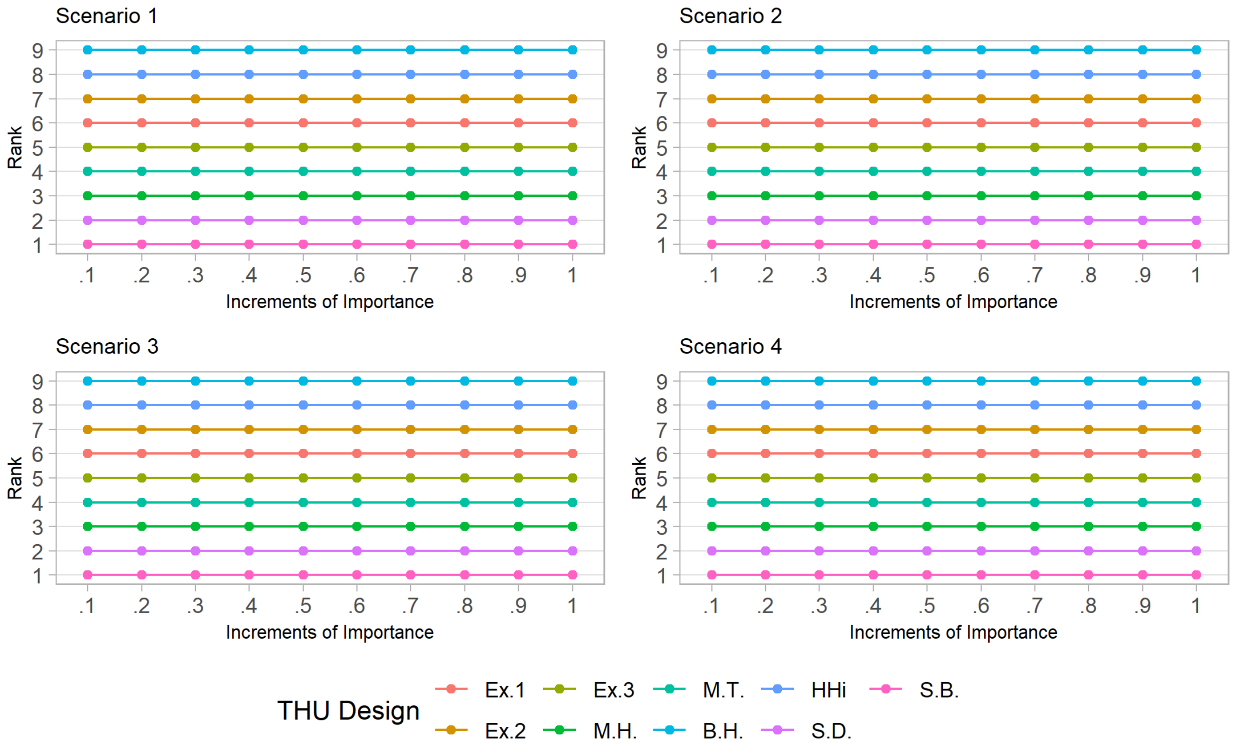


Figure 34: Sensitivity Analysis on Feasibility for Weighted Sum during all Scenarios

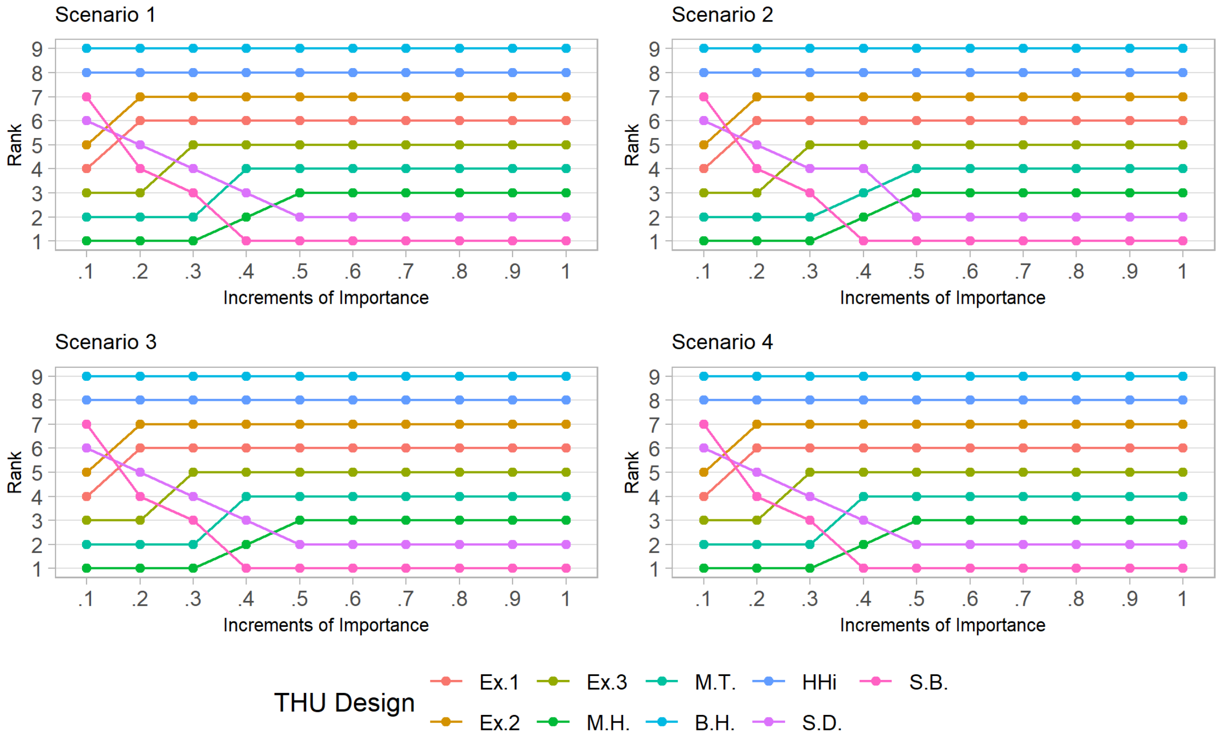


Figure 35: Sensitivity Analysis on Cost for Weighted Sum during all Scenarios

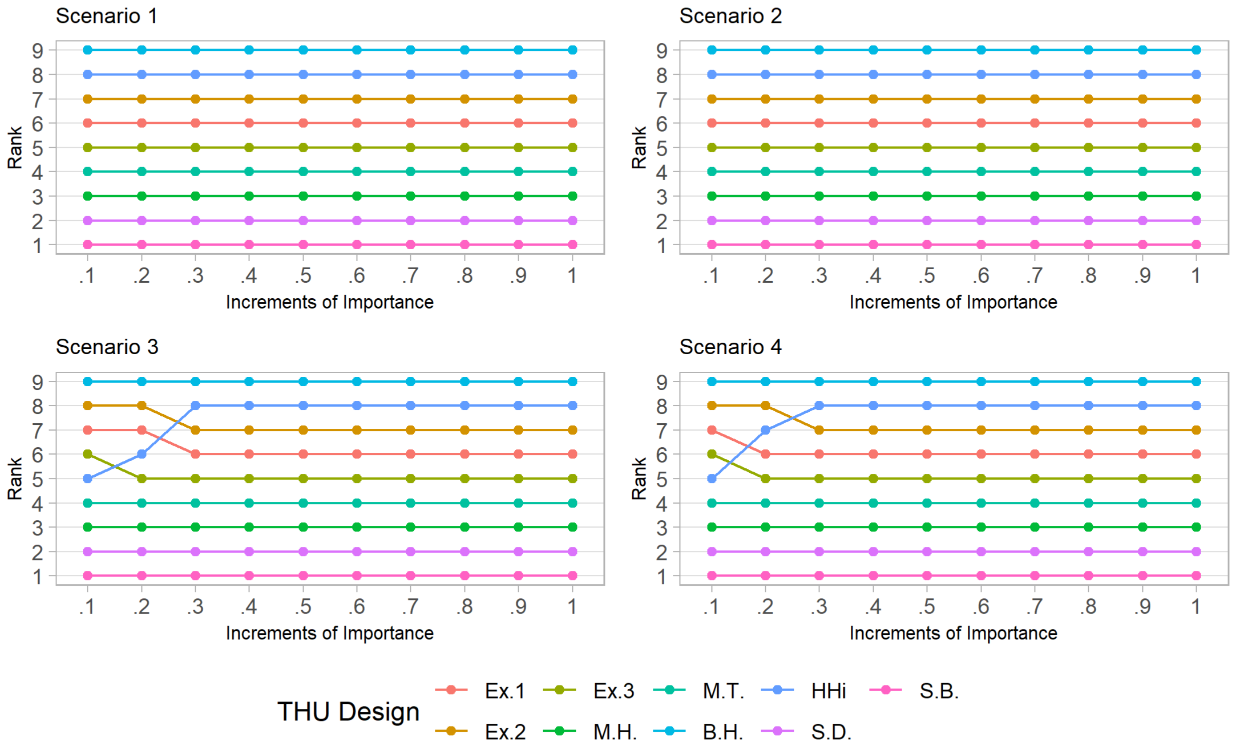


Figure 36: Sensitivity Analysis on Standard of Living for Weighted Sum during all Scenarios

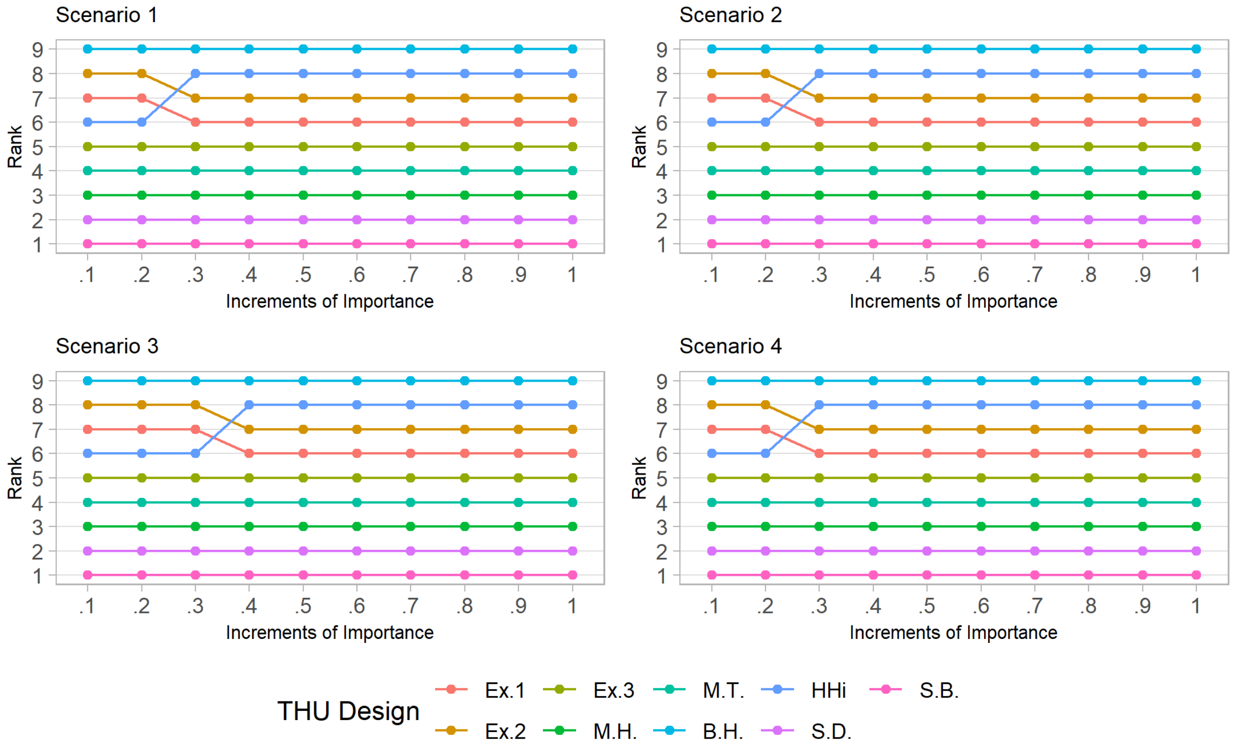


Figure 37: Sensitivity Analysis on Safety for Weighted Sum during all Scenarios

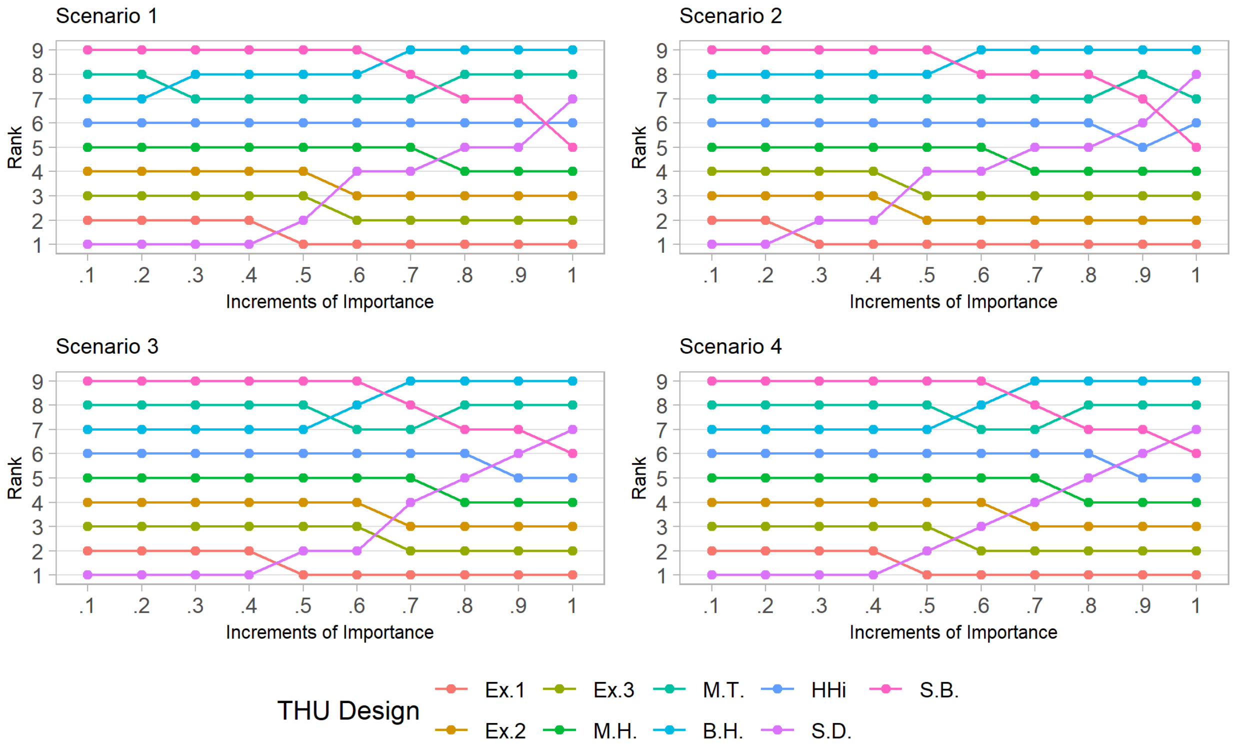


Figure 38: Sensitivity Analysis on Feasibility for TOPSIS during all Scenarios

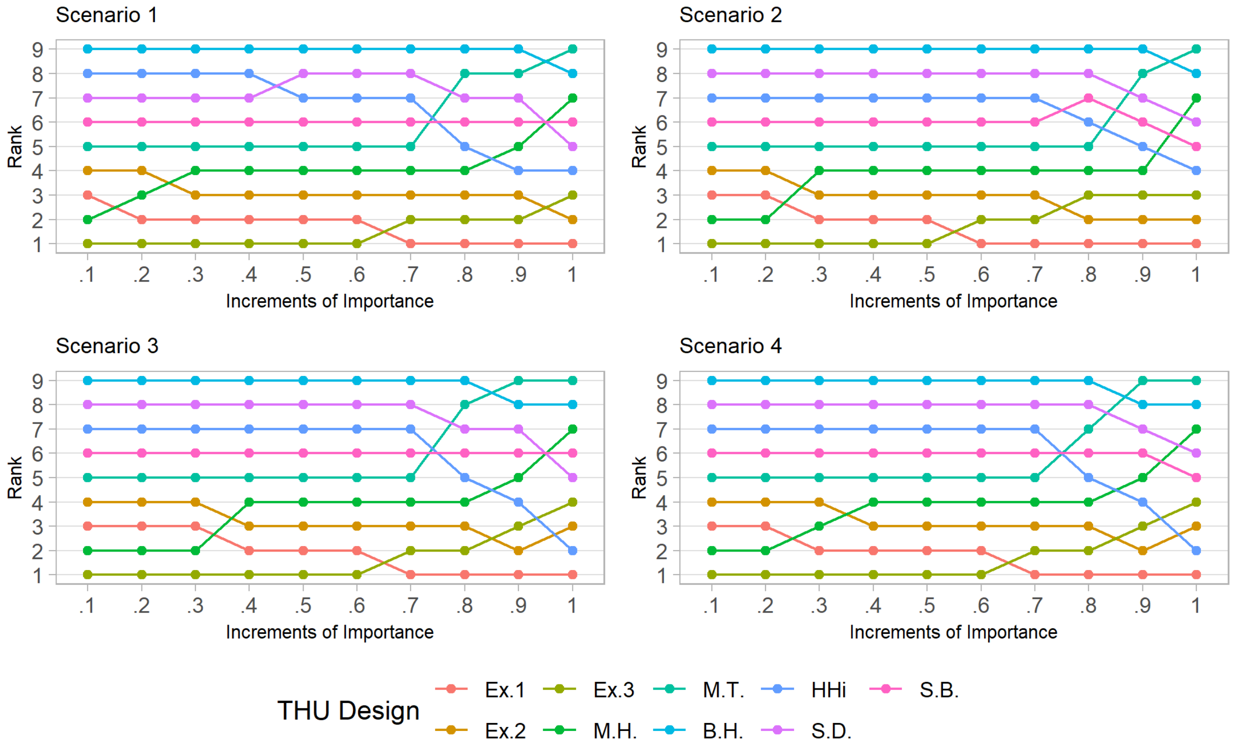
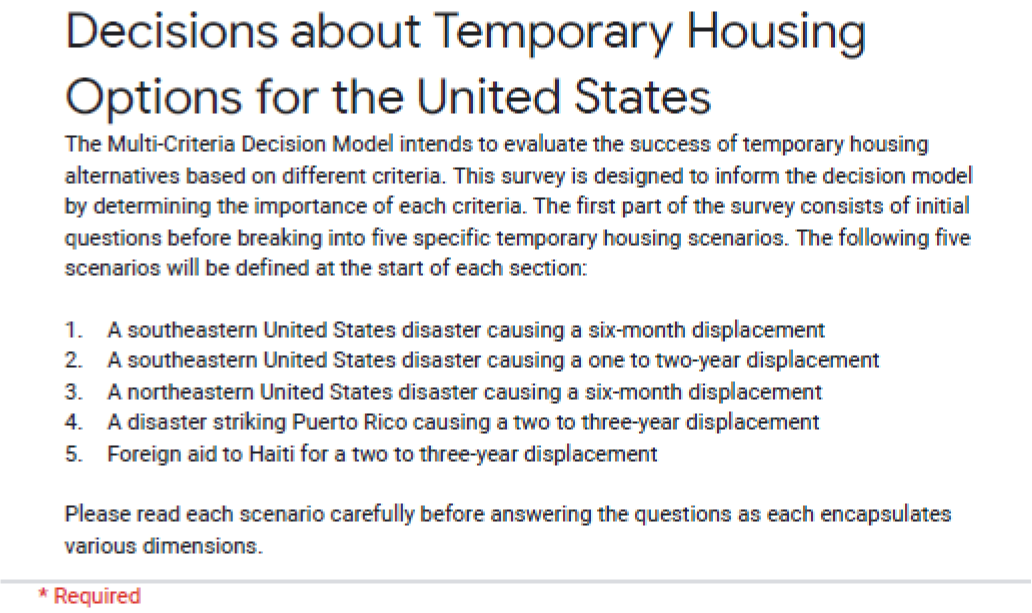


Figure 39: Sensitivity Analysis on Cost for TOPSIS during all Scenarios

Survey Methodology – Expert Elicitation:



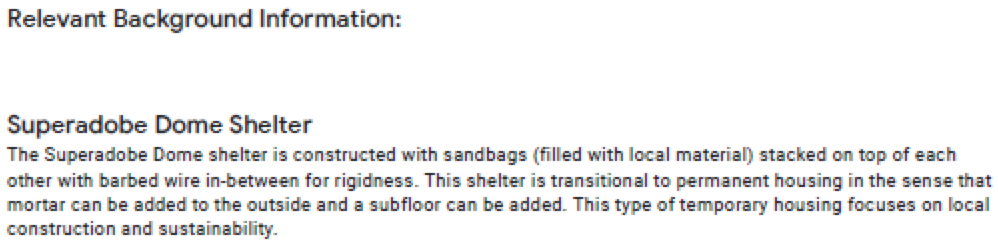
Decisions about Temporary Housing Options for the United States

The Multi-Criteria Decision Model intends to evaluate the success of temporary housing alternatives based on different criteria. This survey is designed to inform the decision model by determining the importance of each criteria. The first part of the survey consists of initial questions before breaking into five specific temporary housing scenarios. The following five scenarios will be defined at the start of each section:

1. A southeastern United States disaster causing a six-month displacement
2. A southeastern United States disaster causing a one to two-year displacement
3. A northeastern United States disaster causing a six-month displacement
4. A disaster striking Puerto Rico causing a two to three-year displacement
5. Foreign aid to Haiti for a two to three-year displacement

Please read each scenario carefully before answering the questions as each encapsulates various dimensions.

* Required



Relevant Background Information:

Superadobe Dome Shelter

The Superadobe Dome shelter is constructed with sandbags (filled with local material) stacked on top of each other with barbed wire in-between for rigidness. This shelter is transitional to permanent housing in the sense that mortar can be added to the outside and a subfloor can be added. This type of temporary housing focuses on local construction and sustainability.

Image Credit: Hany Abulnour, Adham. "The Post-Disaster Temporary Dwelling: Fundamentals of Provision, Design and Construction." HBRC Journal 10, no. 1 (2013): 10–24. https://doi.org/10.1016/j.hbrcj.2013.06.001.

Ex-Container

The Ex-Container shelter is manufactured in a factory in modular units that can be organized depending on the displaced populations needs. The modular organization seen above are the only methodologies considered in this study. These units are designed for quick implementation and flexibility for occupant requirements due to the modular design.

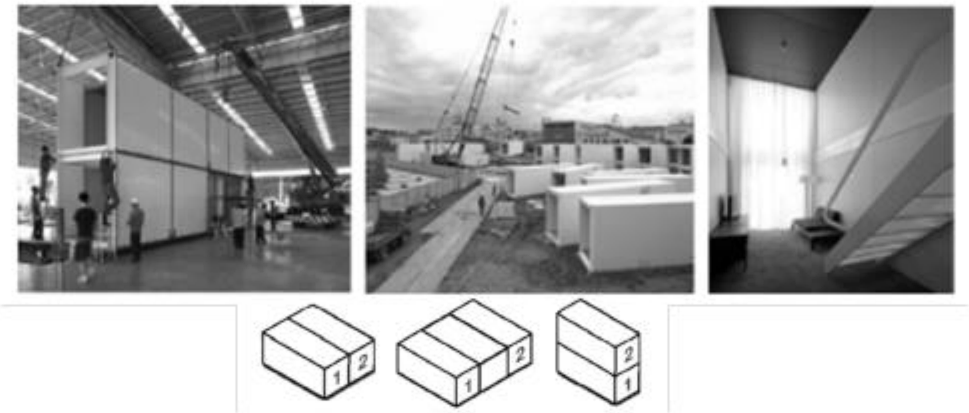
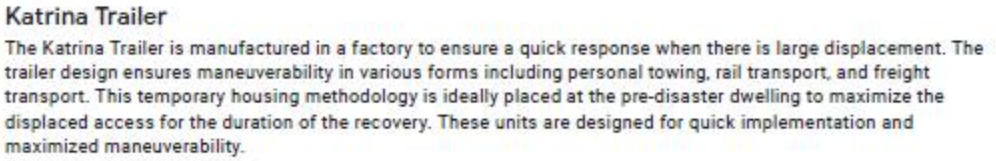


Image Credit: Hany Abulnour, Adham. “The Post-Disaster Temporary Dwelling: Fundamentals of Provision, Design and Construction.” HBRC Journal 10, no. 1 (2013): 10–24. https://doi.org/10.1016/j.hbrcj.2013.06.001.

Blog House

The Blog House is constructed with cardboard tubes, sandbag foundations, fasteners designed to require minimal tools, and a fabric roof. This type of temporary housing provides a sufficient shelter that can be constructed onsite by the displaced population at a low cost and environmental impact. However, this option would do best in moderate climates due to a lack of insulation.

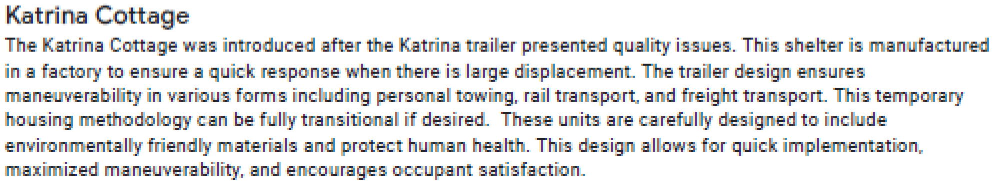
Image Credit: Hany Abulnour, Adham. “The Post-Disaster Temporary Dwelling: Fundamentals of Provision, Design and Construction.” HBRC Journal 10, no. 1 (2013): 10–24. https://doi.org/10.1016/j.hbrcj.2013.06.001.



Katrina Trailer

The Katrina Trailer is manufactured in a factory to ensure a quick response when there is large displacement. The trailer design ensures maneuverability in various forms including personal towing, rail transport, and freight transport. This temporary housing methodology is ideally placed at the pre-disaster dwelling to maximize the displaced access for the duration of the recovery. These units are designed for quick implementation and maximized maneuverability.

Image Credit: Hany Abulnour, Adham. "The Post-Disaster Temporary Dwelling: Fundamentals of Provision, Design and Construction." HBRC Journal 10, no. 1 (2013): 10–24. https://doi.org/10.1016/j.hbrcj.2013.06.001.



Katrina Cottage

The Katrina Cottage was introduced after the Katrina trailer presented quality issues. This shelter is manufactured in a factory to ensure a quick response when there is large displacement. The trailer design ensures maneuverability in various forms including personal towing, rail transport, and freight transport. This temporary housing methodology can be fully transitional if desired. These units are carefully designed to include environmentally friendly materials and protect human health. This design allows for quick implementation, maximized maneuverability, and encourages occupant satisfaction.

Image Credit: Hany Abulnour, Adham. "The Post-Disaster Temporary Dwelling: Fundamentals of Provision, Design and Construction." HBRC Journal 10, no. 1 (2013): 10–24. https://doi.org/10.1016/j.hbrcj.2013.06.001.

HHi House

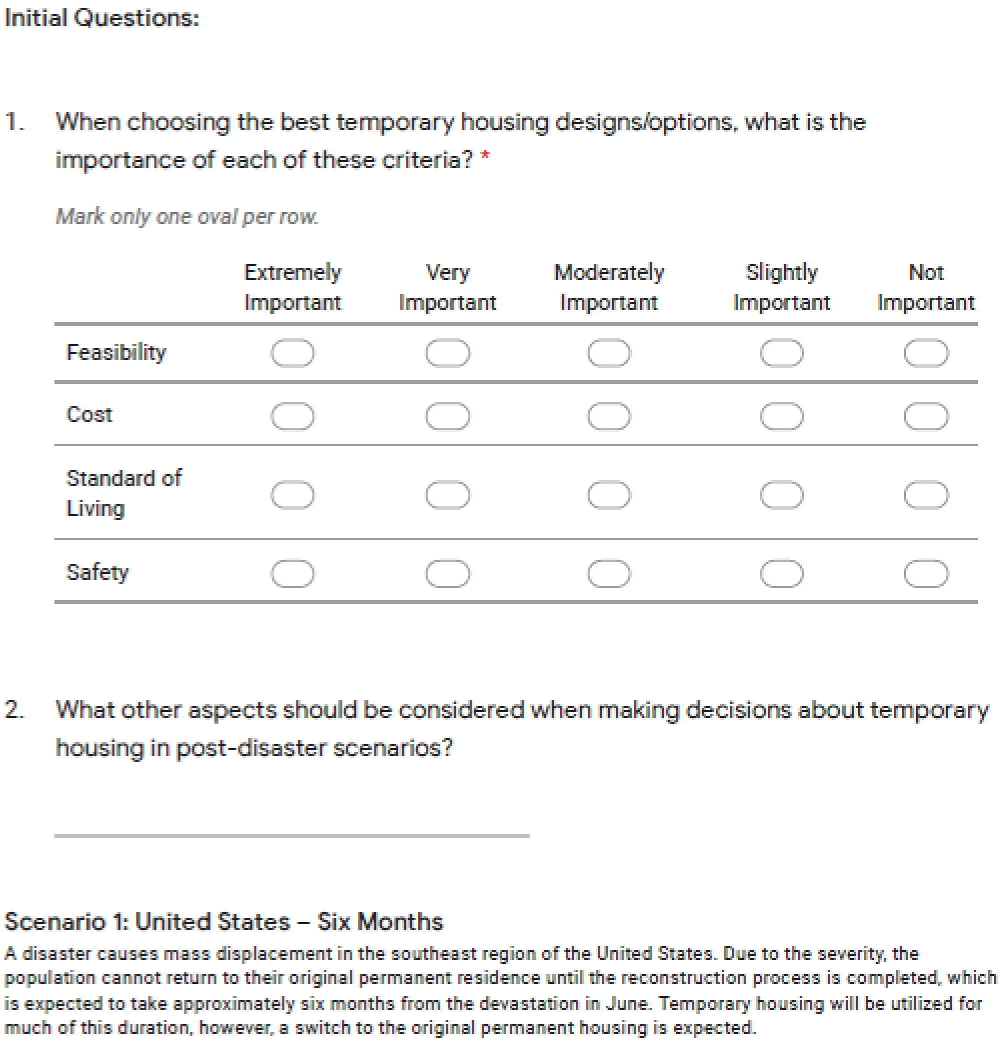
The HHI House is designed with humanitarian operations in mind. The unit is framed with lightweight material that can be easily deconstructed. It provides a shelter lifted off the ground with semi rigid walls. This temporary housing methodology has been designed to be upgraded to a long-term solution, if desired. This design allows for a local implementation, maximized reutilization, and potential to handle longer displacement events.

Image Credit: Ohlson, Stuart. “Designing and Developing Sustainable Housing for Refugee and Disaster Communities.” IEEE, 2014.

Shelter Box

The Shelter Box is designed for compact storage and shipping for remote locations. The unit comes if a variety of different sizes and consists of high-quality fabric and tent poles to retain heat, withstand 70 mph winds, provide protection from further debris. This unit would benefit from the "shelters in a shelter" option to provide privacy for families and individuals at mass public shelters in the aftermath of events.

Image Credit: https://www.shelterboxusa.org/



Initial Questions:

1. When choosing the best temporary housing designs/options, what is the importance of each of these criteria? *

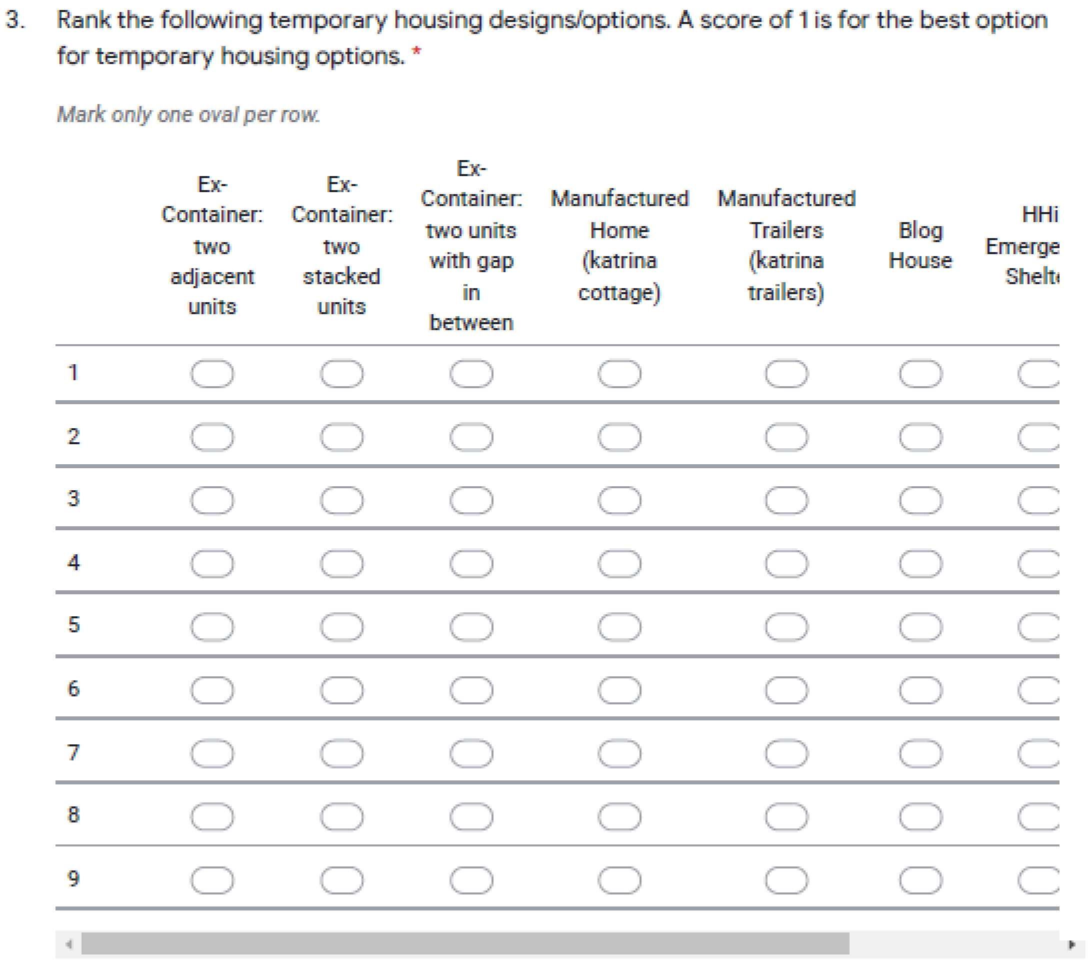
Mark only one oval per row.

	Extremely Important	Very Important	Moderately Important	Slightly Important	Not Important
Feasibility	○	○	○	○	○
Cost	○	○	○	○	○
Standard of Living	○	○	○	○	○
Safety	○	○	○	○	○

2. What other aspects should be considered when making decisions about temporary housing in post-disaster scenarios?

Scenario 1: United States – Six Months

A disaster causes mass displacement in the southeast region of the United States. Due to the severity, the population cannot return to their original permanent residence until the reconstruction process is completed, which is expected to take approximately six months from the devastation in June. Temporary housing will be utilized for much of this duration, however, a switch to the original permanent housing is expected.



3. Rank the following temporary housing designs/options. A score of 1 is for the best option for temporary housing options. *

Mark only one oval per row.

	Ex-Container: two adjacent units	Ex-Container: two stacked units	Ex-Container: two units with gap in between	Manufactured Home (katrina cottage)	Manufactured Trailers (katrina trailers)	Blog House	HHi Emerge Shelt
1	○	○	○	○	○	○	○
2	○	○	○	○	○	○	○
3	○	○	○	○	○	○	○
4	○	○	○	○	○	○	○
5	○	○	○	○	○	○	○
6	○	○	○	○	○	○	○
7	○	○	○	○	○	○	○
8	○	○	○	○	○	○	○
9	○	○	○	○	○	○	○

4. How important are these feasibility aspects to the success of the design/alternative? *

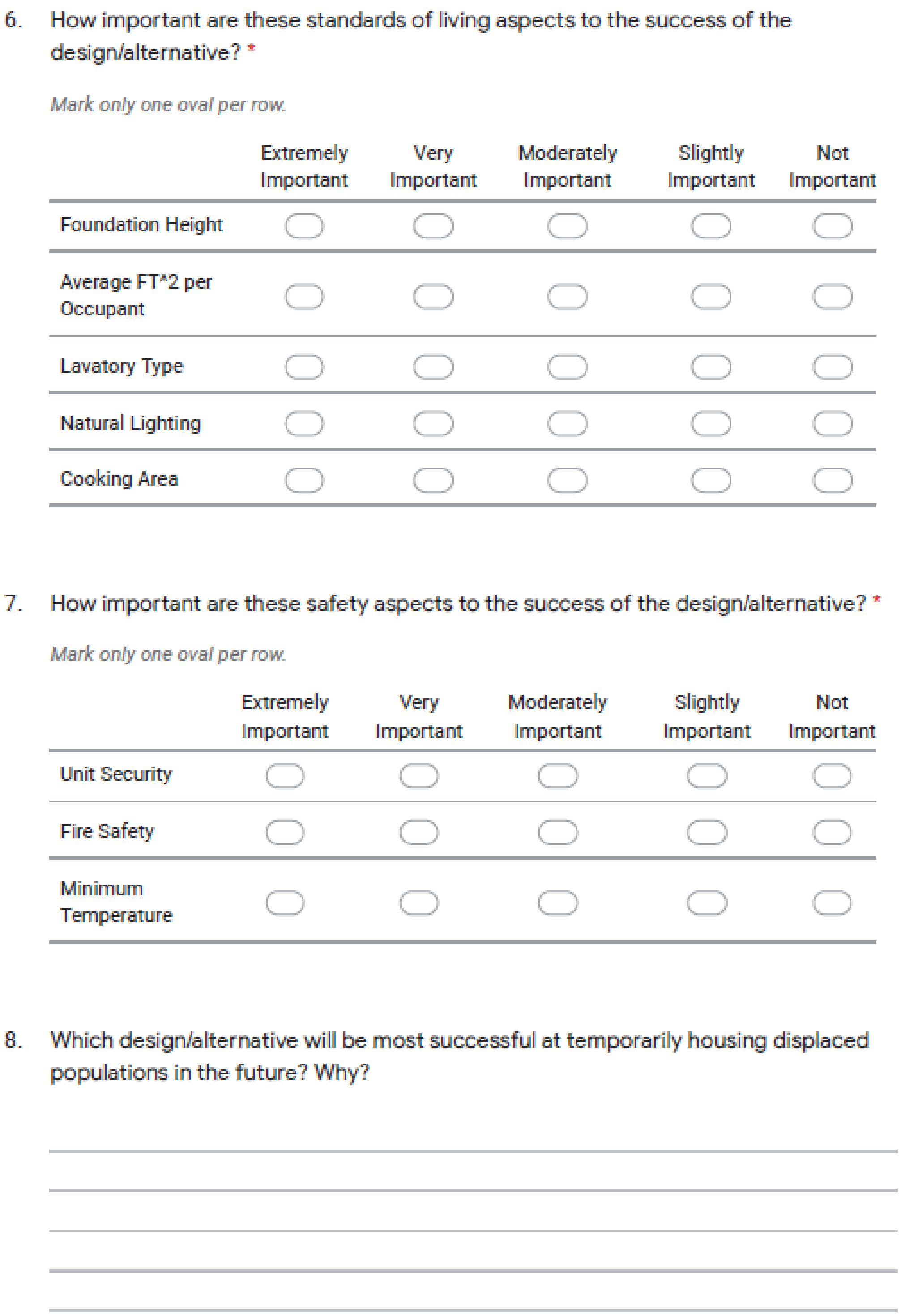
Mark only one oval per row.

	Extremely Important	Very Important	Moderately Important	Slightly Important	Not Important
Mean Occupancy	○	○	○	○	○
Assembly Time	○	○	○	○	○
Sustainability	○	○	○	○	○
Methods of Transport	○	○	○	○	○

5. How important are these economic aspects to the success of the design/alternative? *

Mark only one oval per row.

	Extremely Important	Very Important	Moderately Important	Slightly Important	Not Important
Purchase Price	○	○	○	○	○
Maximum Life Span	○	○	○	○	○
Packaging Weight	○	○	○	○	○
Packaging Volume	○	○	○	○	○



6. How important are these standards of living aspects to the success of the design/alternative? *

Mark only one oval per row.

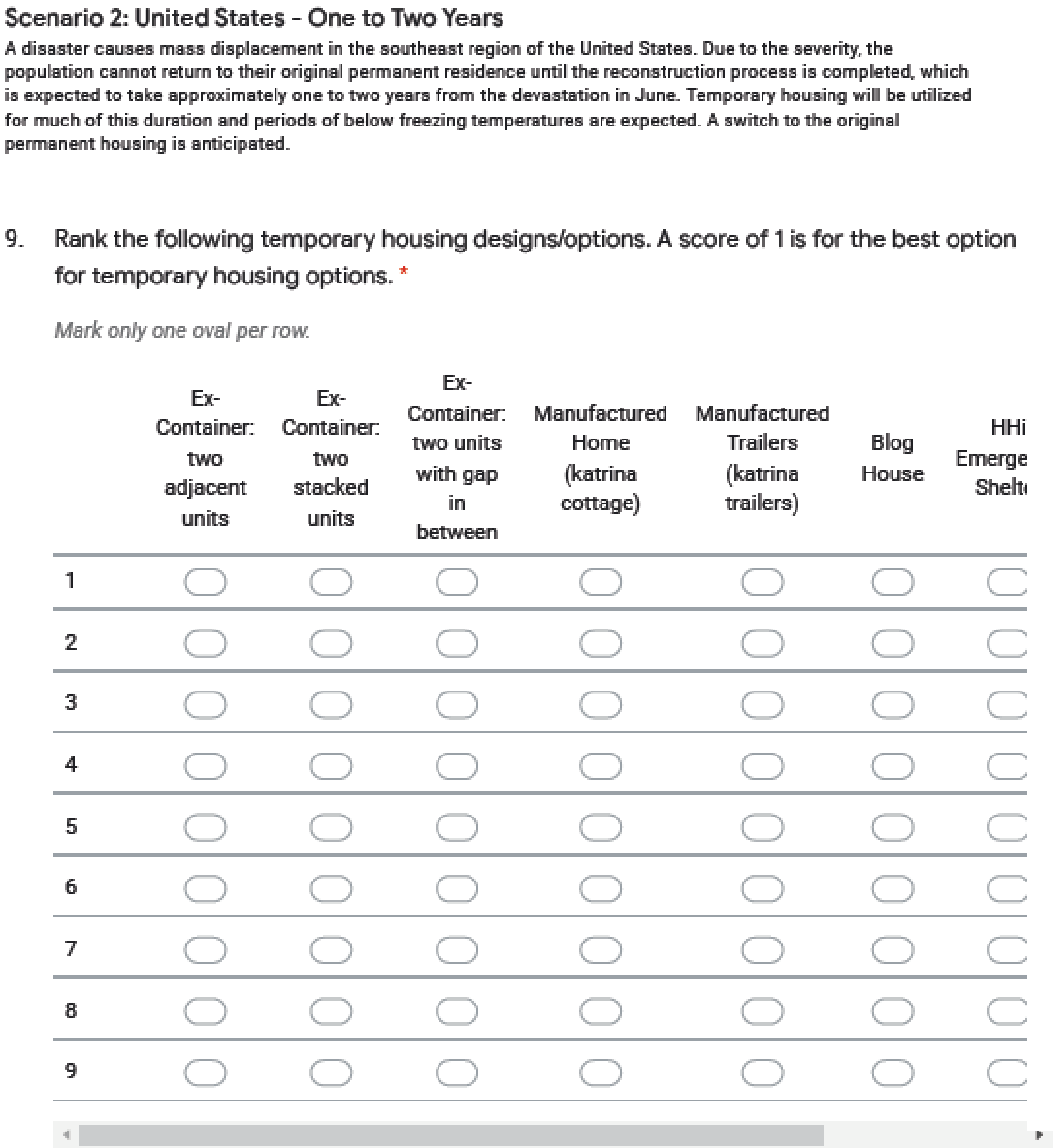
	Extremely Important	Very Important	Moderately Important	Slightly Important	Not Important
Foundation Height	○	○	○	○	○
Average FT^2 per Occupant	○	○	○	○	○
Lavatory Type	○	○	○	○	○
Natural Lighting	○	○	○	○	○
Cooking Area	○	○	○	○	○

7. How important are these safety aspects to the success of the design/alternative? *

Mark only one oval per row.

	Extremely Important	Very Important	Moderately Important	Slightly Important	Not Important
Unit Security	○	○	○	○	○
Fire Safety	○	○	○	○	○
Minimum Temperature	○	○	○	○	○

8. Which design/alternative will be most successful at temporarily housing displaced populations in the future? Why?



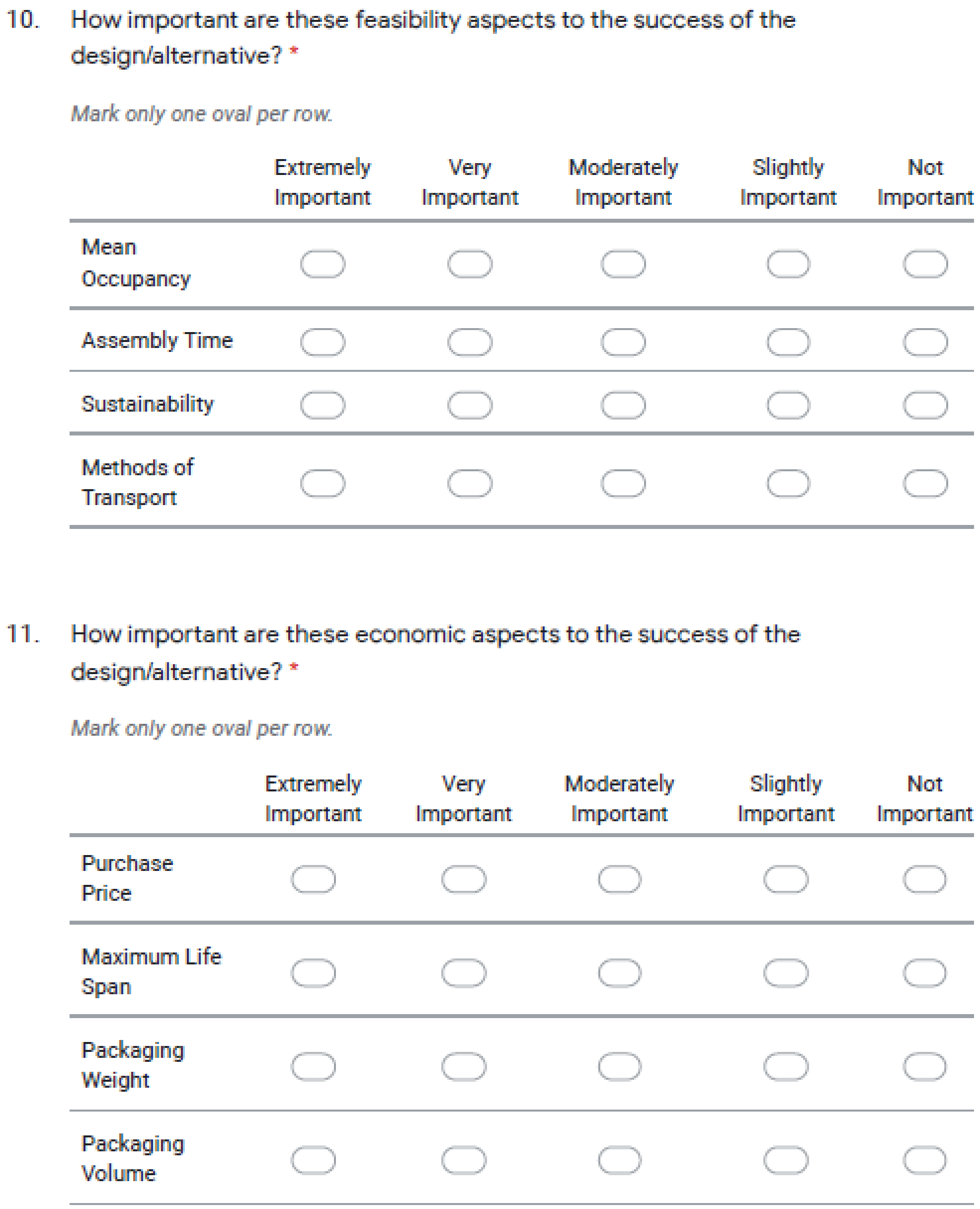
Scenario 2: United States - One to Two Years

A disaster causes mass displacement in the southeast region of the United States. Due to the severity, the population cannot return to their original permanent residence until the reconstruction process is completed, which is expected to take approximately one to two years from the devastation in June. Temporary housing will be utilized for much of this duration and periods of below freezing temperatures are expected. A switch to the original permanent housing is anticipated.

9. Rank the following temporary housing designs/options. A score of 1 is for the best option for temporary housing options. *

Mark only one oval per row.

	Ex-Container: two adjacent units	Ex-Container: two stacked units	Ex-Container: two units with gap in between	Manufactured Home (katrina cottage)	Manufactured Trailers (katrina trailers)	Blog House	HHi Emerge Shelt
1	○	○	○	○	○	○	○
2	○	○	○	○	○	○	○
3	○	○	○	○	○	○	○
4	○	○	○	○	○	○	○
5	○	○	○	○	○	○	○
6	○	○	○	○	○	○	○
7	○	○	○	○	○	○	○
8	○	○	○	○	○	○	○
9	○	○	○	○	○	○	○



10. How important are these feasibility aspects to the success of the design/alternative? *

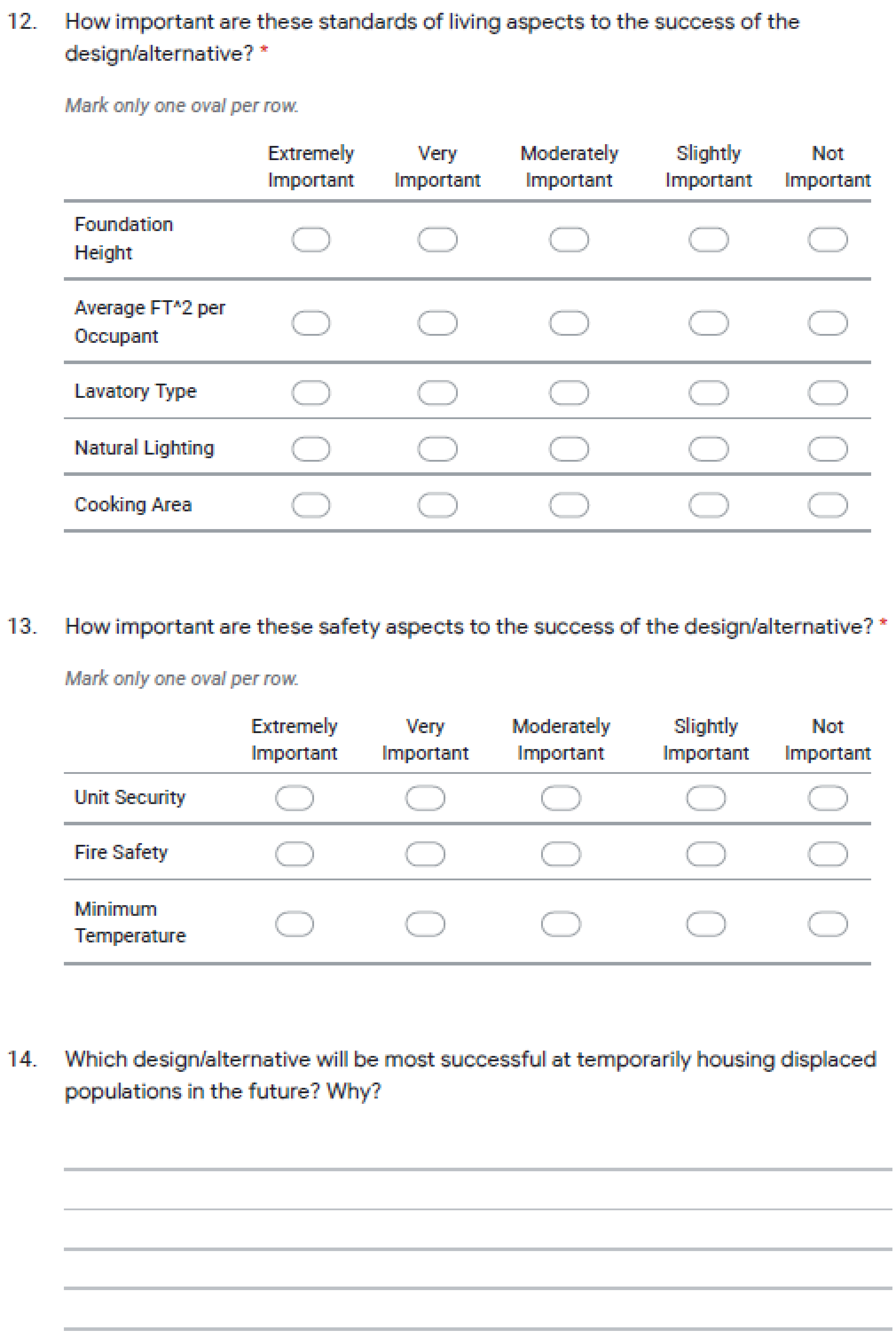
Mark only one oval per row.

	Extremely Important	Very Important	Moderately Important	Slightly Important	Not Important
Mean Occupancy	○	○	○	○	○
Assembly Time	○	○	○	○	○
Sustainability	○	○	○	○	○
Methods of Transport	○	○	○	○	○

11. How important are these economic aspects to the success of the design/alternative? *

Mark only one oval per row.

	Extremely Important	Very Important	Moderately Important	Slightly Important	Not Important
Purchase Price	○	○	○	○	○
Maximum Life Span	○	○	○	○	○
Packaging Weight	○	○	○	○	○
Packaging Volume	○	○	○	○	○



12. How important are these standards of living aspects to the success of the design/alternative? *

Mark only one oval per row.

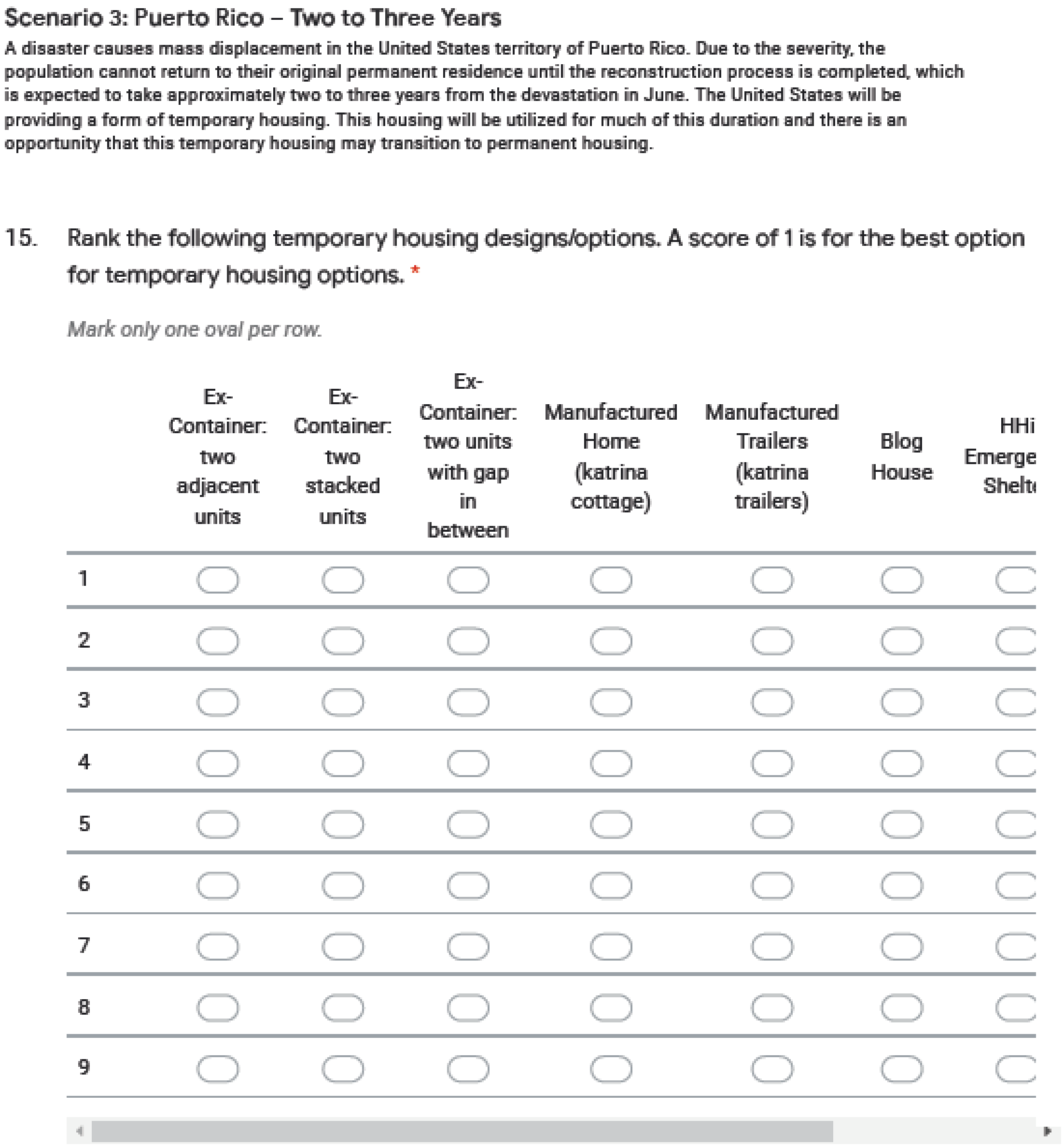
	Extremely Important	Very Important	Moderately Important	Slightly Important	Not Important
Foundation Height	○	○	○	○	○
Average FT^2 per Occupant	○	○	○	○	○
Lavatory Type	○	○	○	○	○
Natural Lighting	○	○	○	○	○
Cooking Area	○	○	○	○	○

13. How important are these safety aspects to the success of the design/alternative? *

Mark only one oval per row.

	Extremely Important	Very Important	Moderately Important	Slightly Important	Not Important
Unit Security	○	○	○	○	○
Fire Safety	○	○	○	○	○
Minimum Temperature	○	○	○	○	○

14. Which design/alternative will be most successful at temporarily housing displaced populations in the future? Why?



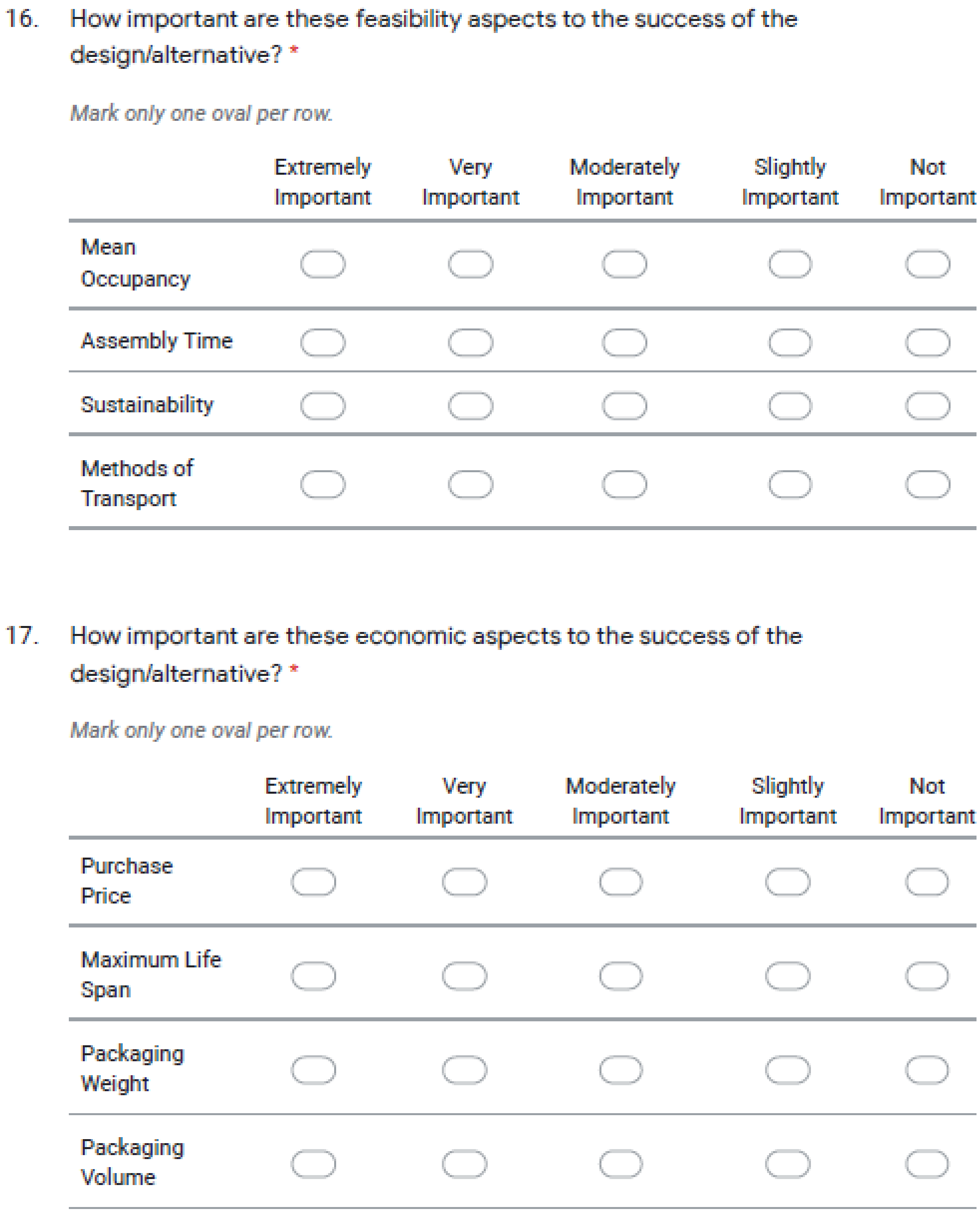
Scenario 3: Puerto Rico – Two to Three Years

A disaster causes mass displacement in the United States territory of Puerto Rico. Due to the severity, the population cannot return to their original permanent residence until the reconstruction process is completed, which is expected to take approximately two to three years from the devastation in June. The United States will be providing a form of temporary housing. This housing will be utilized for much of this duration and there is an opportunity that this temporary housing may transition to permanent housing.

15. Rank the following temporary housing designs/options. A score of 1 is for the best option for temporary housing options. *

Mark only one oval per row.

	Ex-Container: two adjacent units	Ex-Container: two stacked units	Ex-Container: two units with gap in between	Manufactured Home (katrina cottage)	Manufactured Trailers (katrina trailers)	Blog House	HHi Emerge Shelt
1	○	○	○	○	○	○	○
2	○	○	○	○	○	○	○
3	○	○	○	○	○	○	○
4	○	○	○	○	○	○	○
5	○	○	○	○	○	○	○
6	○	○	○	○	○	○	○
7	○	○	○	○	○	○	○
8	○	○	○	○	○	○	○
9	○	○	○	○	○	○	○



16. How important are these feasibility aspects to the success of the design/alternative? *

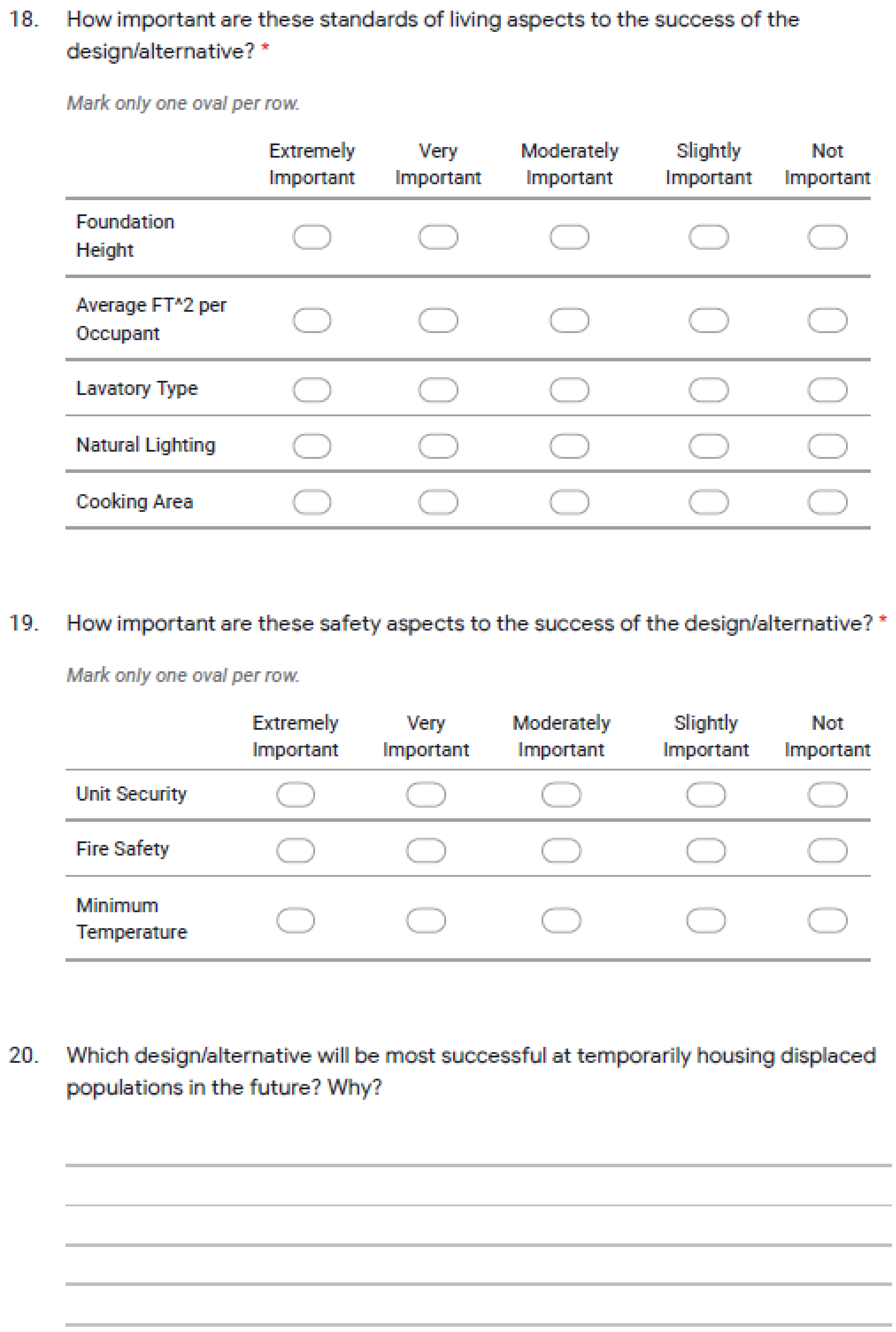
Mark only one oval per row.

	Extremely Important	Very Important	Moderately Important	Slightly Important	Not Important
Mean Occupancy	○	○	○	○	○
Assembly Time	○	○	○	○	○
Sustainability	○	○	○	○	○
Methods of Transport	○	○	○	○	○

17. How important are these economic aspects to the success of the design/alternative? *

Mark only one oval per row.

	Extremely Important	Very Important	Moderately Important	Slightly Important	Not Important
Purchase Price	○	○	○	○	○
Maximum Life Span	○	○	○	○	○
Packaging Weight	○	○	○	○	○
Packaging Volume	○	○	○	○	○



18. How important are these standards of living aspects to the success of the design/alternative? *

Mark only one oval per row.

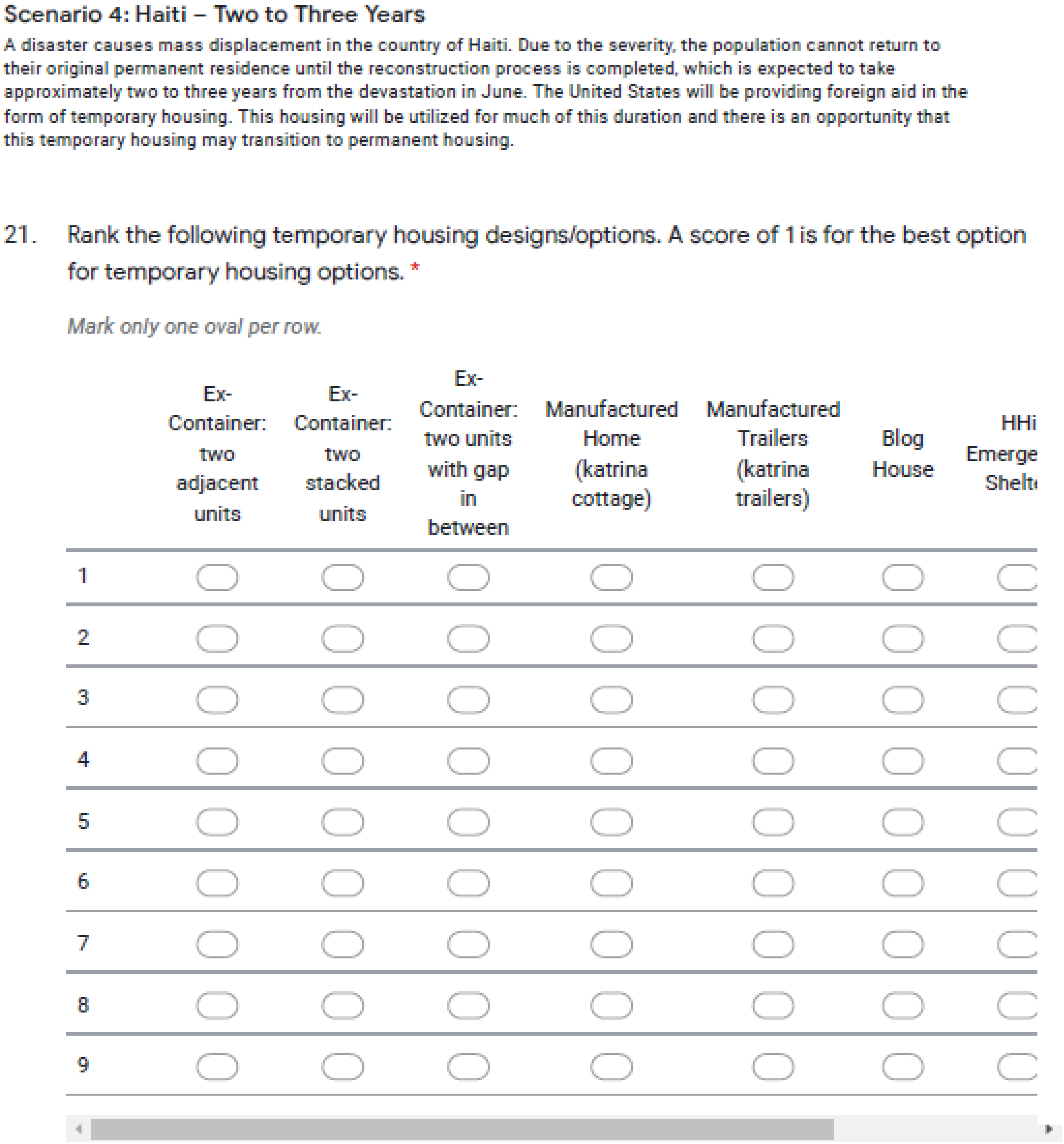
	Extremely Important	Very Important	Moderately Important	Slightly Important	Not Important
Foundation Height	○	○	○	○	○
Average FT^2 per Occupant	○	○	○	○	○
Lavatory Type	○	○	○	○	○
Natural Lighting	○	○	○	○	○
Cooking Area	○	○	○	○	○

19. How important are these safety aspects to the success of the design/alternative? *

Mark only one oval per row.

	Extremely Important	Very Important	Moderately Important	Slightly Important	Not Important
Unit Security	○	○	○	○	○
Fire Safety	○	○	○	○	○
Minimum Temperature	○	○	○	○	○

20. Which design/alternative will be most successful at temporarily housing displaced populations in the future? Why?



Scenario 4: Haiti – Two to Three Years

A disaster causes mass displacement in the country of Haiti. Due to the severity, the population cannot return to their original permanent residence until the reconstruction process is completed, which is expected to take approximately two to three years from the devastation in June. The United States will be providing foreign aid in the form of temporary housing. This housing will be utilized for much of this duration and there is an opportunity that this temporary housing may transition to permanent housing.

21. Rank the following temporary housing designs/options. A score of 1 is for the best option for temporary housing options. *

Mark only one oval per row.

	Ex-Container: two adjacent units	Ex-Container: two stacked units	Ex-Container: two units with gap in between	Manufactured Home (katrina cottage)	Manufactured Trailers (katrina trailers)	Blog House	HHi Emerge Shelt
1	○	○	○	○	○	○	○
2	○	○	○	○	○	○	○
3	○	○	○	○	○	○	○
4	○	○	○	○	○	○	○
5	○	○	○	○	○	○	○
6	○	○	○	○	○	○	○
7	○	○	○	○	○	○	○
8	○	○	○	○	○	○	○
9	○	○	○	○	○	○	○

22. How important are these feasibility aspects to the success of the design/alternative? *

Mark only one oval per row.

	Extremely Important	Very Important	Moderately Important	Slightly Important	Not Important
Mean Occupancy	○	○	○	○	○
Assembly Time	○	○	○	○	○
Sustainability	○	○	○	○	○
Methods of Transport	○	○	○	○	○

23. How important are these economic aspects to the success of the design/alternative? *

Mark only one oval per row.

	Extremely Important	Very Important	Moderately Important	Slightly Important	Not Important
Purchase Price	○	○	○	○	○
Maximum Life Span	○	○	○	○	○
Packaging Weight	○	○	○	○	○
Packaging Volume	○	○	○	○	○

24. How important are these standards of living aspects to the success of the design/alternative? *

Mark only one oval per row.

	Extremely Important	Very Important	Moderately Important	Slightly Important	Not Important
Foundation Height	○	○	○	○	○
Average FT^2 per Occupant	○	○	○	○	○
Lavatory Type	○	○	○	○	○
Natural Lighting	○	○	○	○	○
Cooking Area	○	○	○	○	○

25. How important are these safety aspects to the success of the design/alternative? *

Mark only one oval per row.

	Extremely Important	Very Important	Moderately Important	Slightly Important	Not Important
Unit Security	○	○	○	○	○
Fire Safety	○	○	○	○	○
Minimum Temperature	○	○	○	○	○

26. Which design/alternative will be most successful at temporarily housing displaced populations in the future? Why?

APPENDIX B, TEMPORARY HOUSING OPERATIONS: A SIMULATION-BASED INVENTORY MANAGEMENT APPROACH USING THE NEWSVENDOR MODEL

B.1 Alabama

B.1.1 Inventory Optimization Results

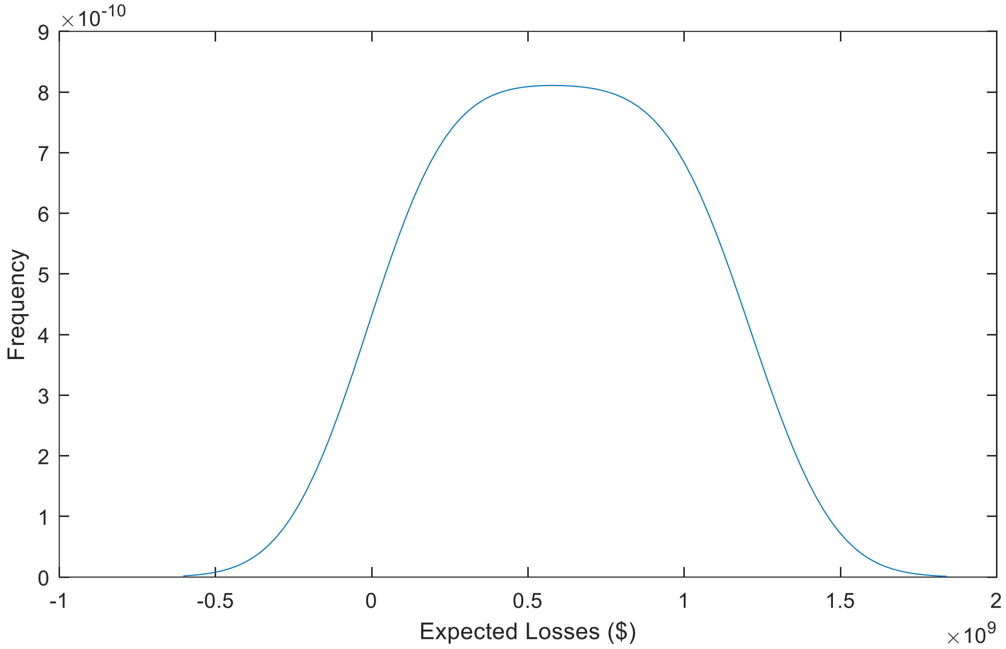


Figure 40: Alabama Density of Mean Expected Losses

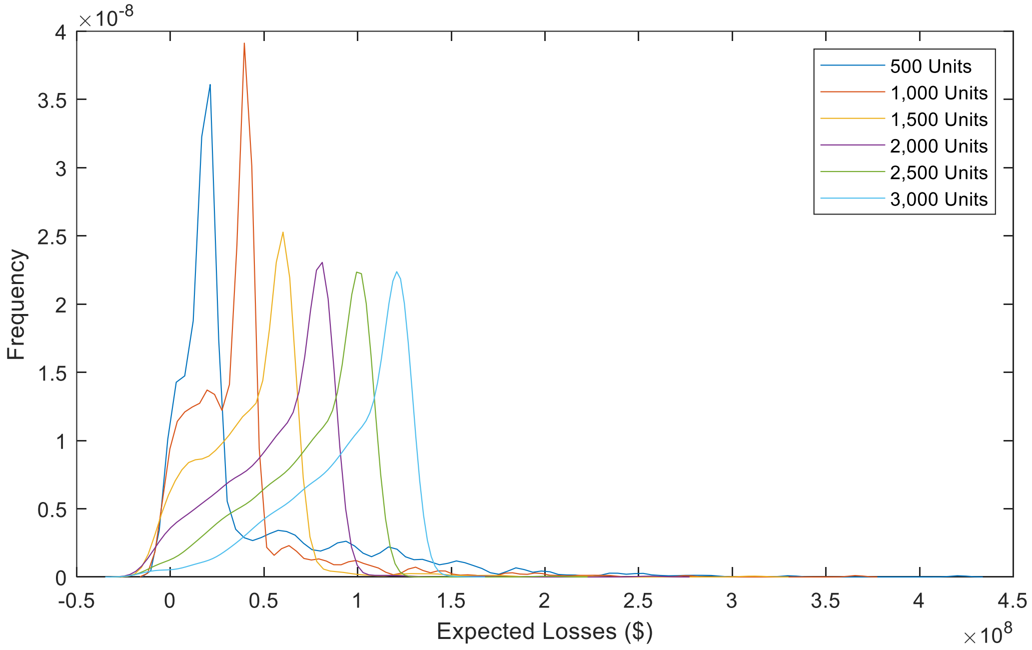


Figure 41: Alabama Overlay of Expected Losses by Stocking

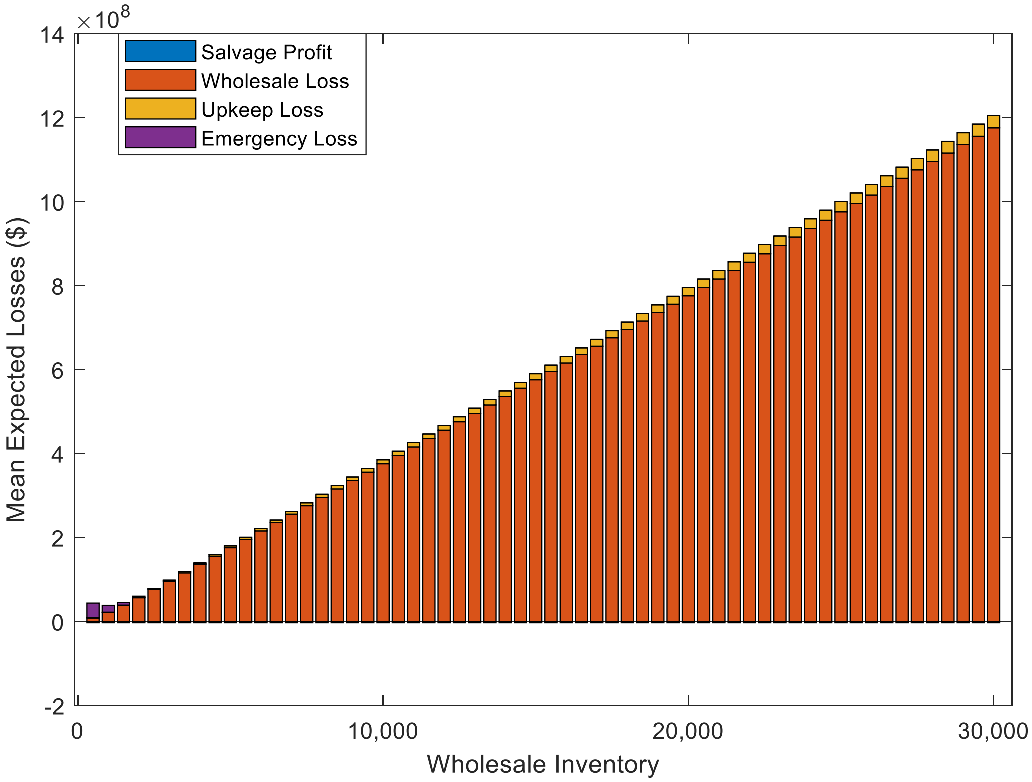


Figure 42: Alabama's Expected Losses for Wholesale

B.1.2 Sensitivity – Housing Damage for Prolonged Displacement

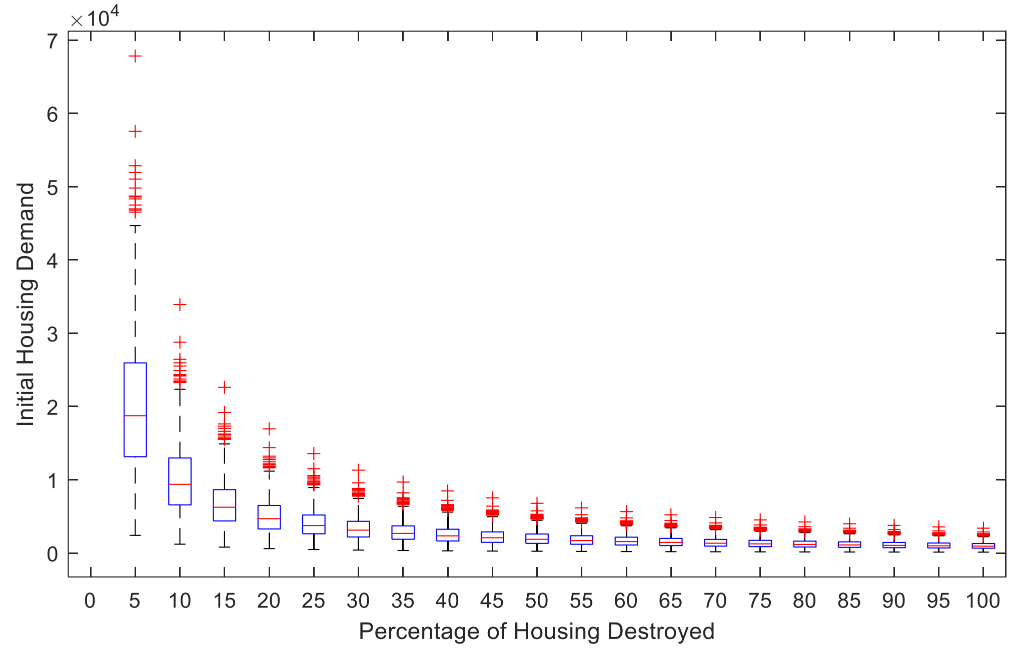


Figure 43: Alabama Sensitivity Analysis on Amount of Housing Damage to Require Temporary Housing

B.1.3 Sensitivity – Residential Damage

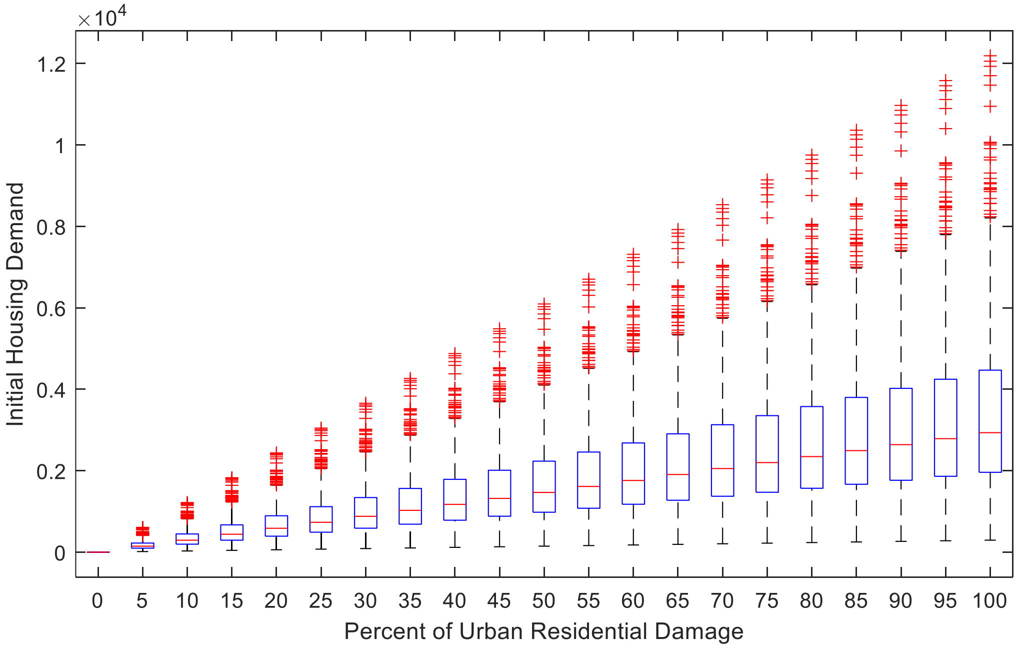


Figure 44: Alabama Sensitivity Analysis on Urban Residential Damage

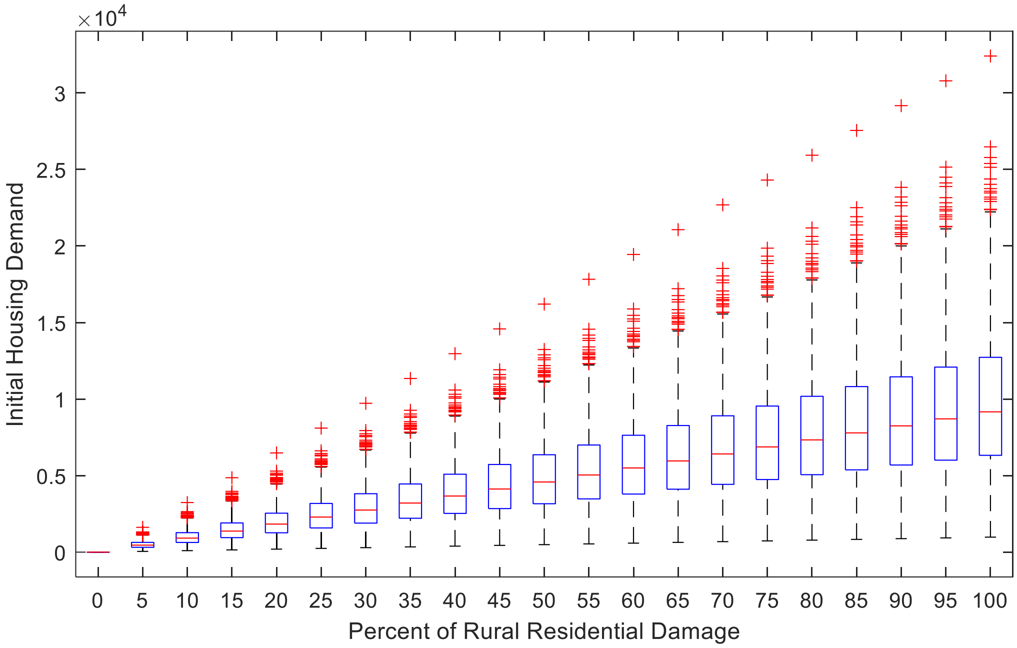


Figure 45: Alabama Sensitivity Analysis on Rural Residential Damage

B.1.4 Sensitivity - Svi and Homelessness sensitivity

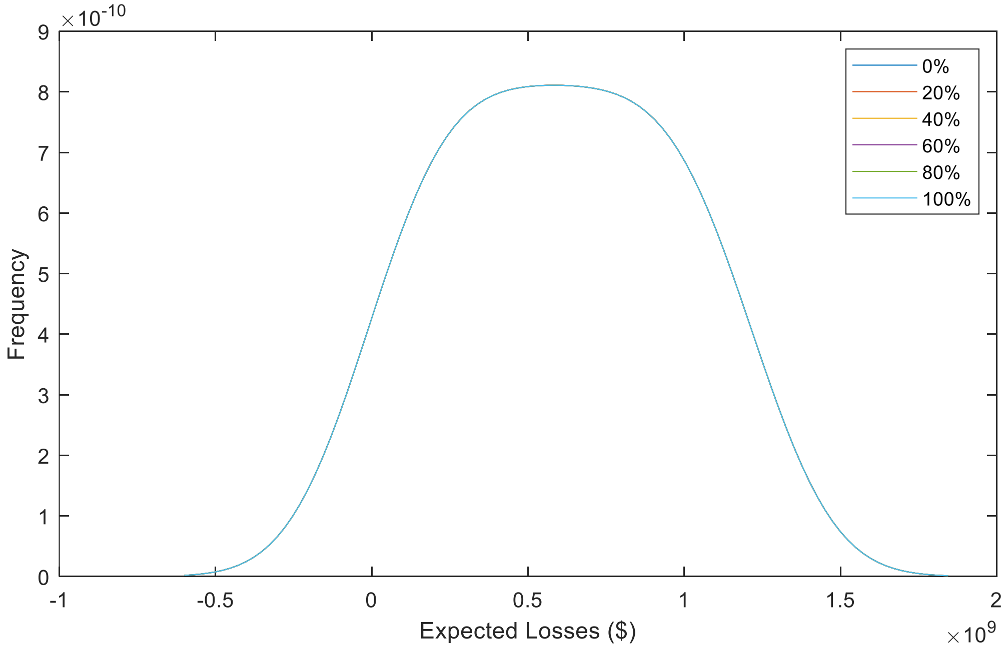


Figure 46: Alabama Sensitivity of Expected Losses from Social Vulnerability

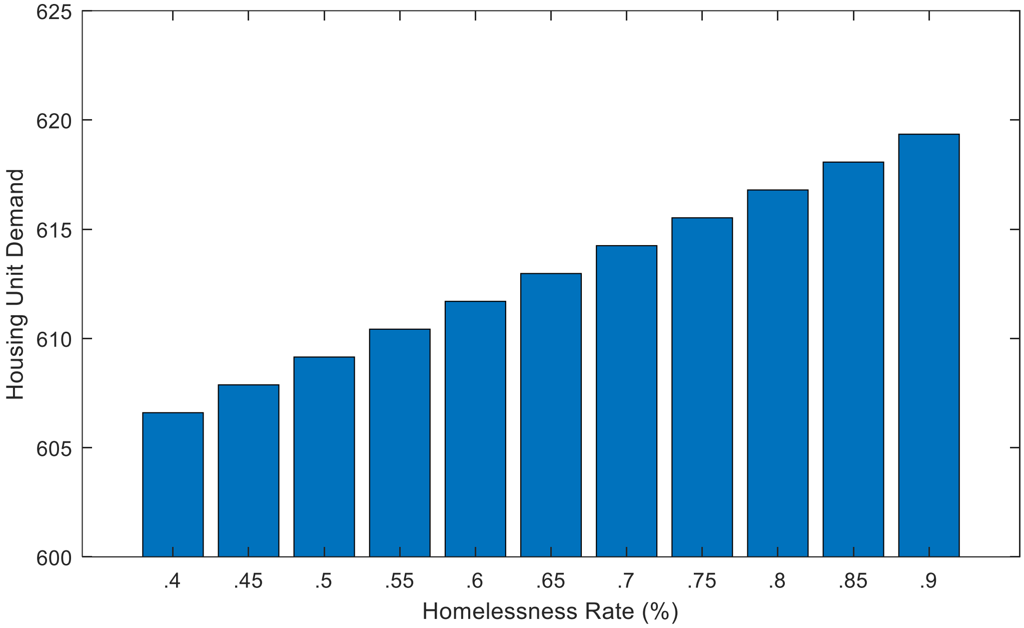


Figure 47: Alabama Sensitivity of Housing Demand from Homelessness Rate

B.2 Florida

B.2.1 Inventory Optimization Results

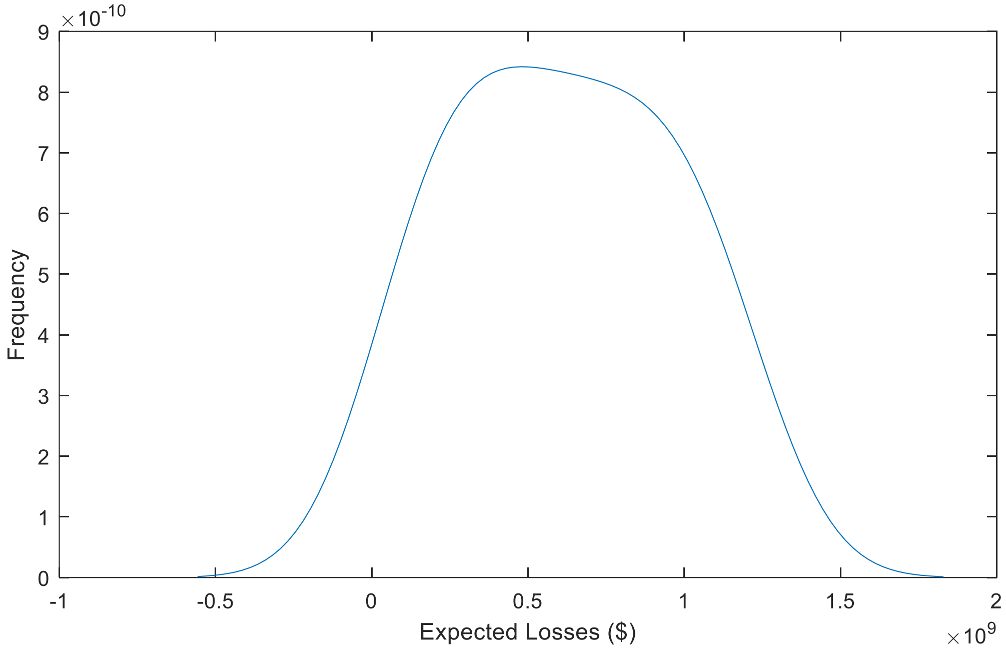


Figure 48: Florida Density of Mean Expected Losses

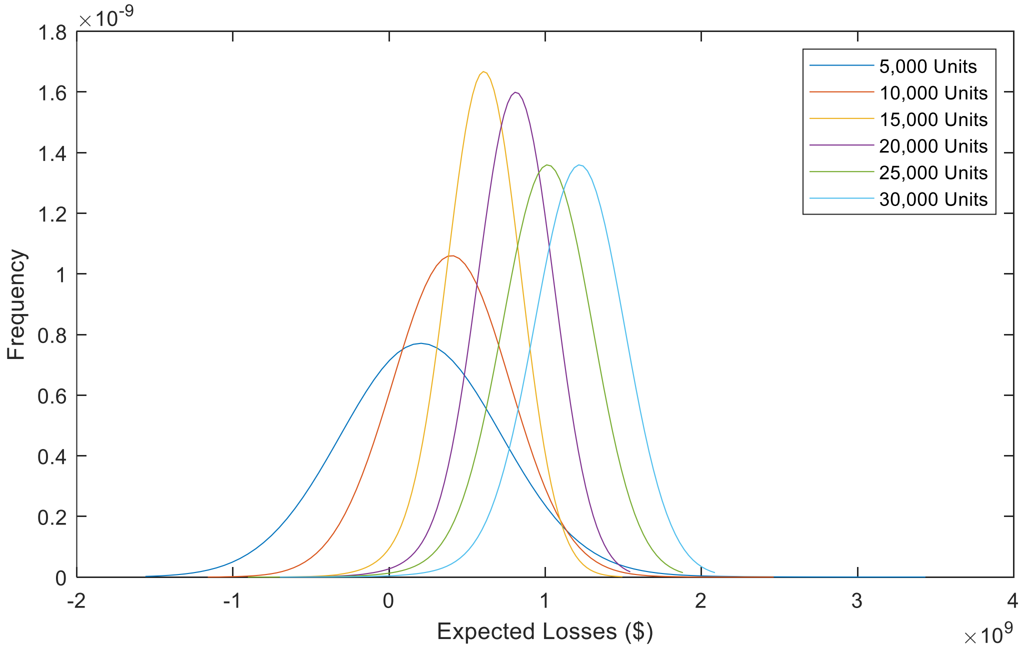


Figure 49: Florida Overlay of Expected Losses by Stocking Inventory

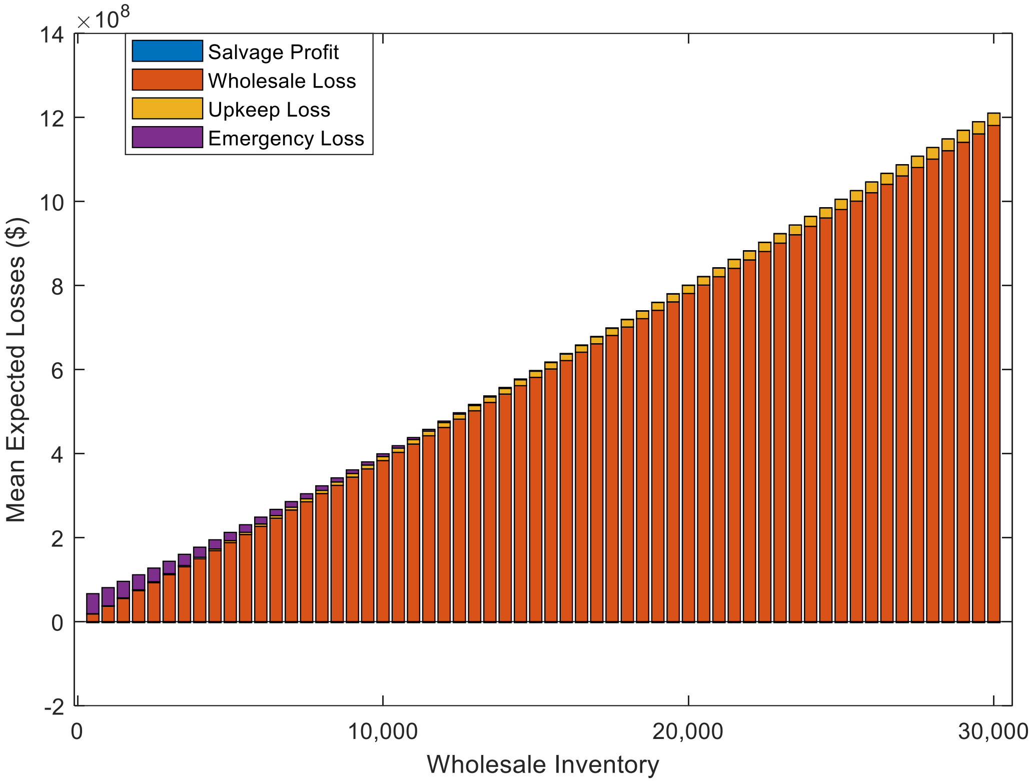


Figure 50: Florida's Expected Losses for Wholesale Inventories

B.2.2 Sensitivity – Housing Damage for Prolonged Displacement

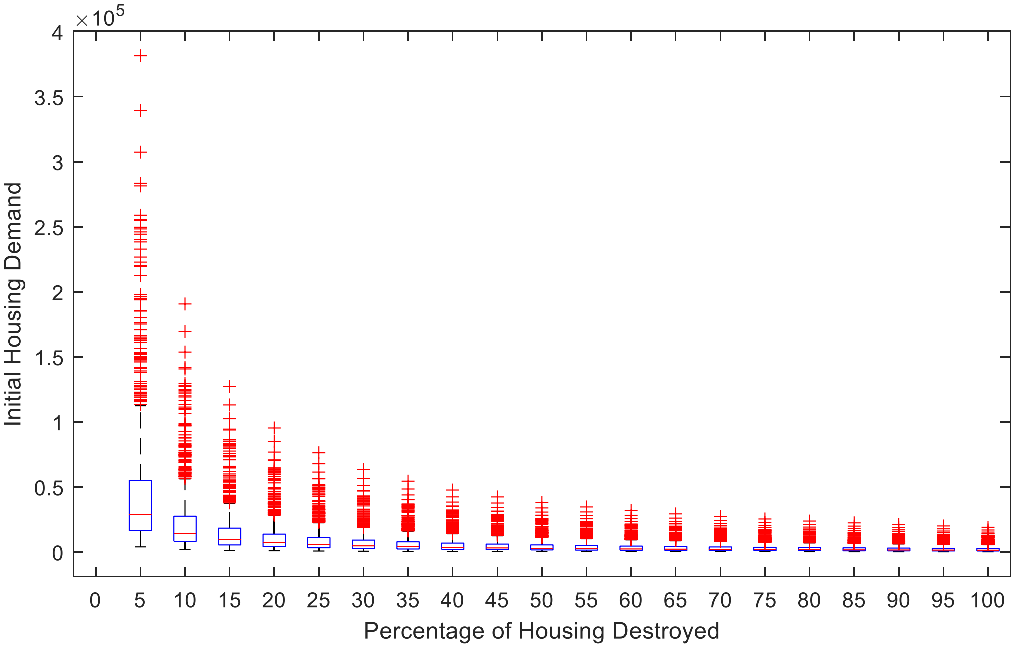


Figure 51: Florida's Sensitivity Analysis on Amount of Housing Damage to Require Temporary Housing

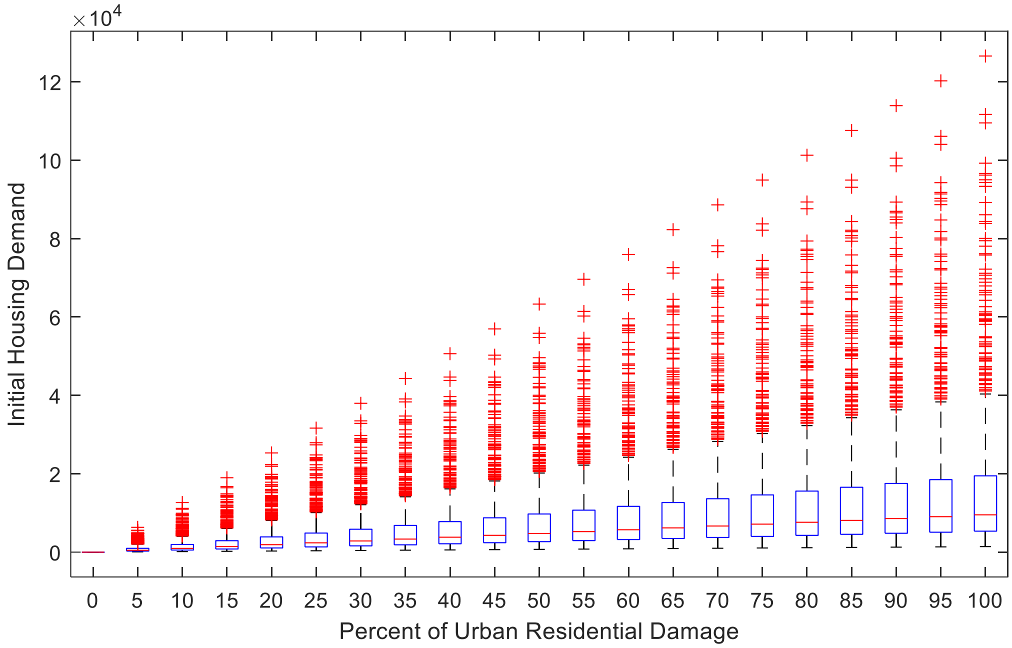


Figure 52: Florida's Sensitivity Analysis on Urban Residential Damage

B.2.3 Sensitivity – Residential Damage

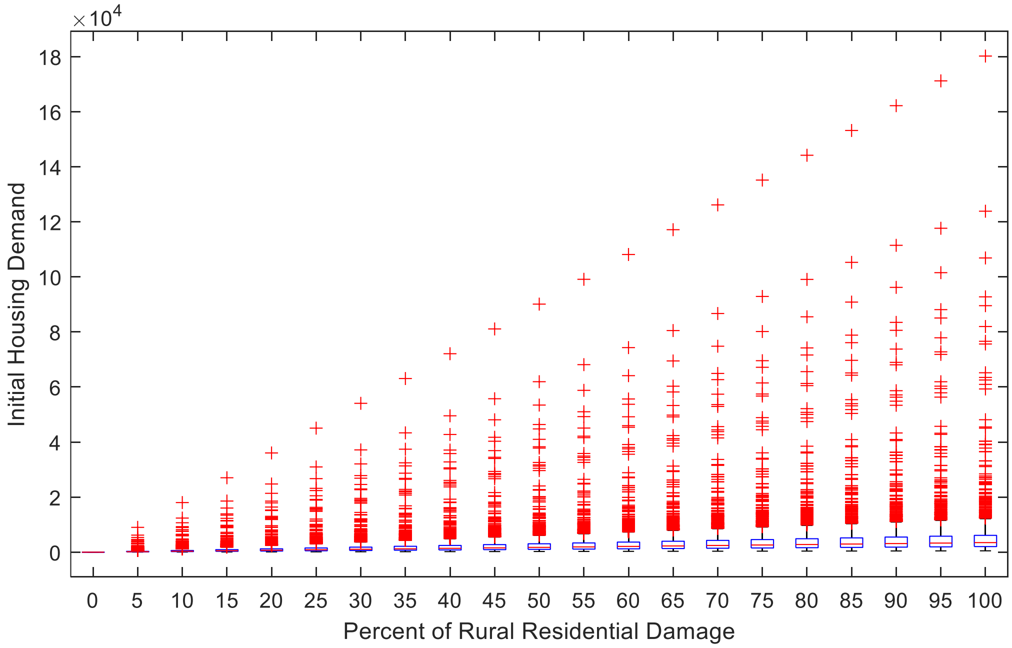


Figure 53: Florida's Sensitivity Analysis on Rural Residential Damage

B.2.4 Sensitivity - Svi and Homelessness sensitivity

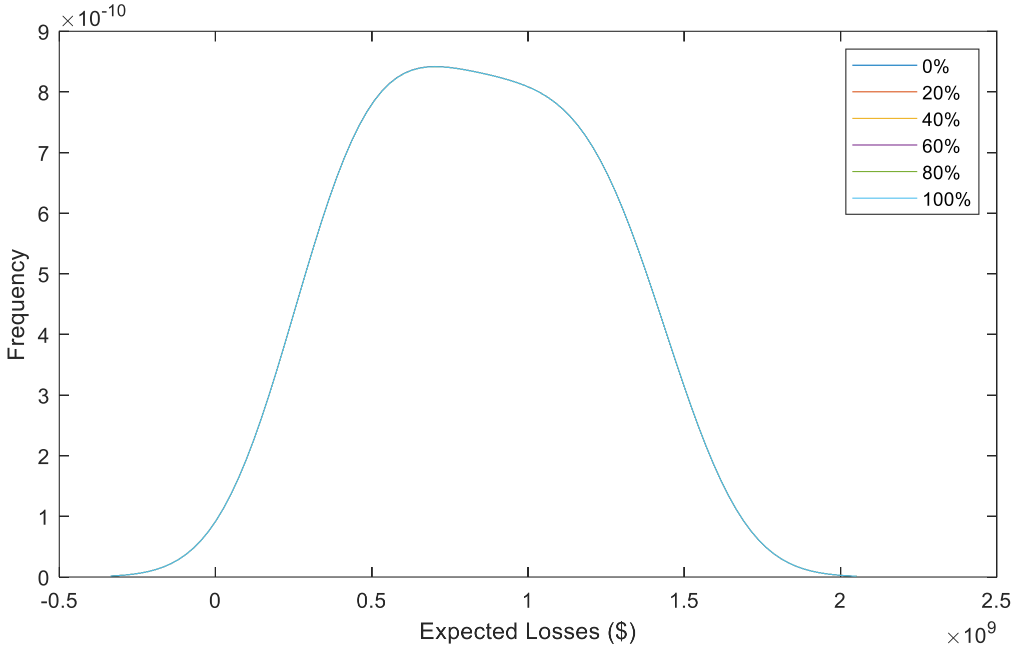


Figure 54: Florida's Sensitivity of Expected Losses from Social Vulnerability

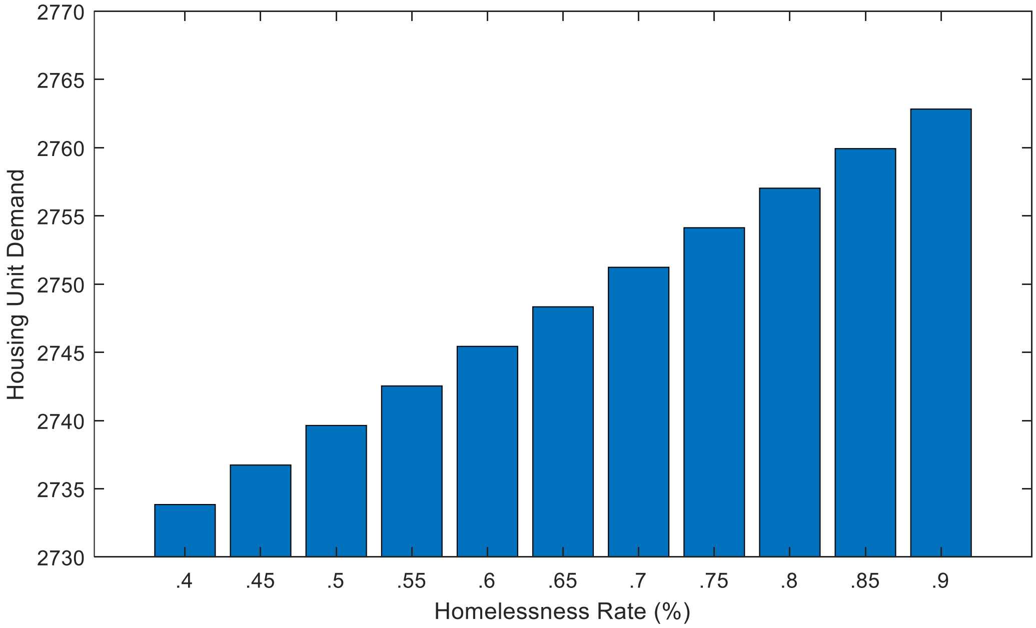


Figure 55: Florida's Sensitivity of Housing Demand from Homelessness Rate

B.3 Georgia

B.3.1 Inventory Optimization Results

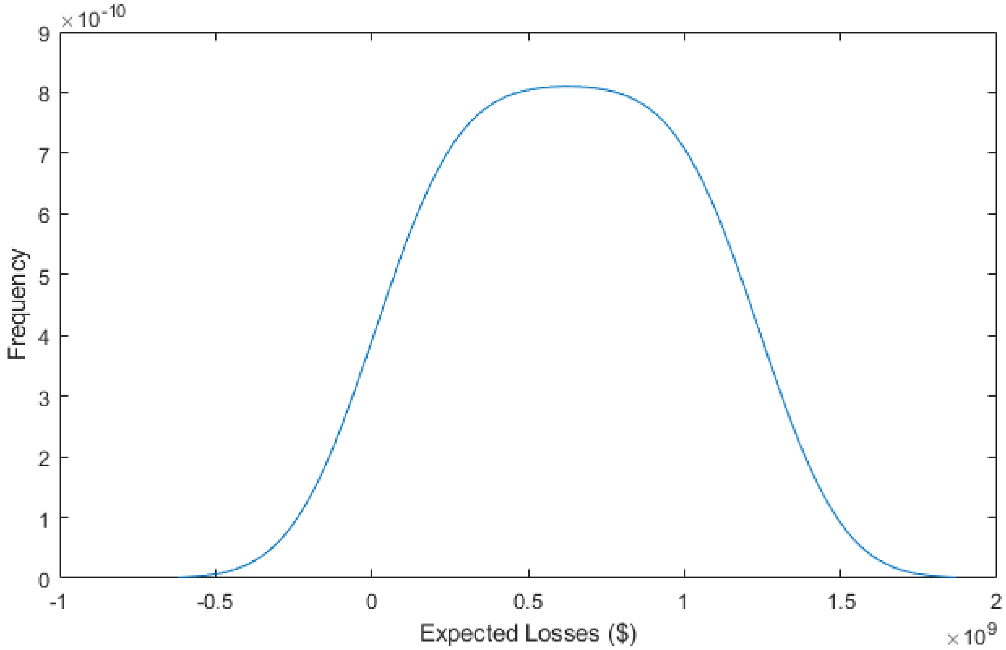


Figure 56: Georgia's Density of Mean Expected Losses

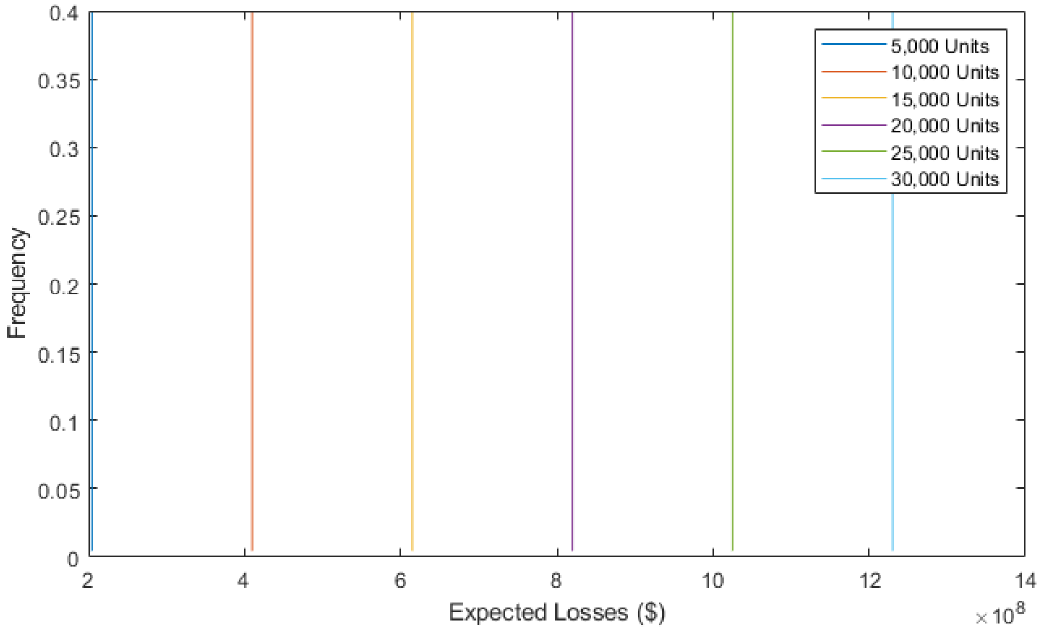


Figure 57: Georgia's Overlay of Expected Losses by Stocking Inventory

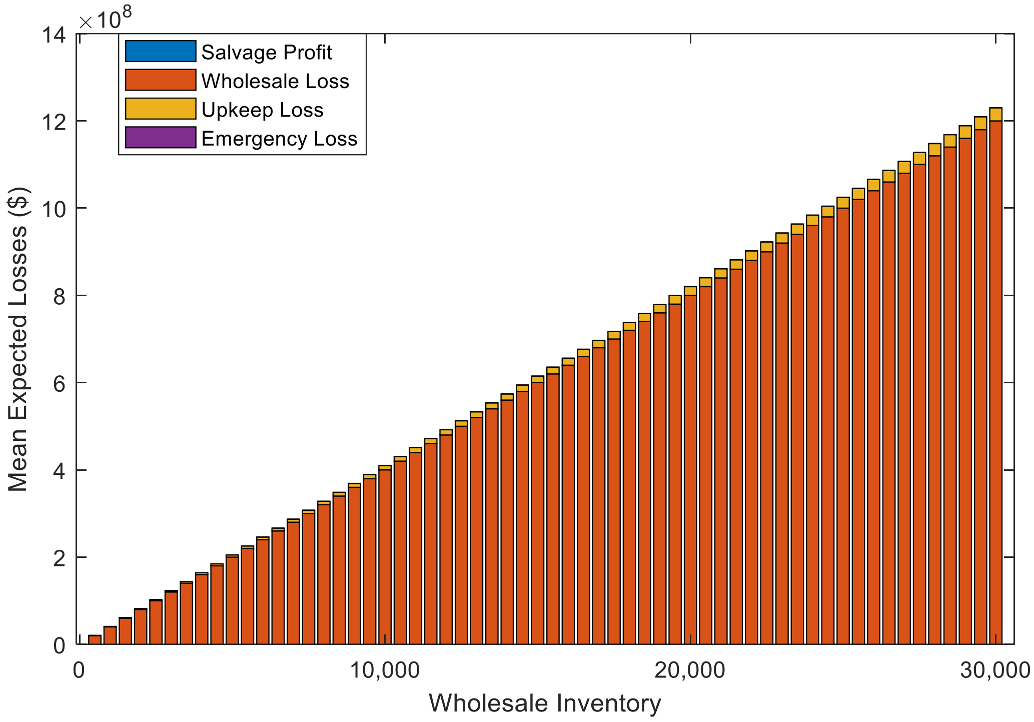


Figure 58: Georgia's Expected Losses for Wholesale Inventories

B.3.2 Sensitivity – Housing Damage for Prolonged Displacement

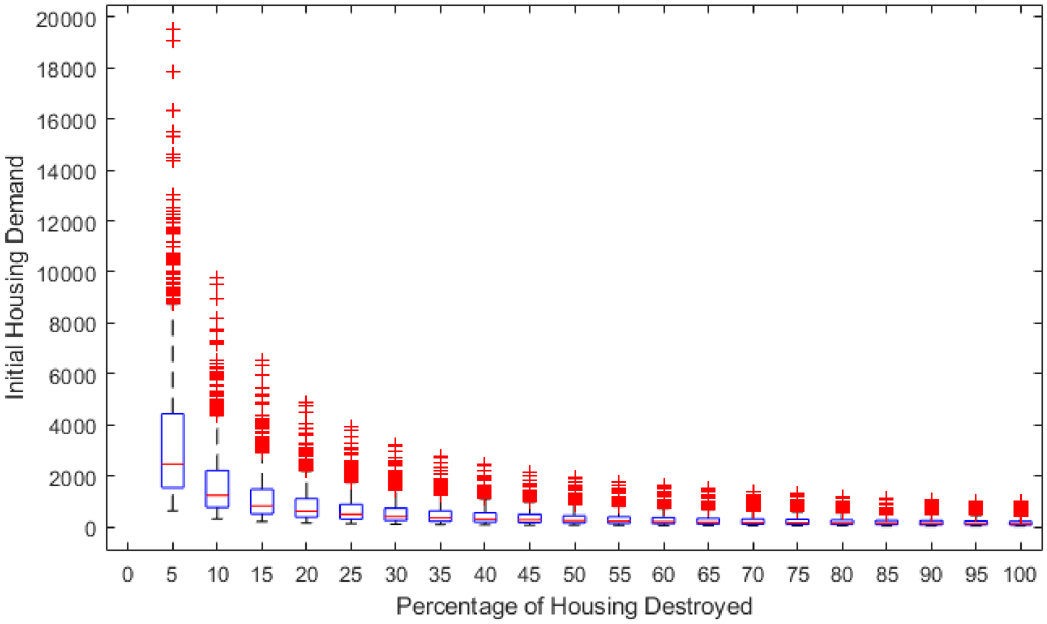


Figure 59: Georgia's Sensitivity Analysis on Amount of Housing Damage to Require Temporary Housing

B.3.3 Sensitivity – Residential Damage

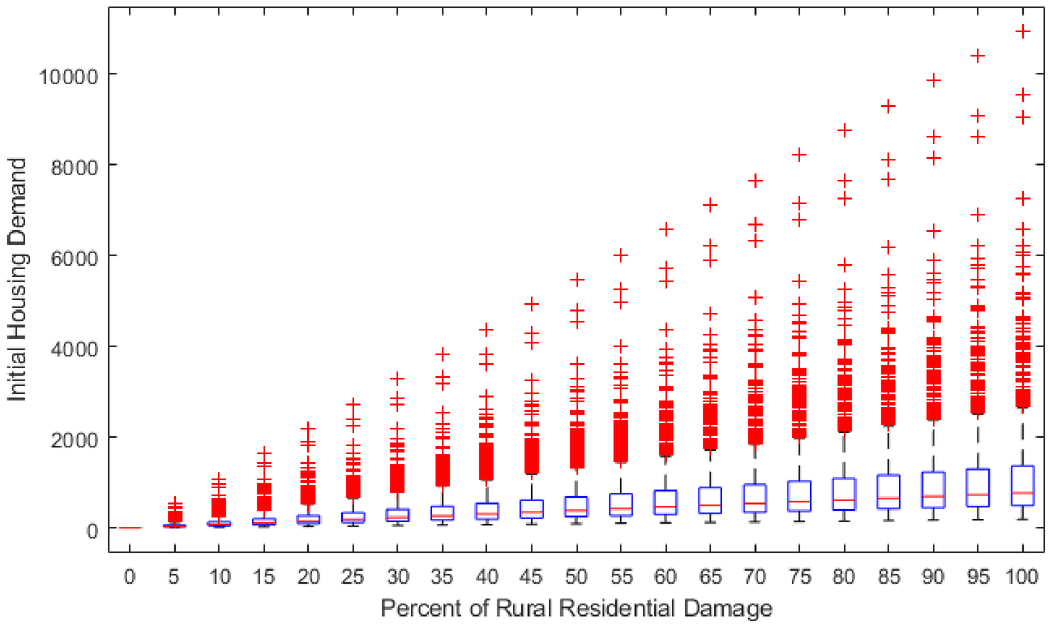


Figure 60: Georgia's Sensitivity Analysis on Rural Residential Damage

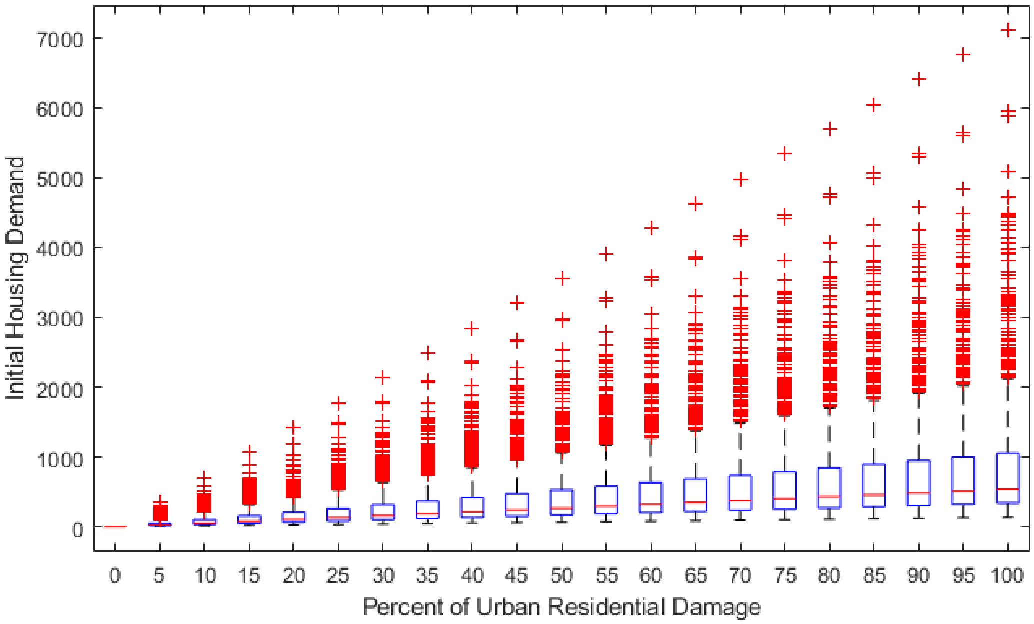


Figure 61: Georgia's Sensitivity Analysis on Urban Residential Damage

B.3.4 Sensitivity - Svi and Homelessness sensitivity

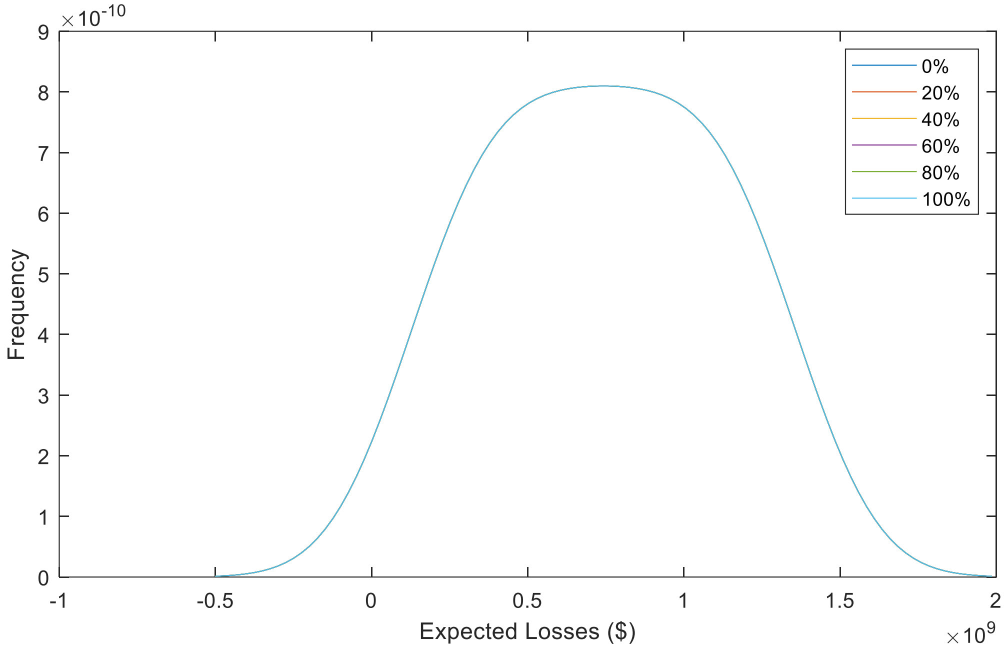


Figure 62: Georgia's Sensitivity of Expected Losses from Social Vulnerability

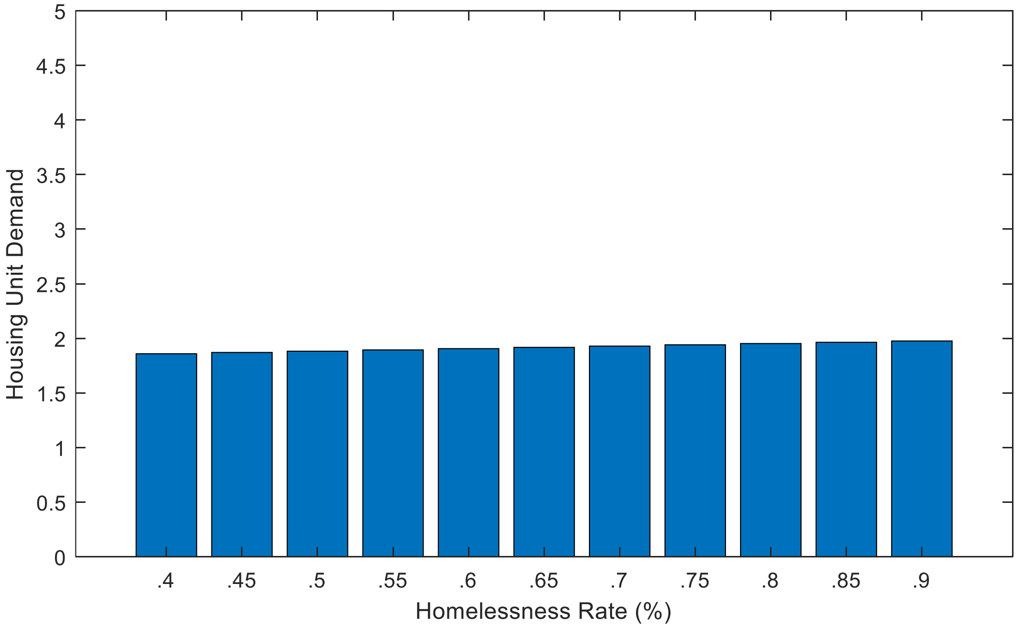


Figure 63: Georgia's Sensitivity of Housing Demand from Homelessness Rate

B.4 Louisiana

B.4.1 Inventory Optimization Results

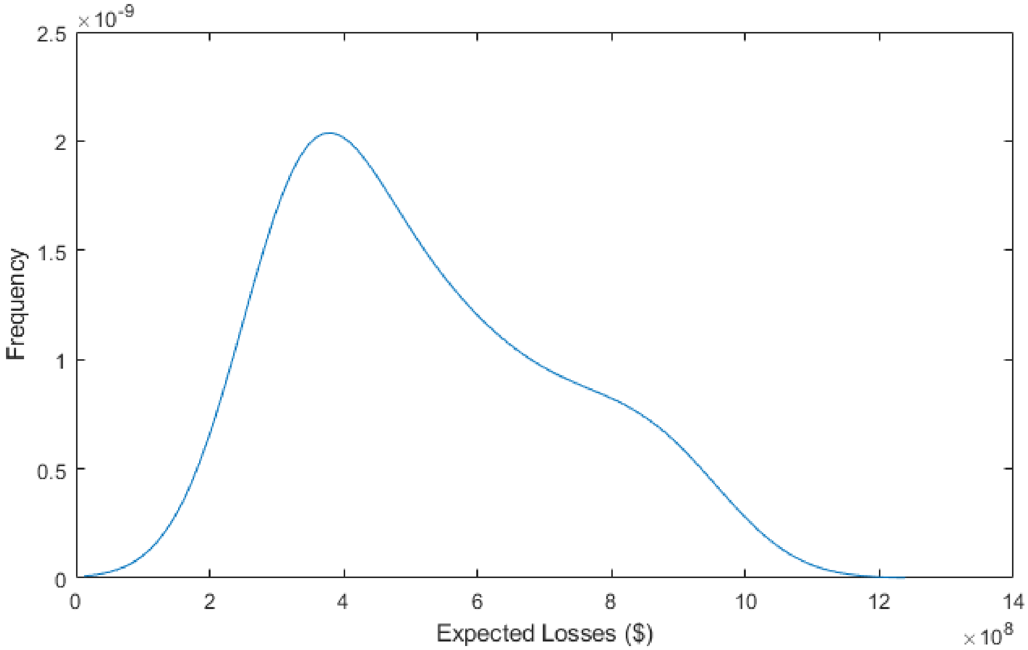


Figure 64: Louisiana's Density of Mean Expected Losses

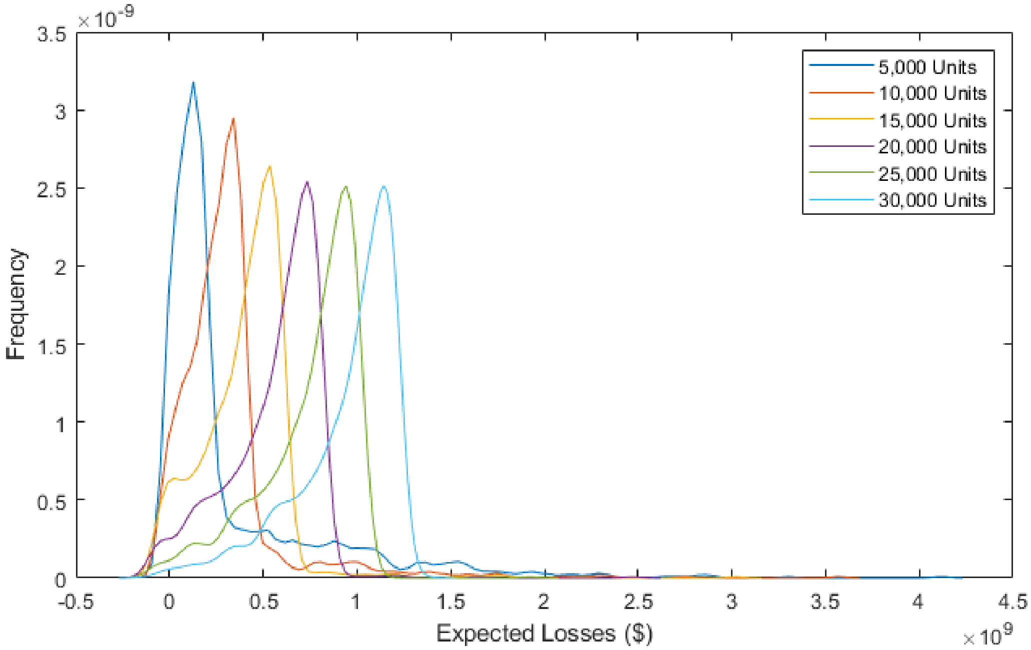


Figure 65: Louisiana Overlay of Expected Losses by Stocking Inventory

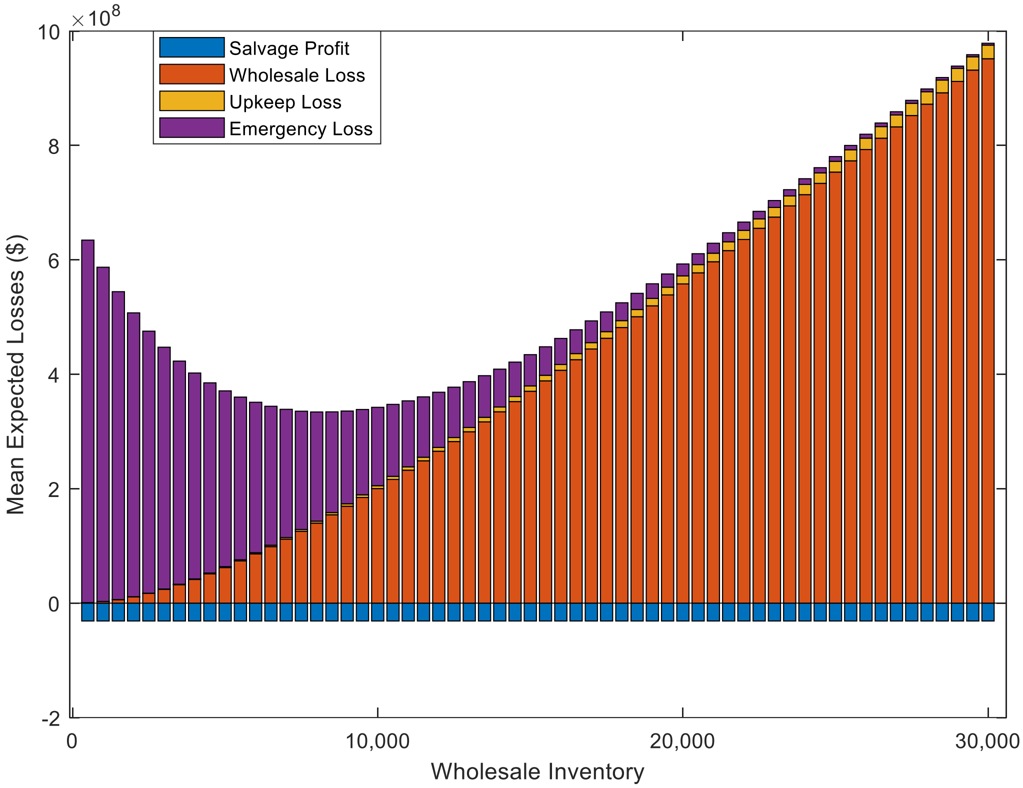


Figure 66: Louisiana's Expected Losses for Wholesale Inventories

B.4.2 Sensitivity – Housing Damage for Prolonged Displacement

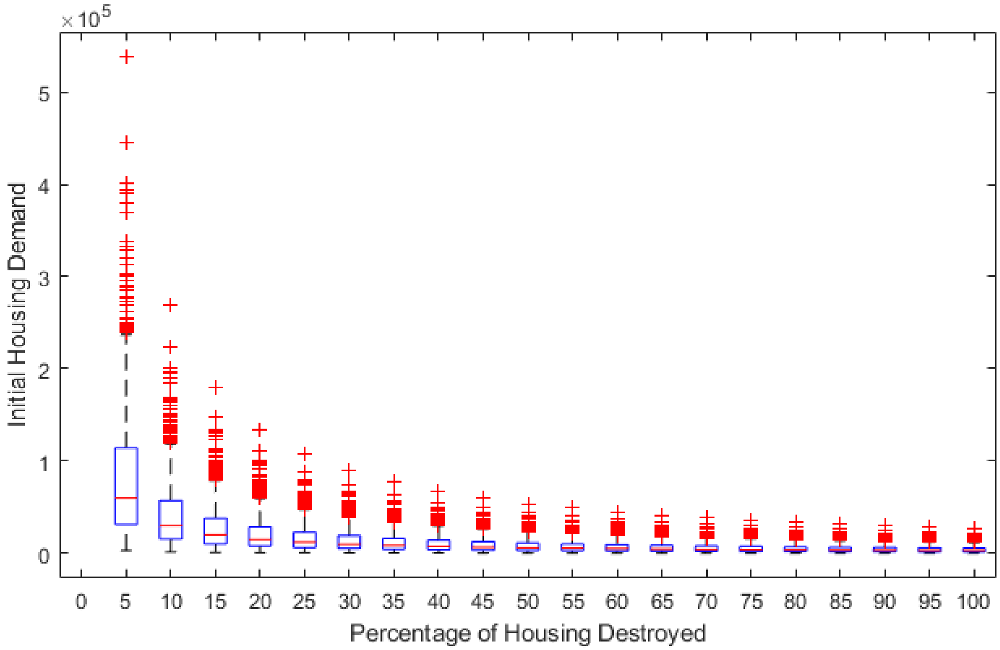


Figure 67: Louisiana Sensitivity Analysis on Amount of Housing Damage to Require Temporary Housing

B.4.3 Sensitivity – Residential Damage

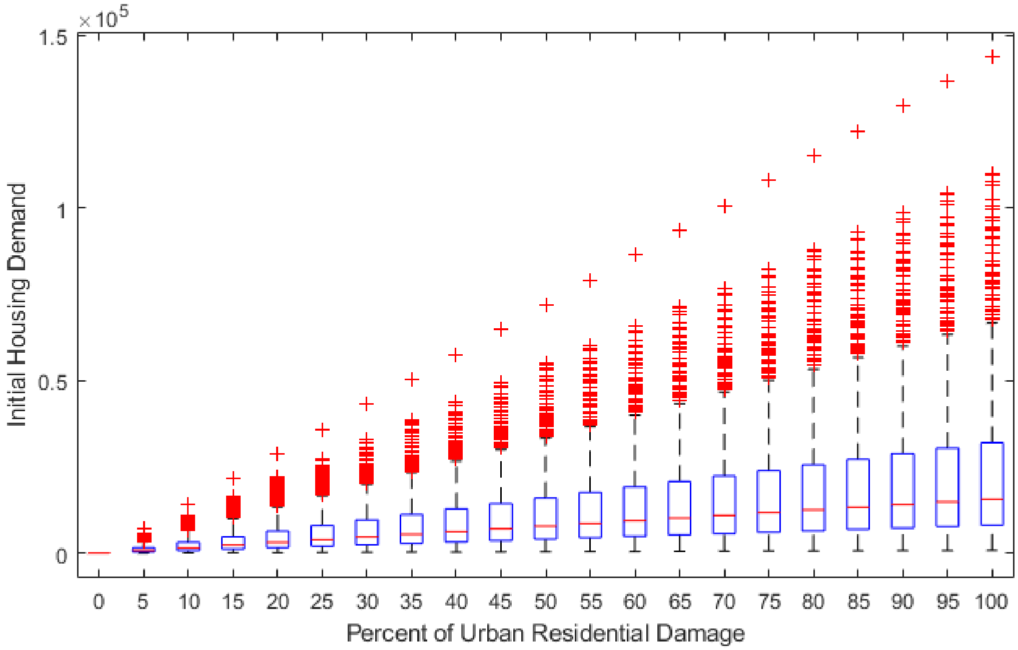


Figure 68: Louisiana Sensitivity Analysis on Urban Residential Damage

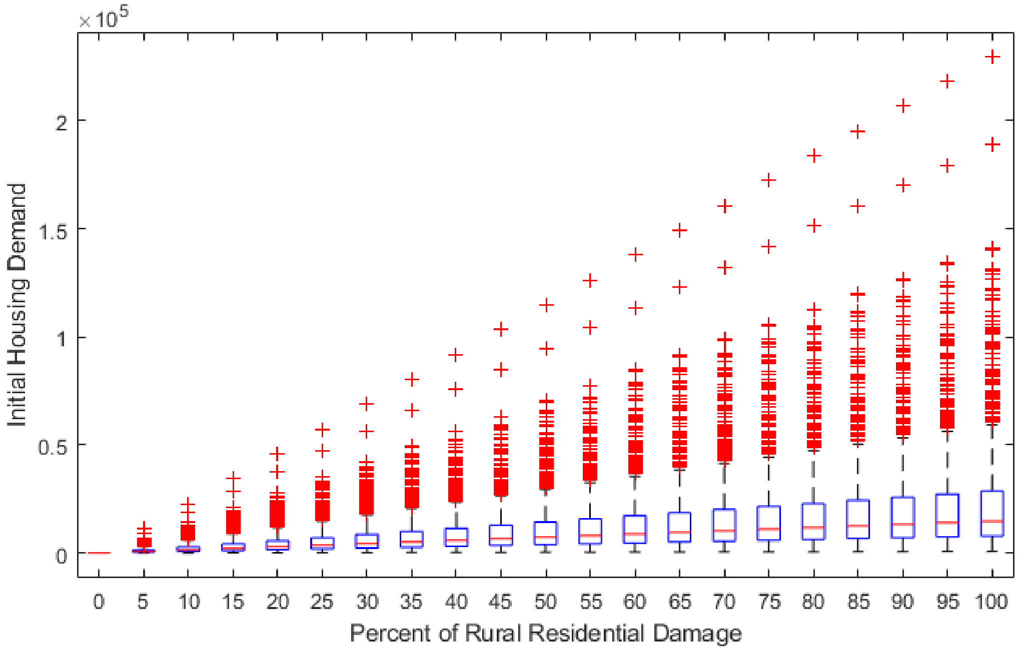


Figure 69: Louisiana Sensitivity Analysis on Rural Residential Damage

B.4.4 Sensitivity - Svi and Homelessness sensitivity

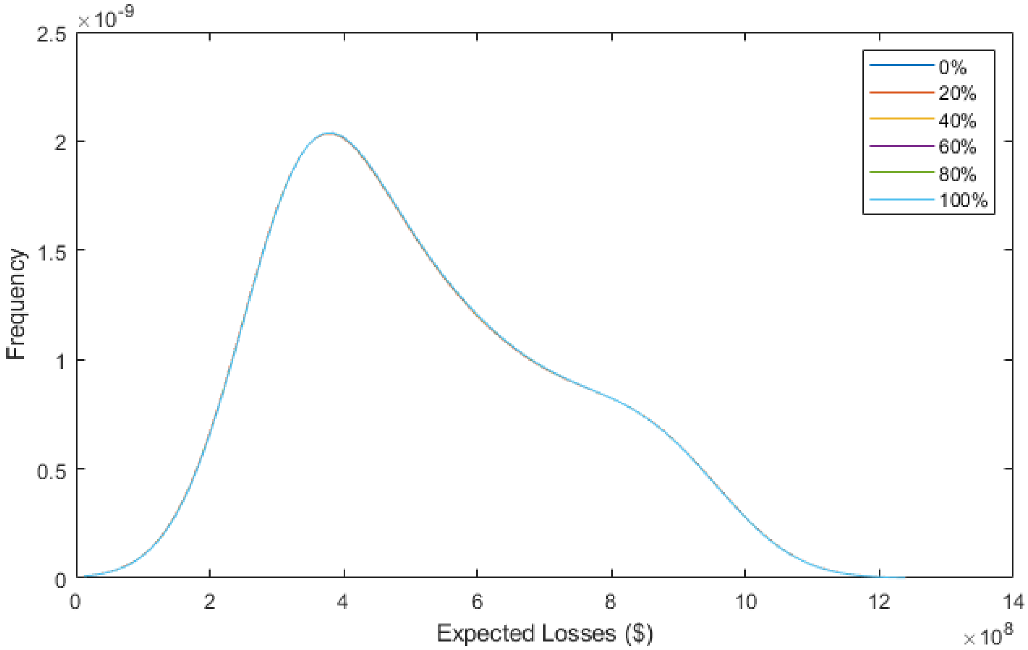


Figure 70: Louisiana Sensitivity of Expected Losses from Social Vulnerability

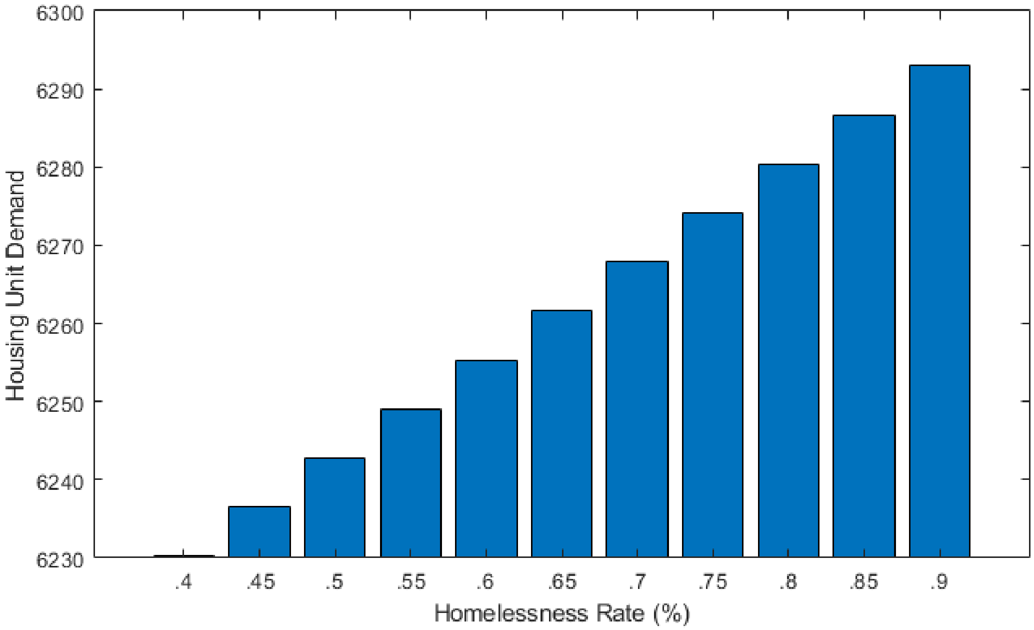


Figure 71: Louisiana Sensitivity of Housing Demand from Homelessness Rate

B.5 Mississippi

B.5.1 Inventory Optimization Results

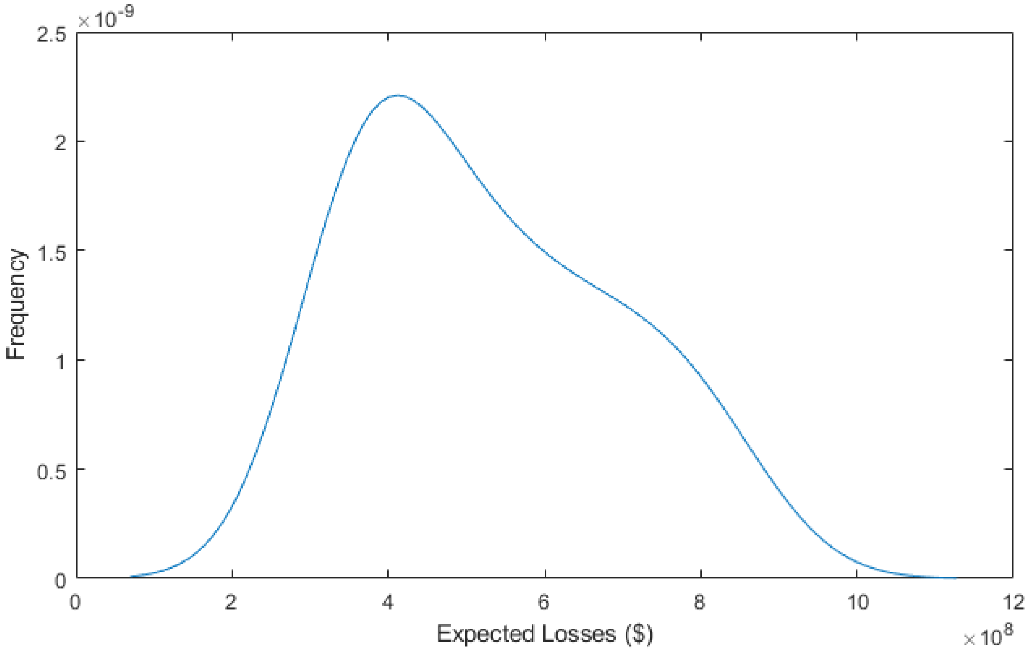


Figure 72: Mississippi's Density of Expected Losses

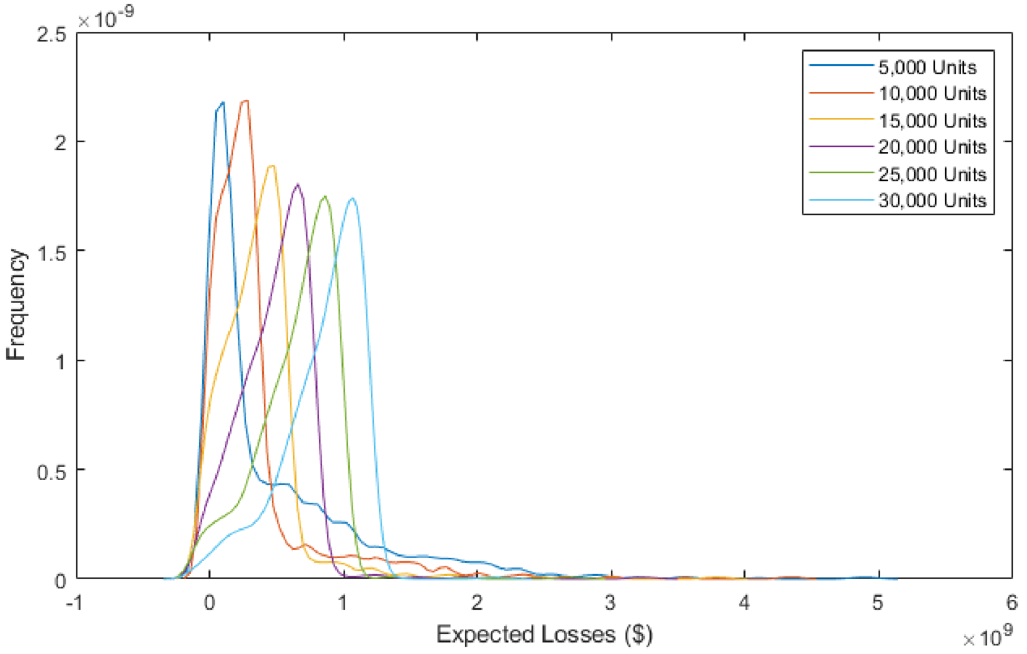


Figure 73: Mississippi's Overlay of Expected Losses by Stocking Inventory

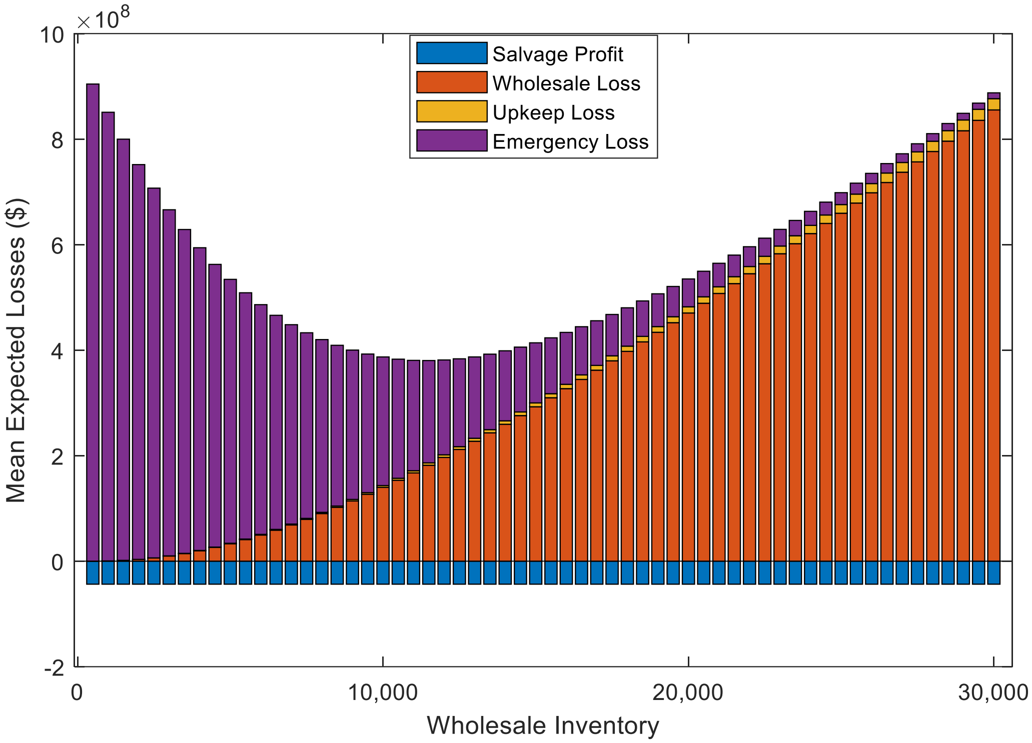


Figure 74: Mississippi's Expected Losses for Wholesale Inventories

B.5.2 Sensitivity – Housing Damage for Prolonged Displacement

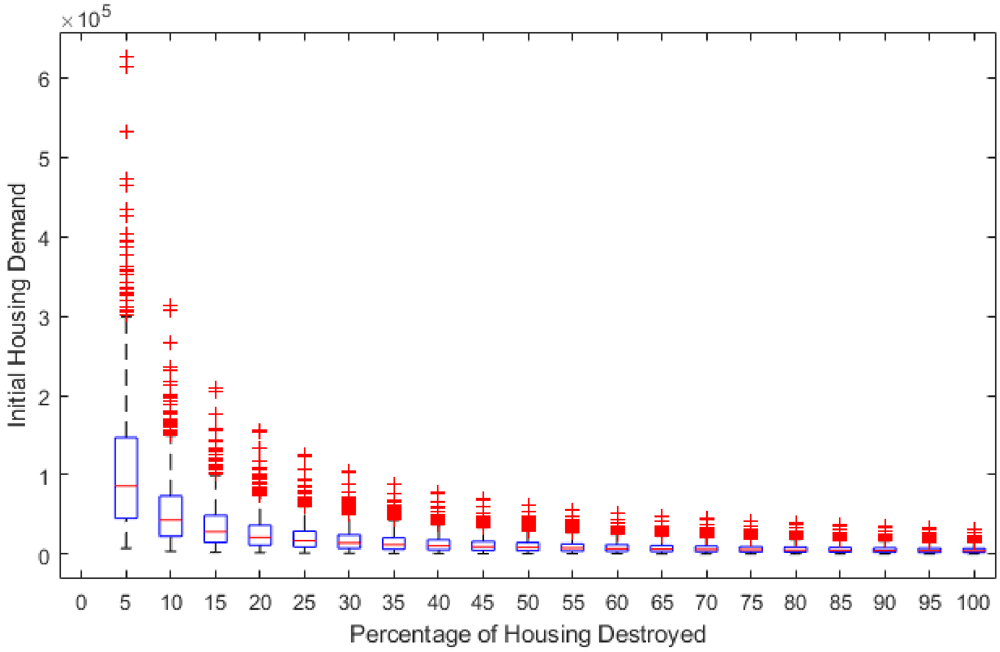


Figure 75: Mississippi's Sensitivity Analysis on Amount of Housing Damage to Require Temporary Housing

B.5.3 Sensitivity – Residential Damage

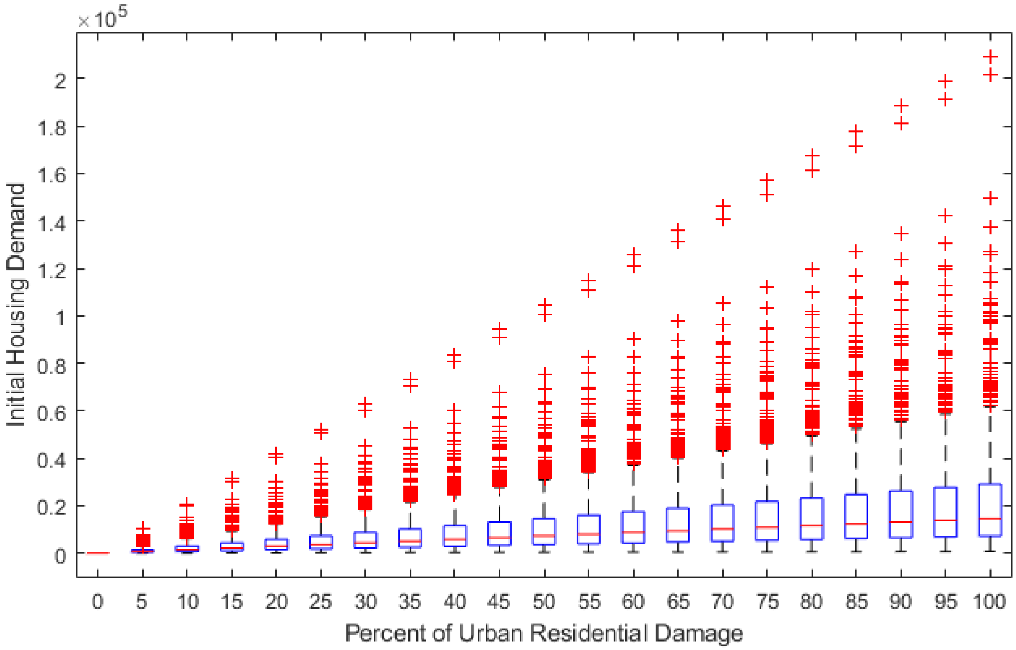


Figure 76: Mississippi's Sensitivity Analysis on Urban Residential Damage

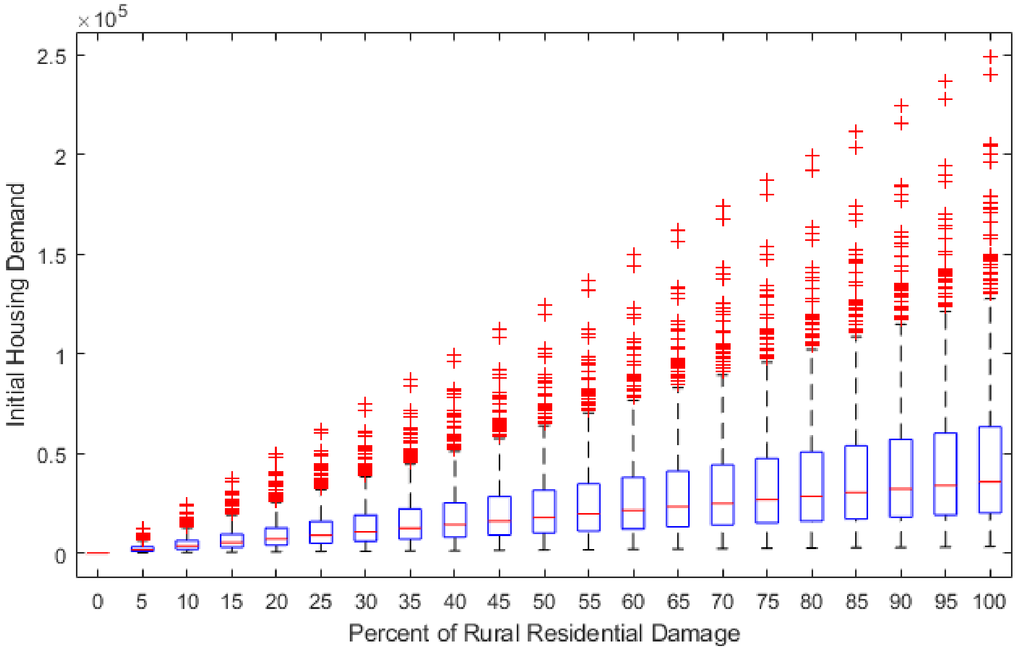


Figure 77: Mississippi's Sensitivity Analysis on Rural Residential Damage

B.5.4 Sensitivity - Svi and Homelessness sensitivity

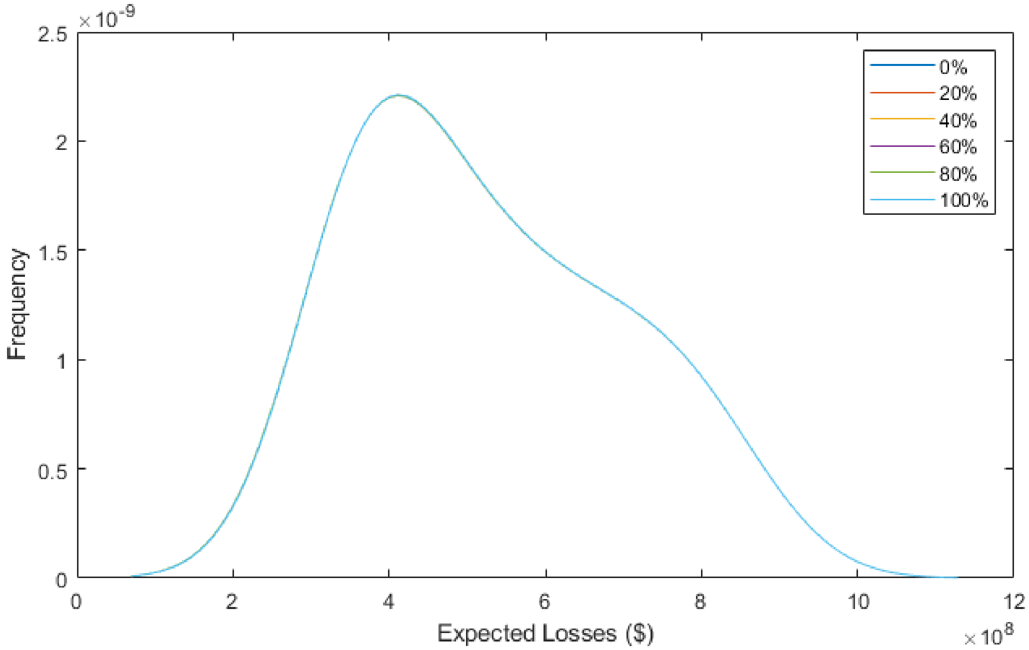


Figure 78: Mississippi's Sensitivity of Expected Losses from Social Vulnerability

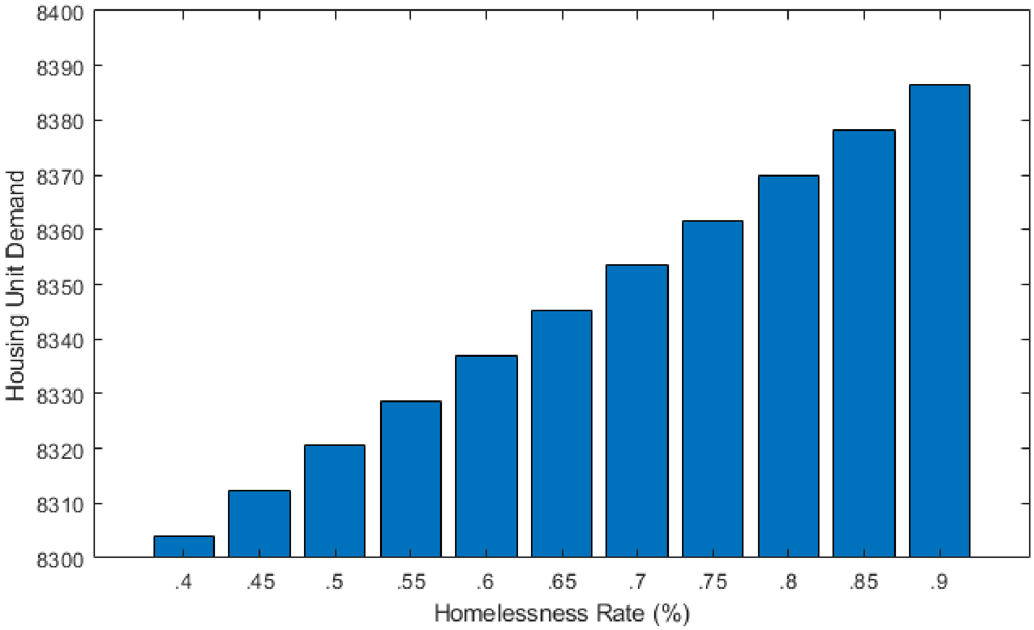


Figure 79: Mississippi's Sensitivity of Housing Demand from Homelessness Rate

B.6 North Carolina

B.6.1 Inventory Optimization Results

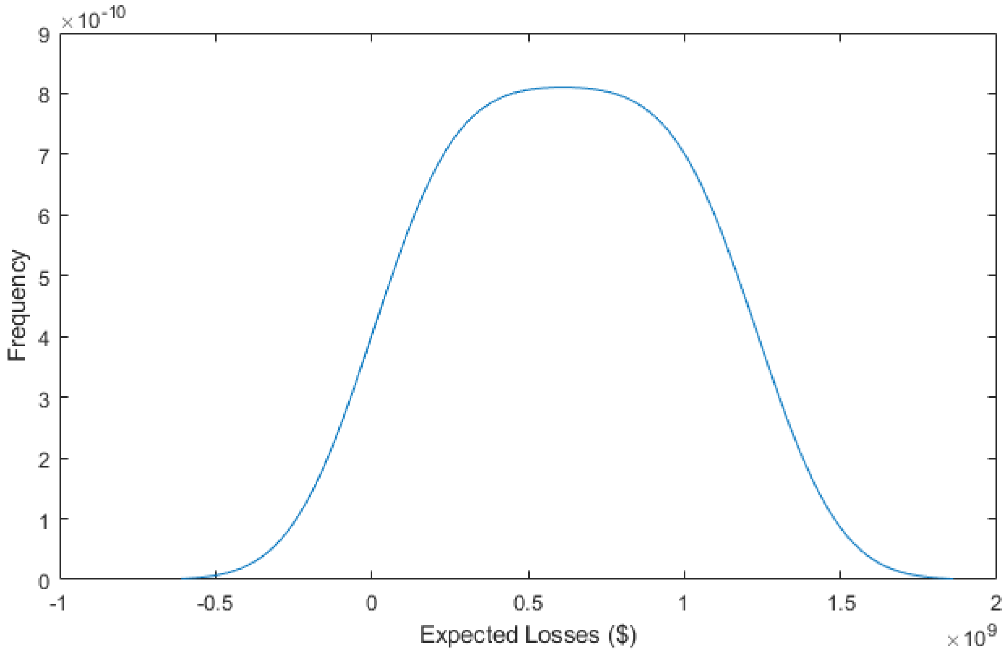


Figure 80: North Carolina’s Density of Mean Expected Losses

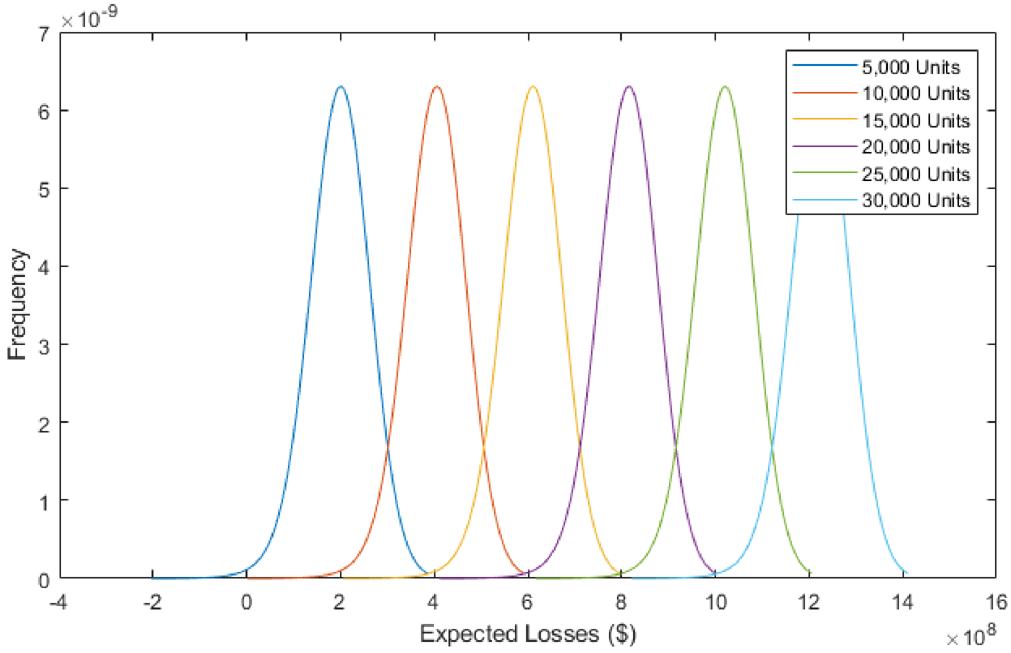


Figure 81: North Carolina's Overlay of Expected Losses by Stocking Inventory

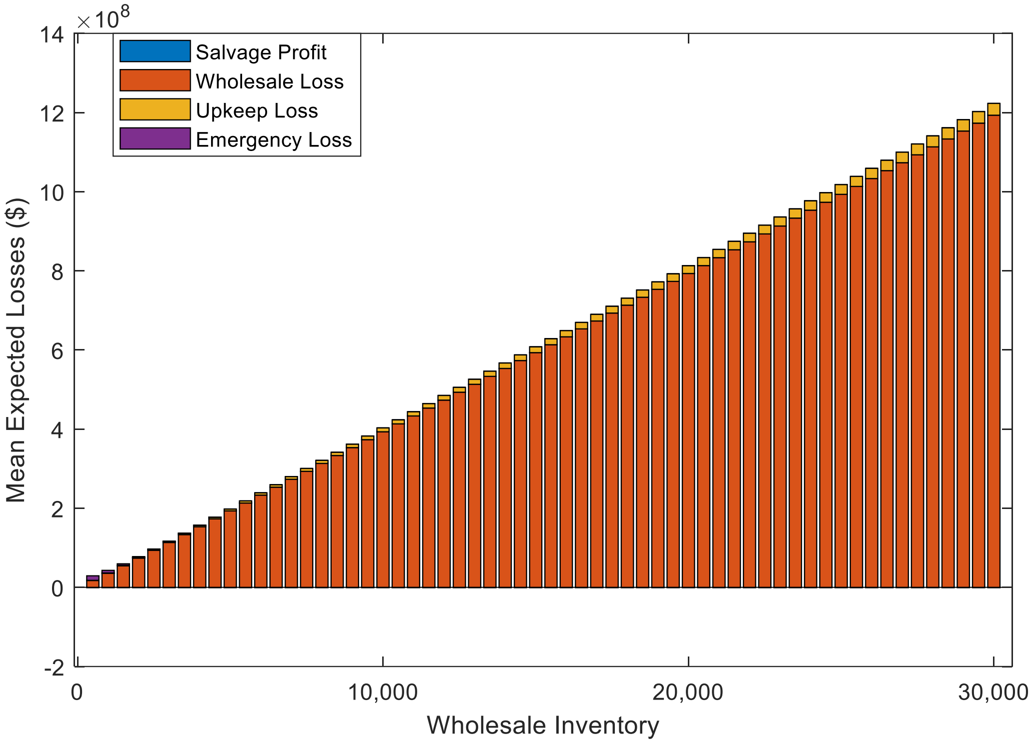


Figure 82: North Carolina's Expected Losses for Wholesale Inventories

B.6.2 Sensitivity – Housing Damage for Prolonged Displacement

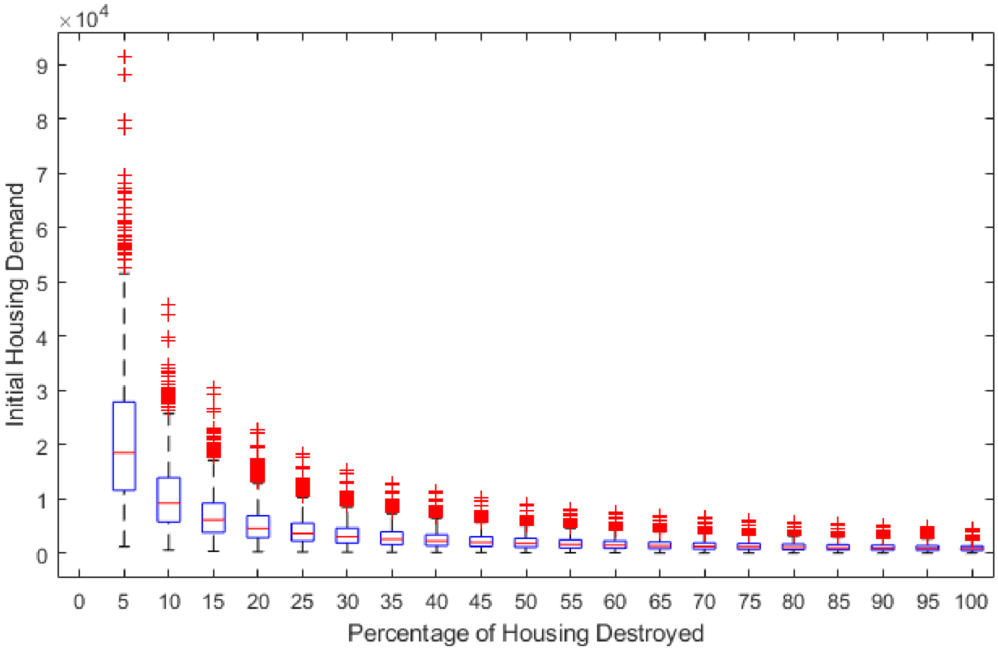


Figure 83: North Carolina's Sensitivity Analysis on Amount of Housing Damage to Require Temporary Housing

B.6.3 Sensitivity – Residential Damage

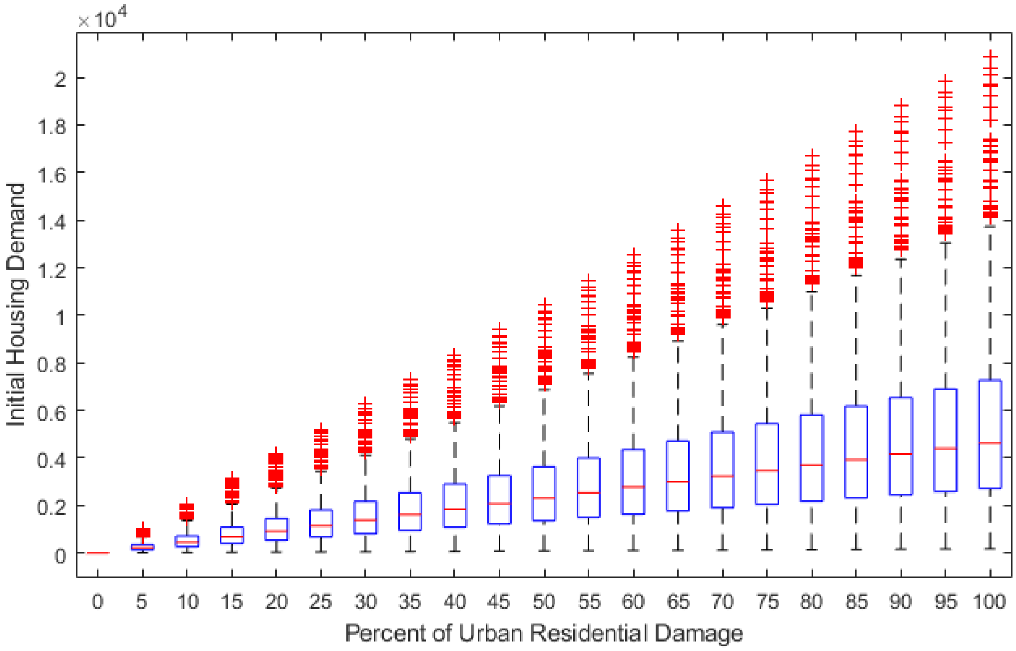


Figure 84: North Carolina's Sensitivity Analysis on Urban Residential Damage

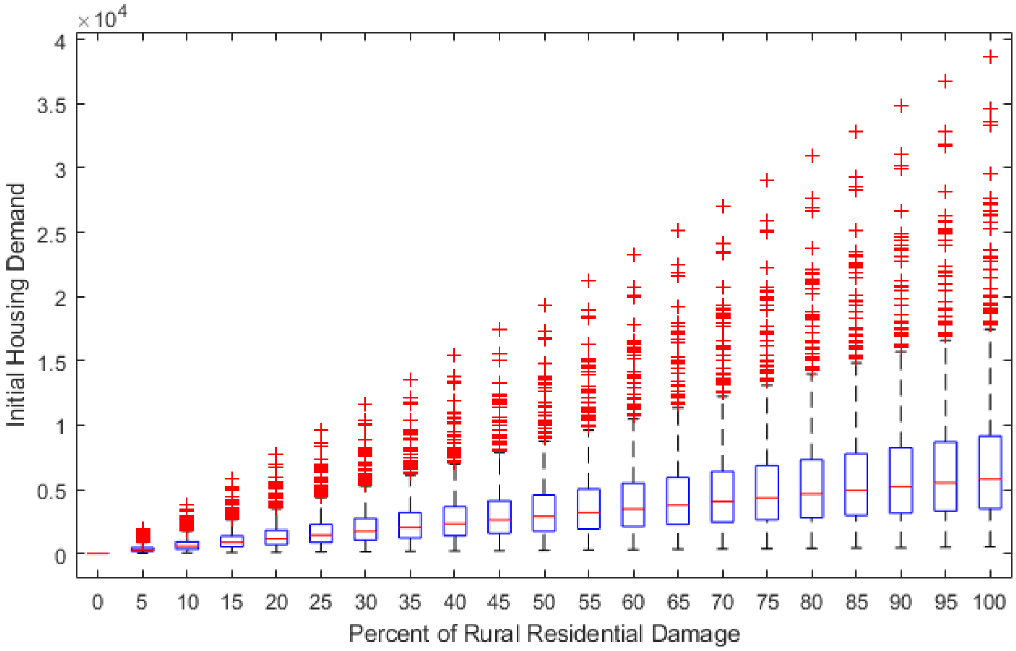


Figure 85: North Carolina's Sensitivity Analysis on Rural Residential Damage

B.6.3 Sensitivity - Svi and Homelessness sensitivity

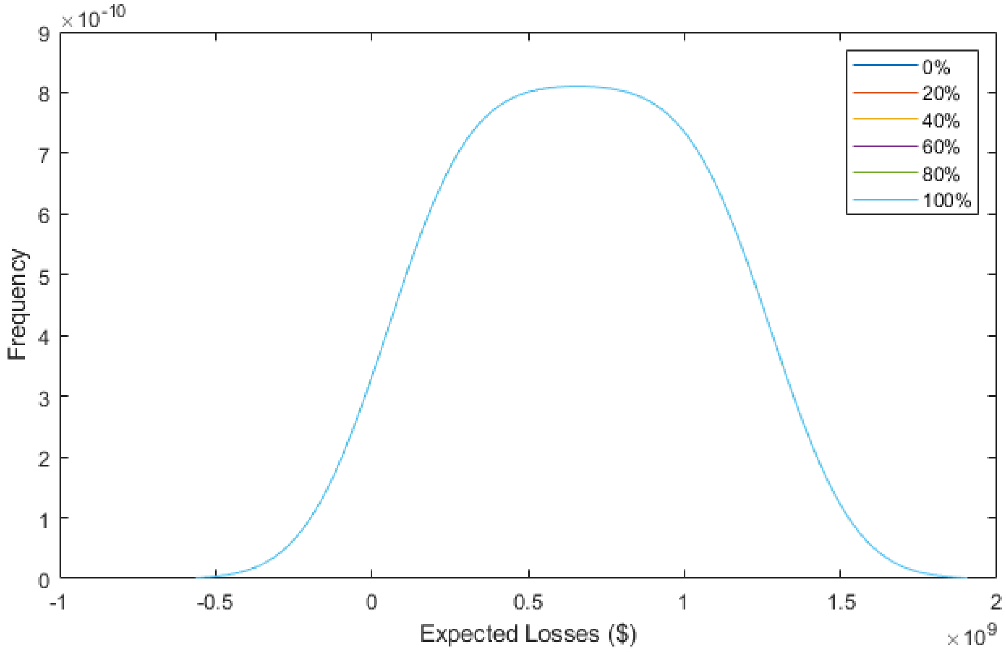


Figure 86: North Carolina's Sensitivity of Expected Losses from Social Vulnerability

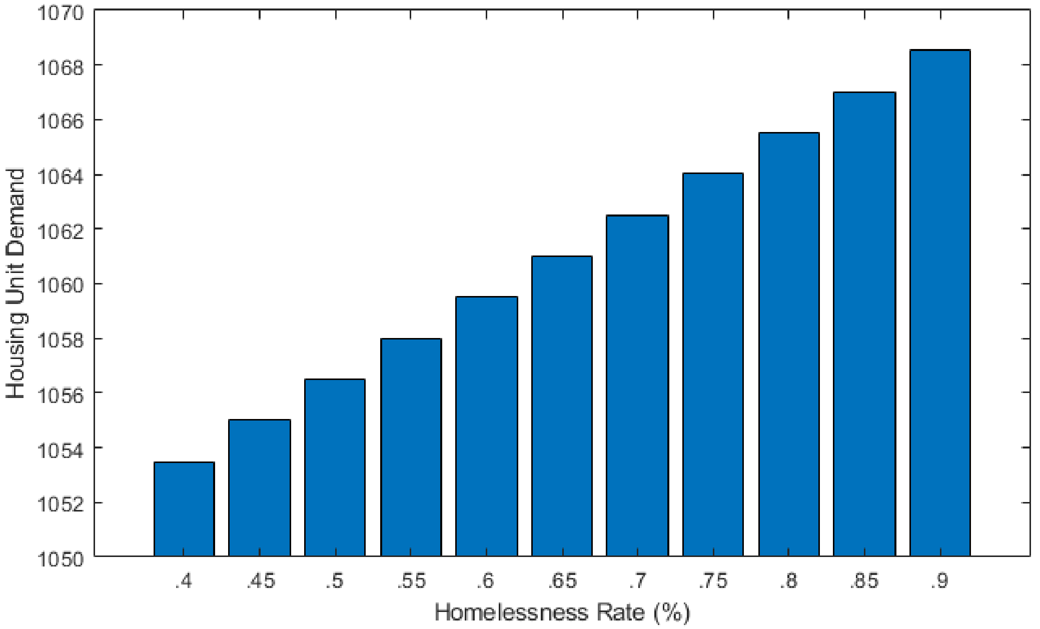


Figure 87: North Carolina's Sensitivity of Housing Demand from Homelessness Rate

B.7 South Carolina

B.7.1 Inventory Optimization Results

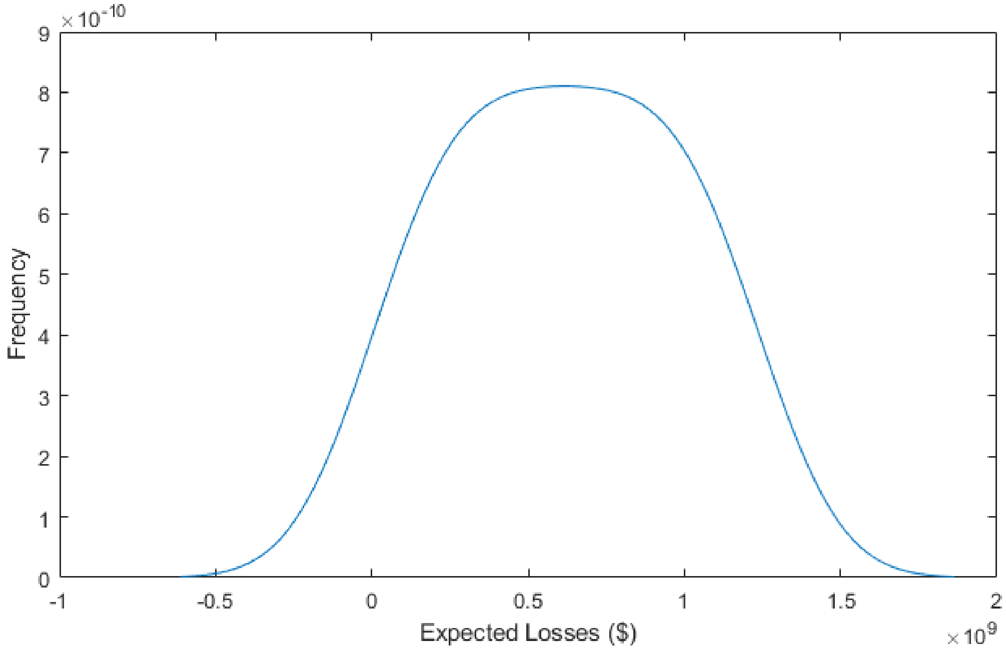


Figure 88: South Carolina's Density of Expected Losses

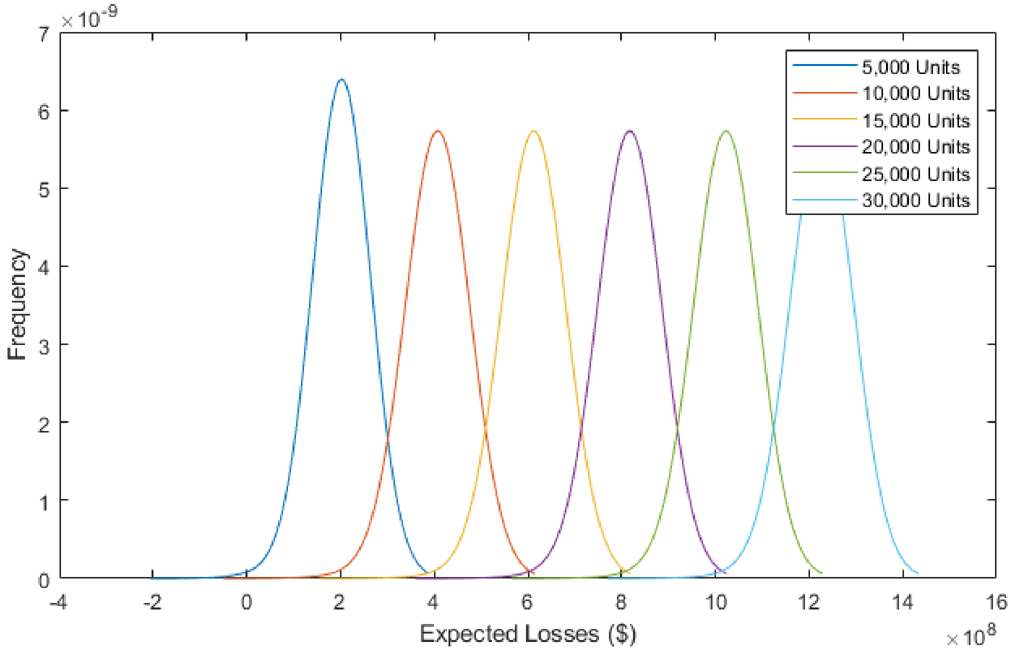


Figure 89: South Carolina's Overlay of Expected Losses by Stocking Inventory

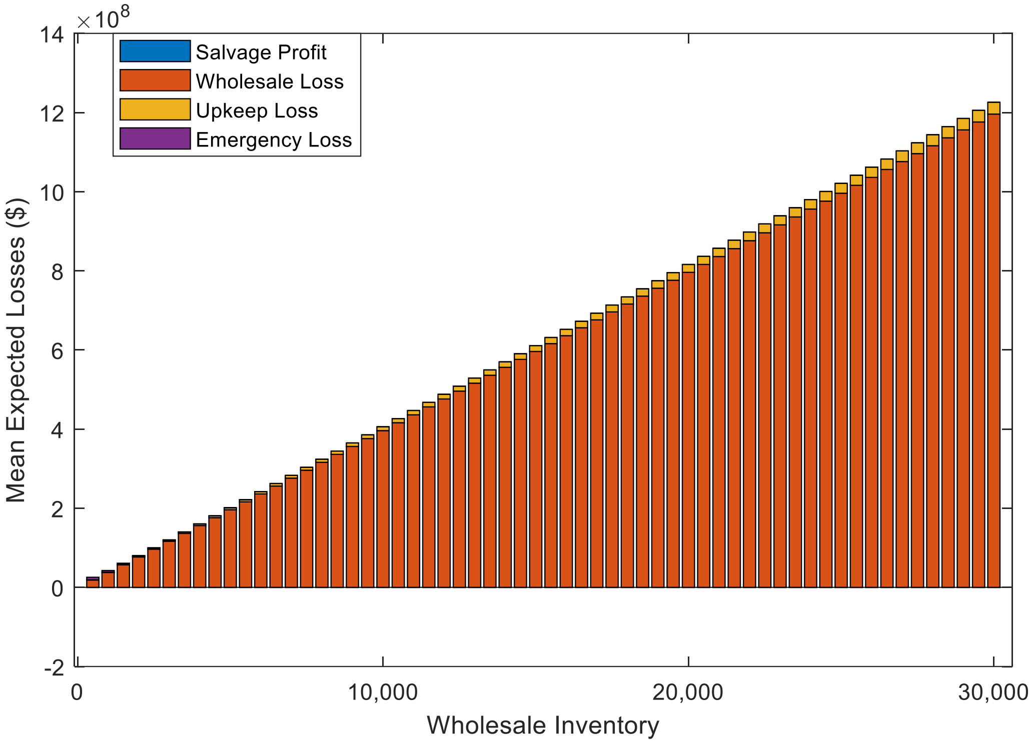


Figure 90: South Carolina's Expected Losses for Wholesale Inventories

B.7.2 Sensitivity – Housing Damage for Prolonged Displacement

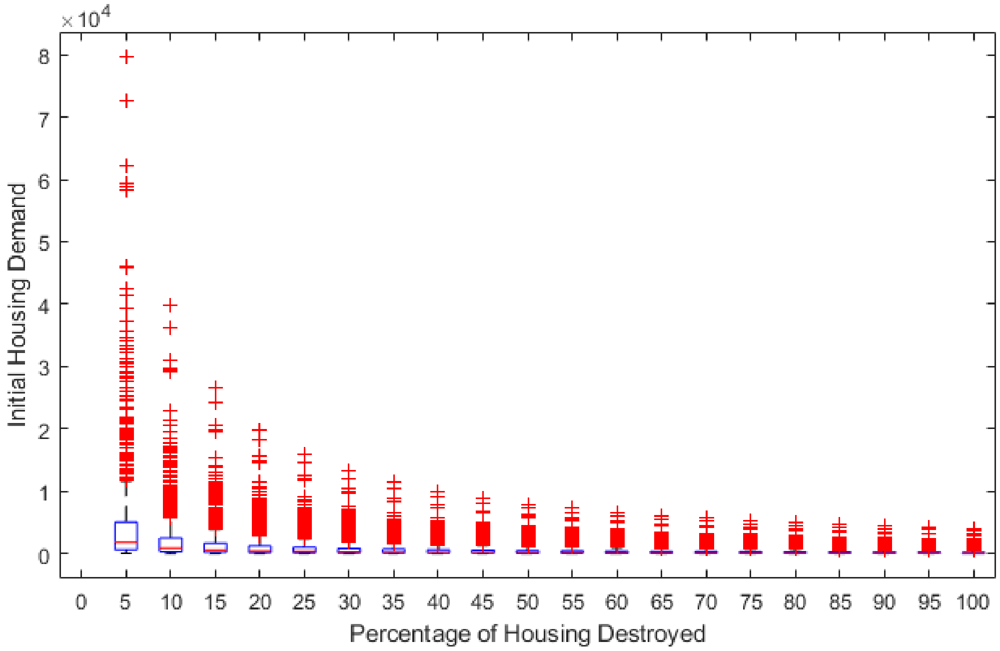


Figure 91: South Carolina's Sensitivity Analysis of Amount of Housing Damage to Require Temporary Housing

B.7.3 Sensitivity – Residential Damage

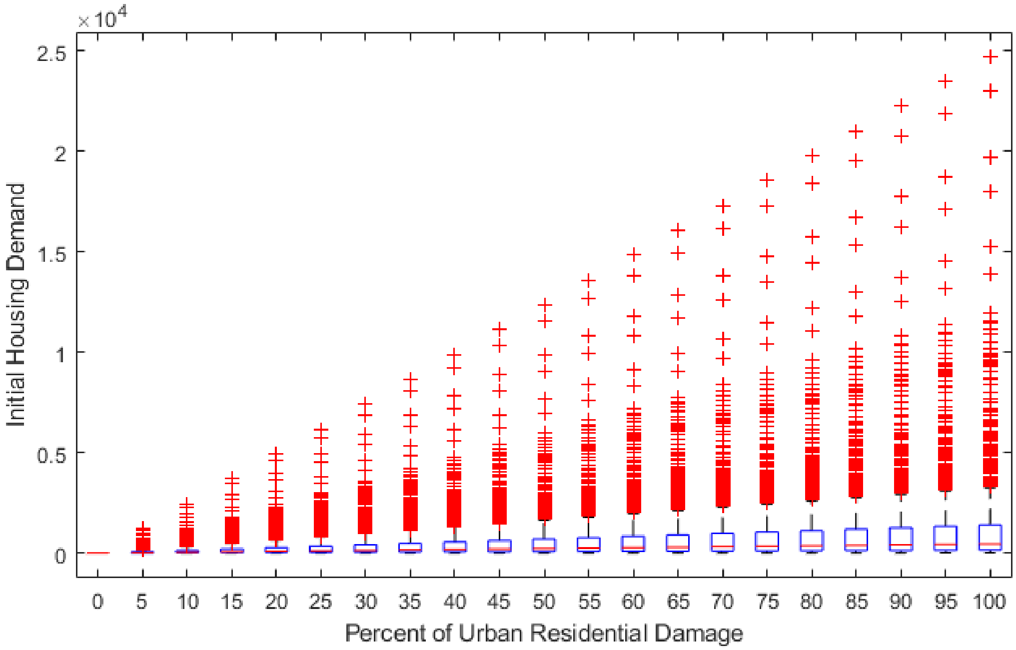


Figure 92: South Carolina's Sensitivity Analysis on Urban Residential Damage

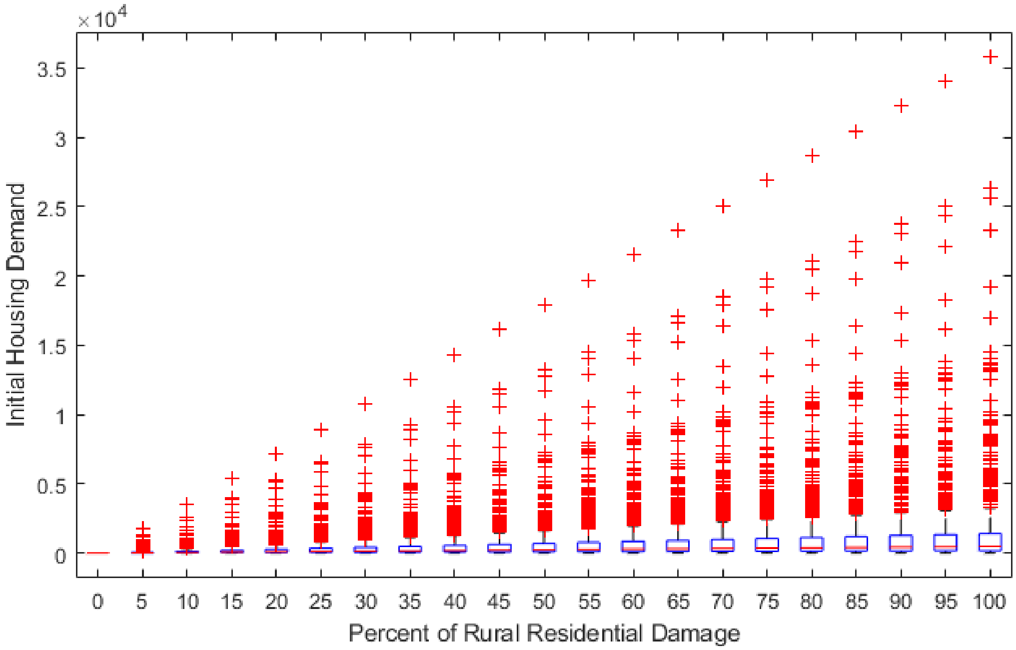


Figure 93: South Carolina's Sensitivity on Rural Residential Damage

B.7.3 Sensitivity - Svi and Homelessness sensitivity

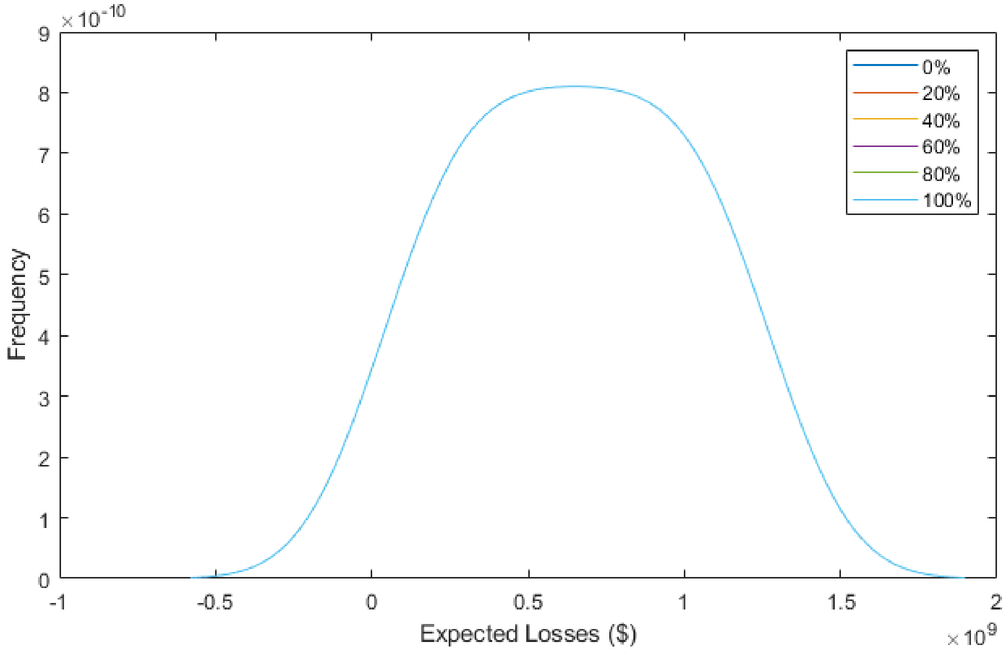


Figure 94: South Carolina's Sensitivity of Expected Losses from Social Vulnerability

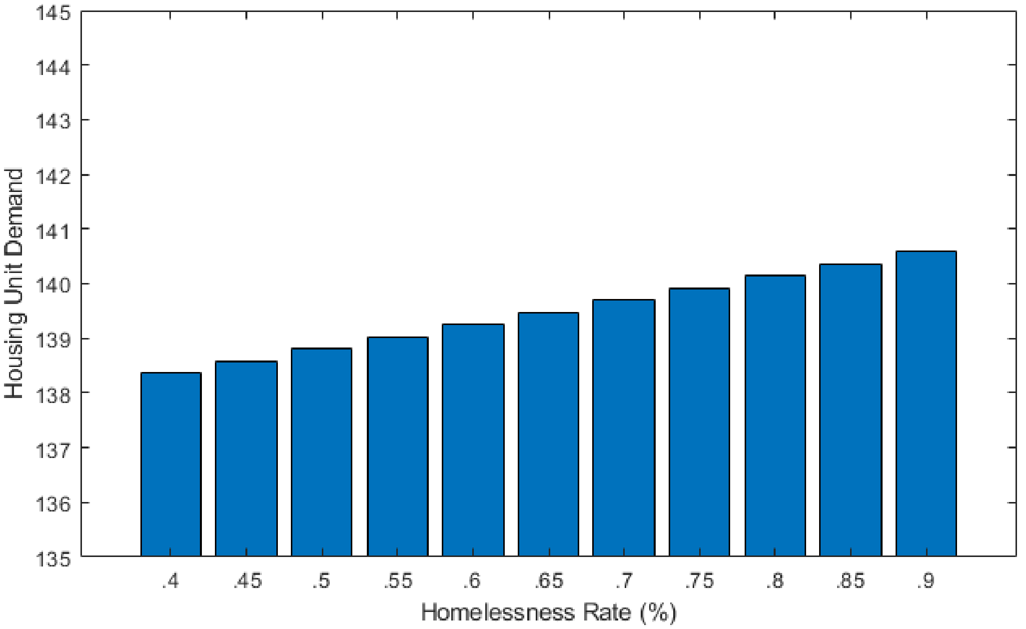


Figure 95: South Carolina's Sensitivity of Housing Demand from Homelessness Rate

B.8 Texas

B.8.1 Inventory Optimization Results

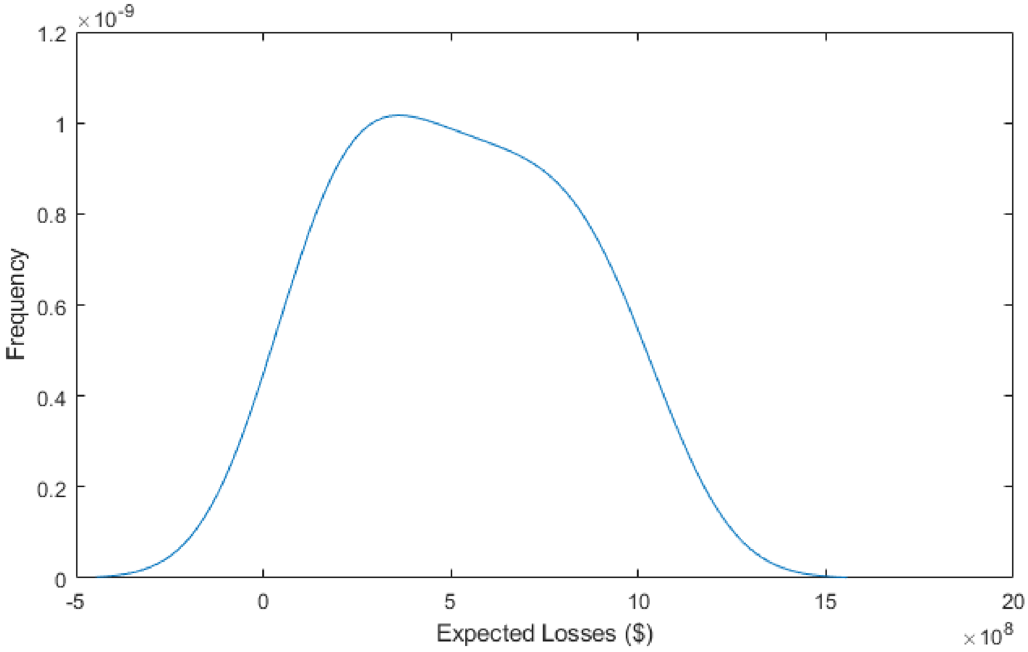


Figure 96: Texas's Density of Expected Losses

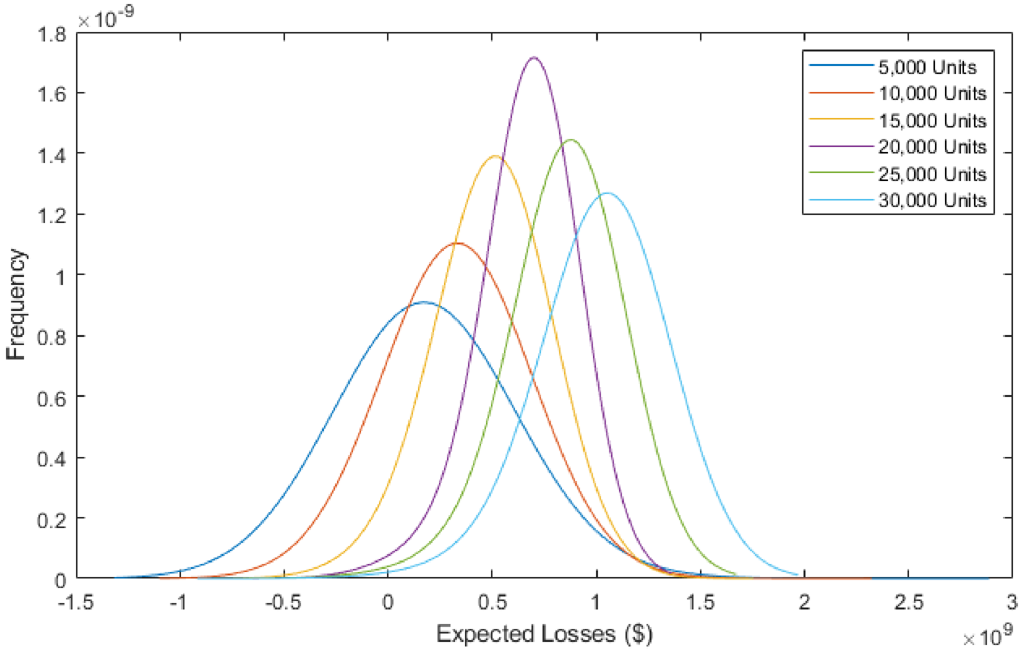


Figure 97: Texas's Overlay of Expected Losses by Stocking Inventory

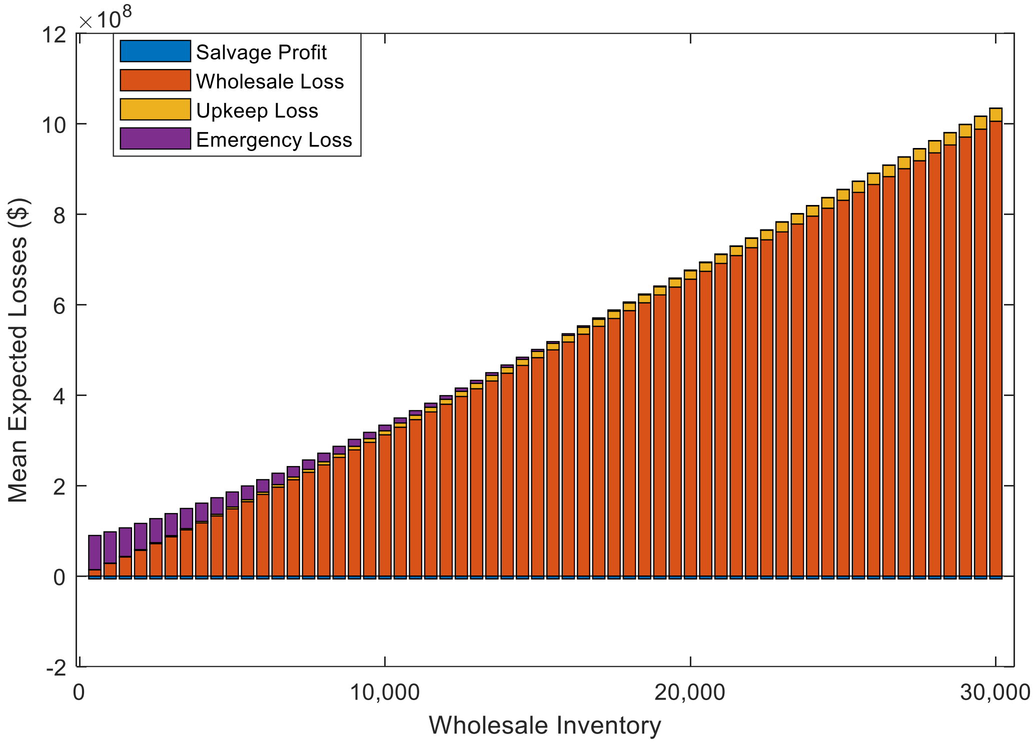


Figure 98: Texas's Expected Losses for Wholesale Inventories

B.8.2 Sensitivity – Housing Damage for Prolonged Displacement

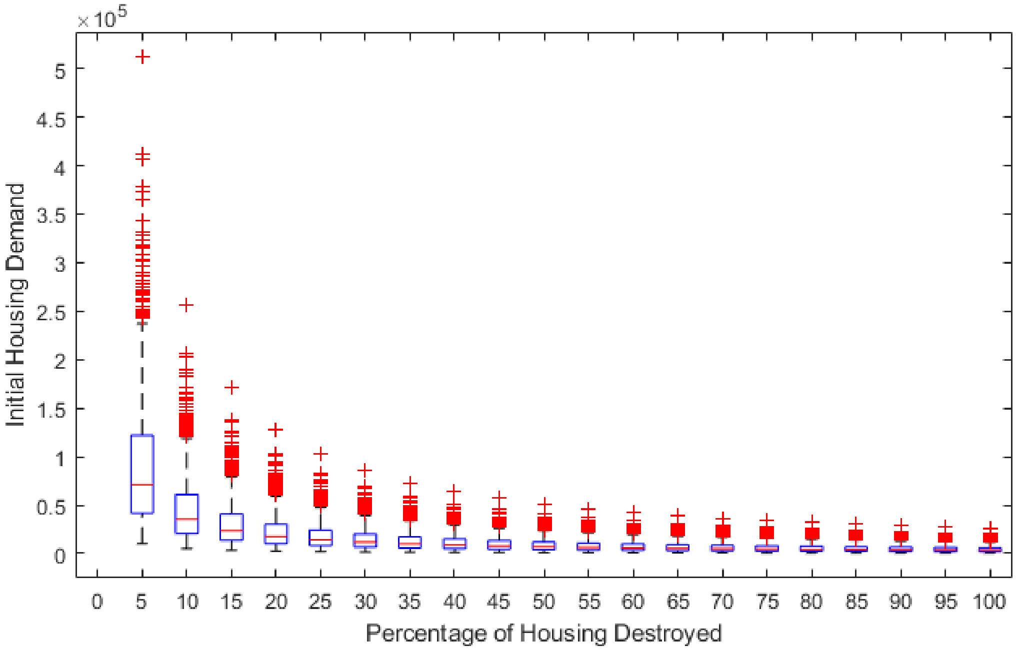


Figure 99: Texas's Sensitivity Analysis on Amount of Housing Damage to Require Temporary Housing

B.8.3 Sensitivity – Residential Damage

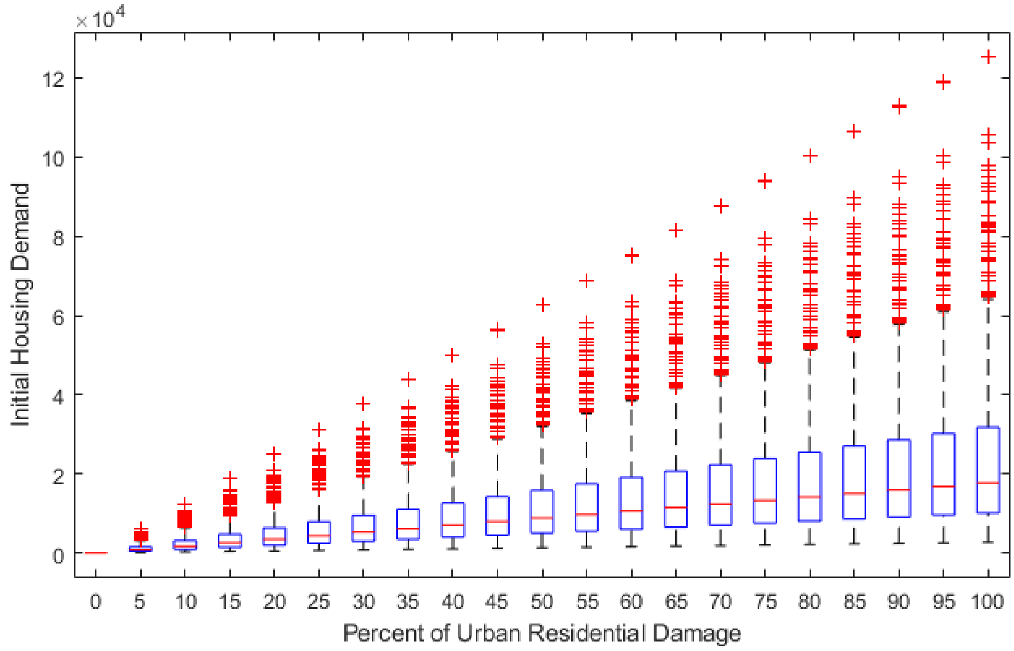


Figure 100: Texas’s Sensitivity Analysis on Urban Residential Damage

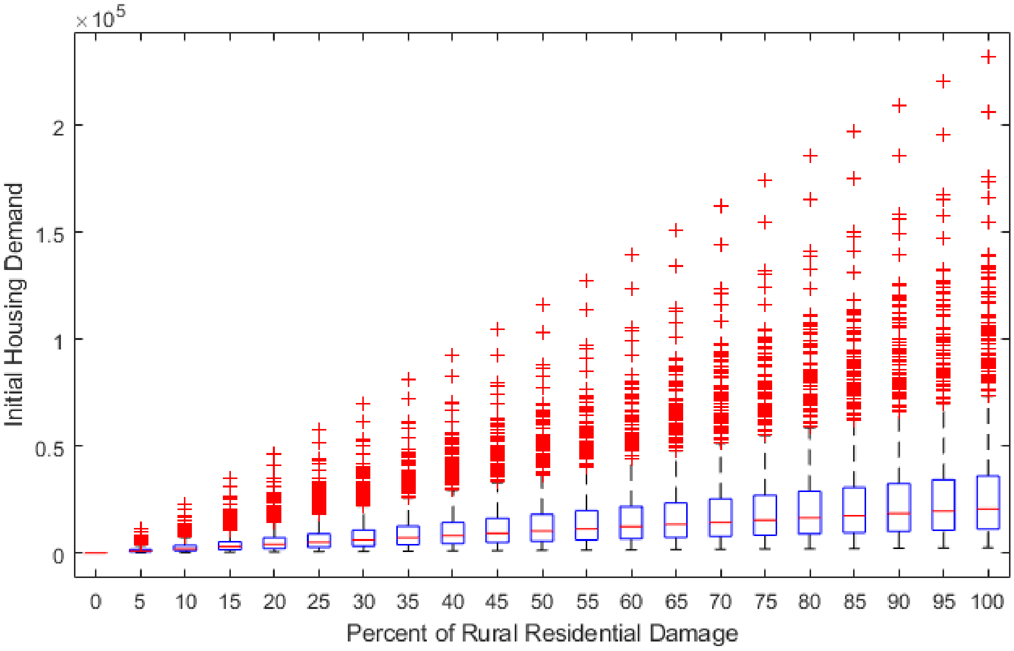


Figure 101: Texas's Sensitivity on Rural Residential Damage

B.8.4 Sensitivity - Svi and Homelessness sensitivity

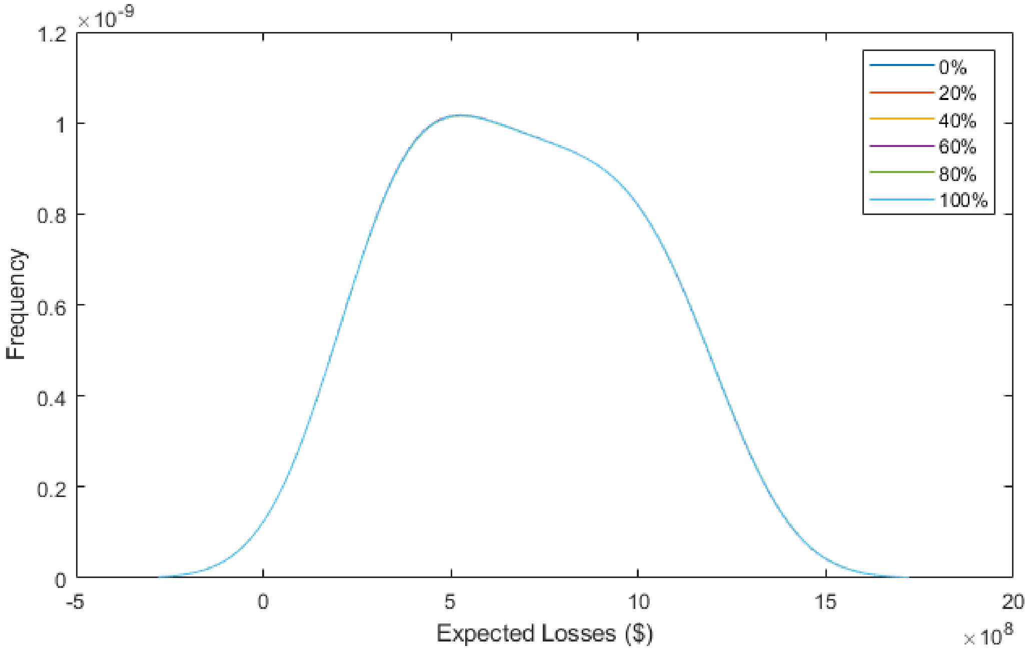


Figure 102: Texas's Sensitivity of Expected Losses from Social Vulnerability

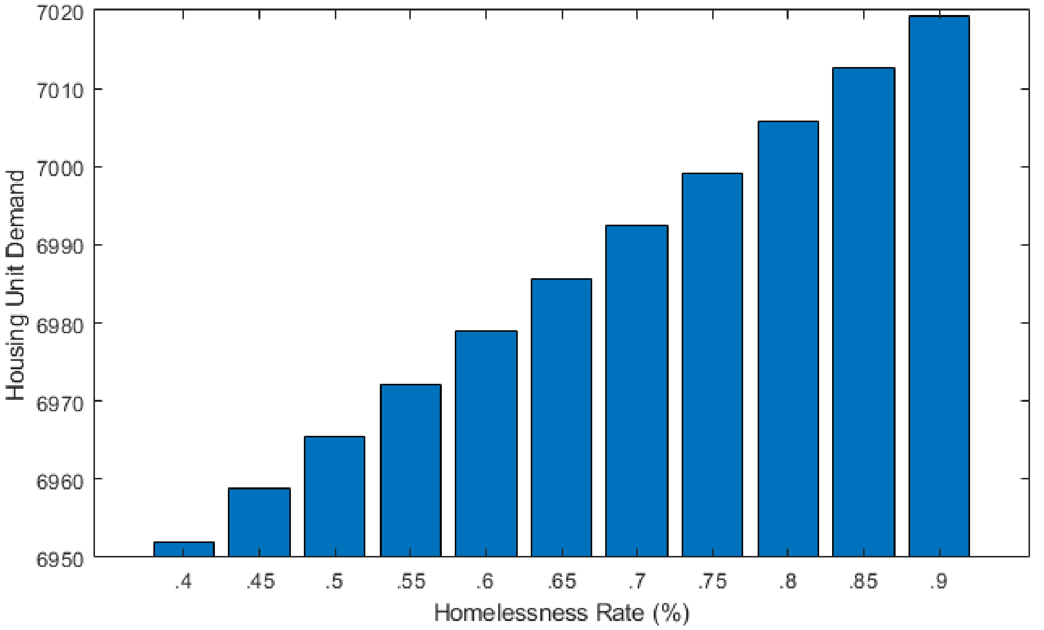


Figure 103: Texas's Sensitivity of Housing Demand from Homelessness Rate

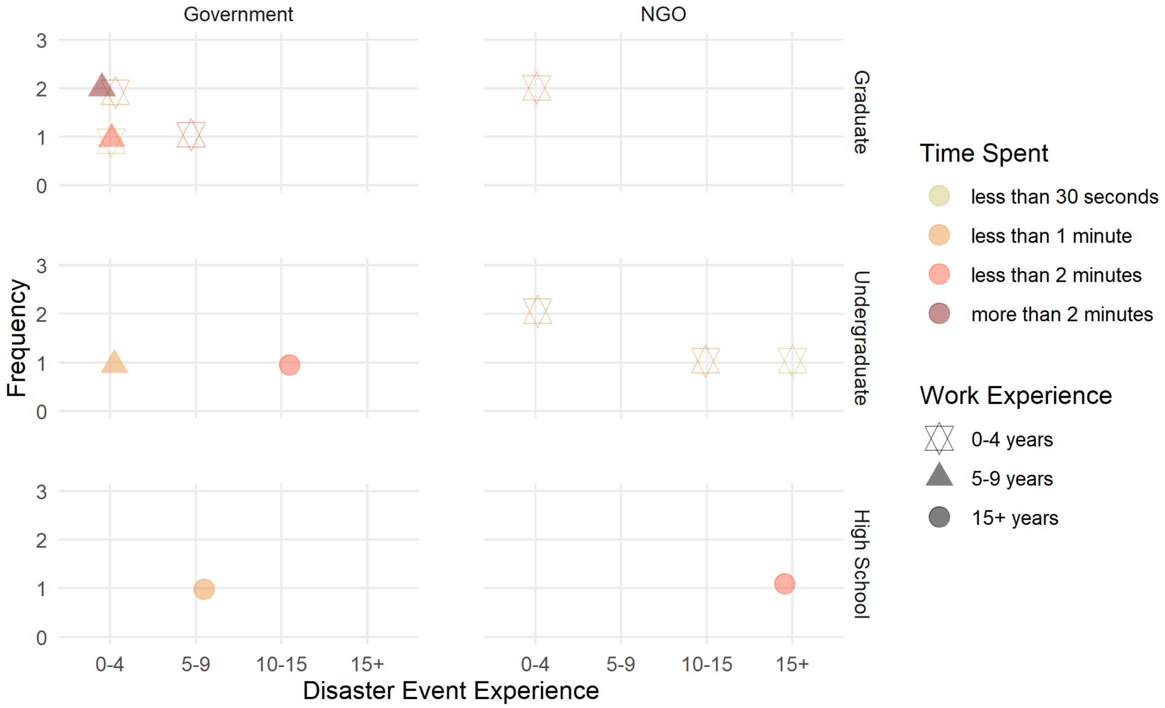


Figure 104: Time Commitment for Initial Property Damage Evaluation by Stakeholder Type, Education Level, Work Experience, and Disaster Event Experience

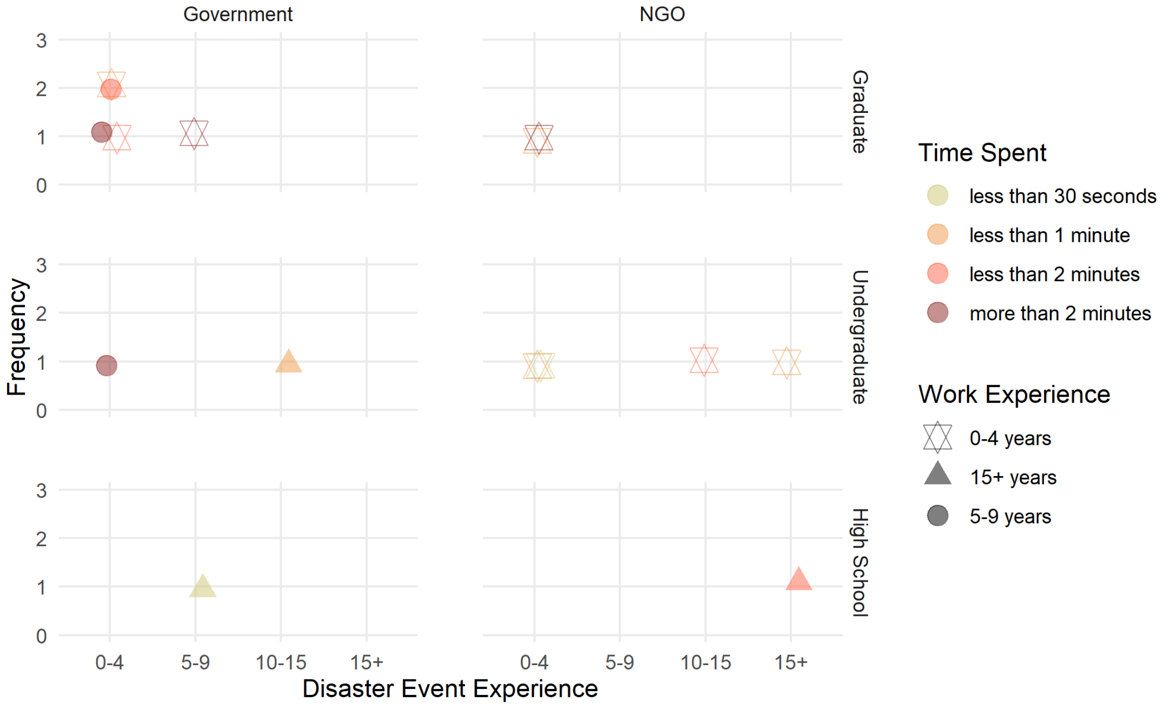


Figure 105: Time Commitment for Evaluating Regions for More Assistance by Stakeholder Type, Education Level, Work Experience, and Disaster Event Experience

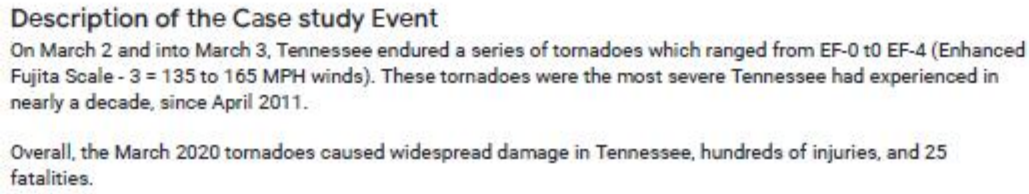
Survey Methodology – Stakeholder Elicitation:

Comparative Survey

The goal of this survey is to evaluate disaster recovery and policy decision-making using real-time photography. Throughout the images in the comparative survey, you will be asked to respond to a few brief questions. By participating in this study, you are helping evaluate how utilizing real-time photography can impact decision-making policies for local and state stakeholders.

This survey is timed to take approximately 15 minutes and increasing the in-browser zoom may provide a better viewing experience. We suggest 150%.

* Required



Description of the Case study Event

On March 2 and into March 3, Tennessee endured a series of tornadoes which ranged from EF-0 t0 EF-4 (Enhanced Fujita Scale - 3 = 135 to 165 MPH winds). These tornadoes were the most severe Tennessee had experienced in nearly a decade, since April 2011.

Overall, the March 2020 tornadoes caused widespread damage in Tennessee, hundreds of injuries, and 25 fatalities.

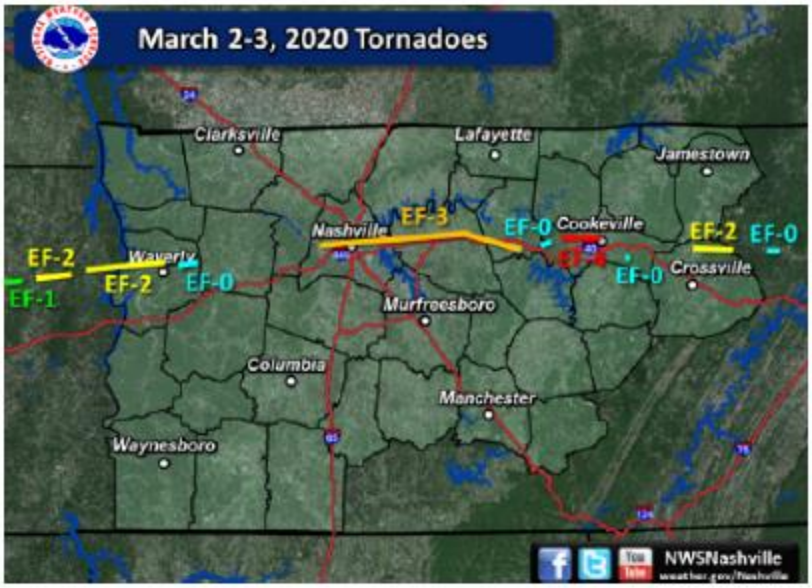
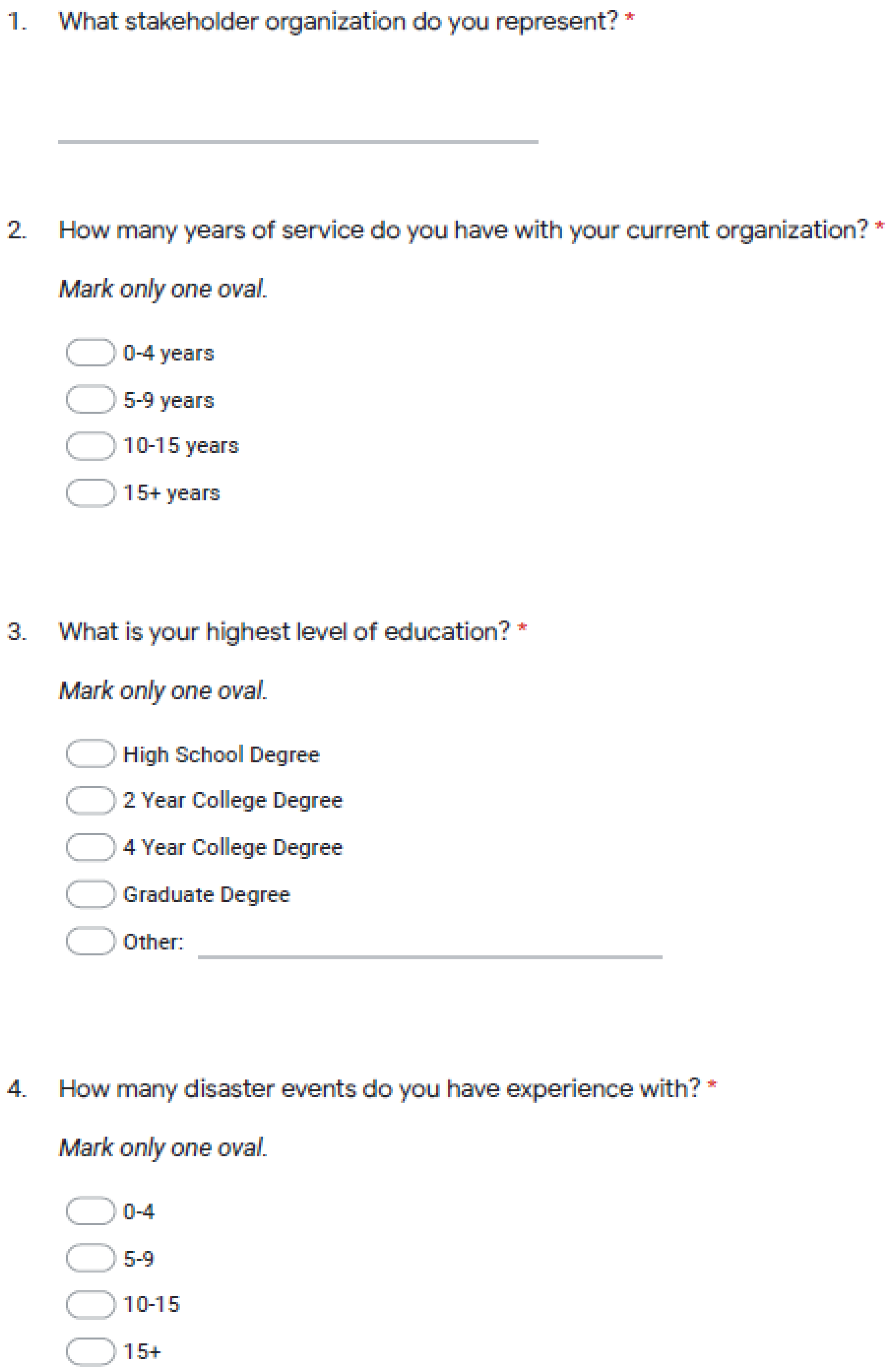


Image Credit: https://www.weather.gov/ohx/20200303



1. What stakeholder organization do you represent? *

____

2. How many years of service do you have with your current organization? *

Mark only one oval.

○ 0-4 years
○ 5-9 years
○ 10-15 years
○ 15+ years

3. What is your highest level of education? *

Mark only one oval.

○ High School Degree
○ 2 Year College Degree
○ 4 Year College Degree
○ Graduate Degree
○ Other: ______________________________

4. How many disaster events do you have experience with? *

Mark only one oval.

○ 0-4
○ 5-9
○ 10-15
○ 15+

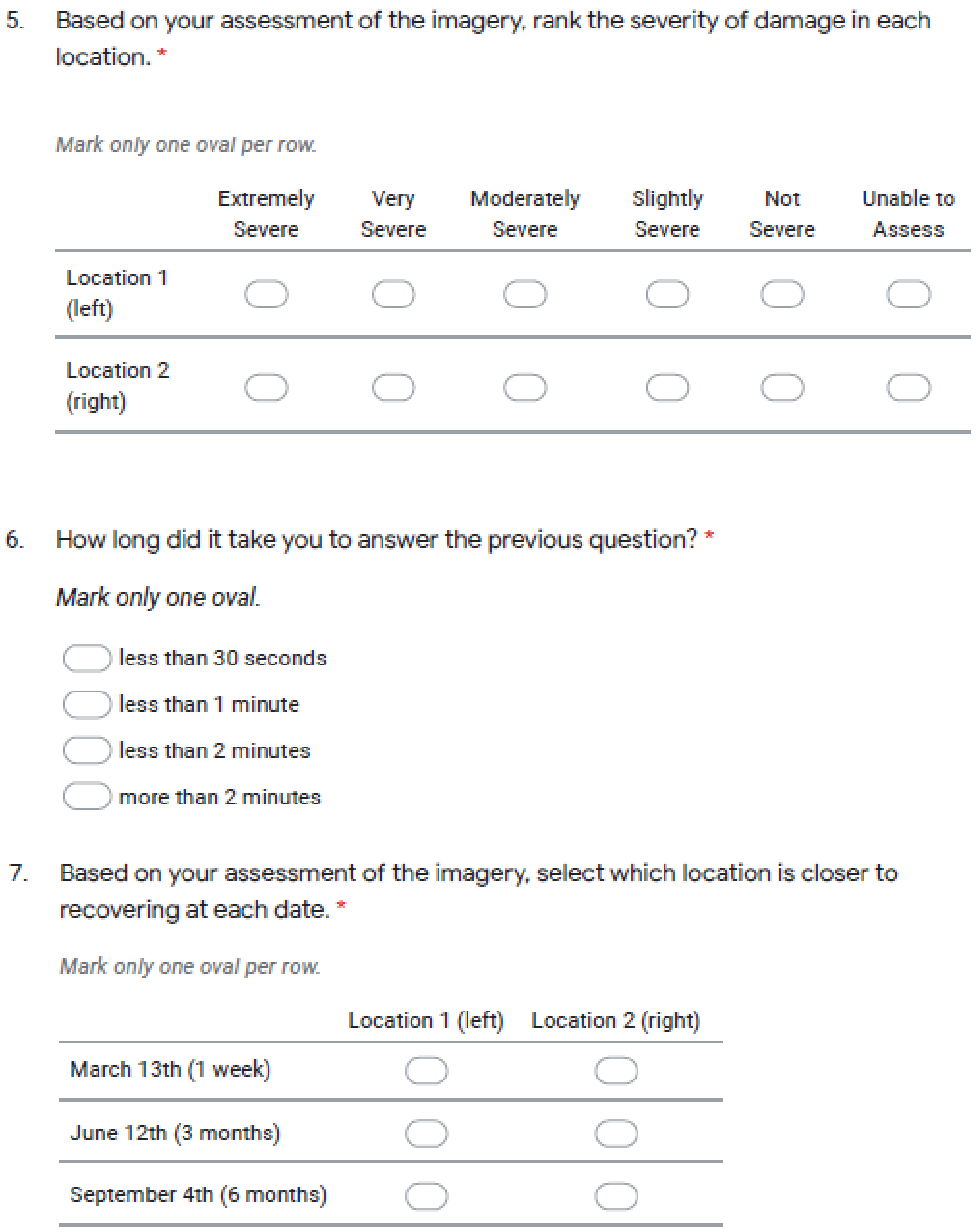
Comparing two different locations, with imagery from three dates spanning 6 months.

Location 1 (left side)   Location 2 (right side)

March 13th (1 week after)

June 12th (3 months after)

September 4th (6 month after)



5. Based on your assessment of the imagery, rank the severity of damage in each location. *

Mark only one oval per row.

	Extremely Severe	Very Severe	Moderately Severe	Slightly Severe	Not Severe	Unable to Assess
Location 1 (left)	○	○	○	○	○	○
Location 2 (right)	○	○	○	○	○	○

6. How long did it take you to answer the previous question? *

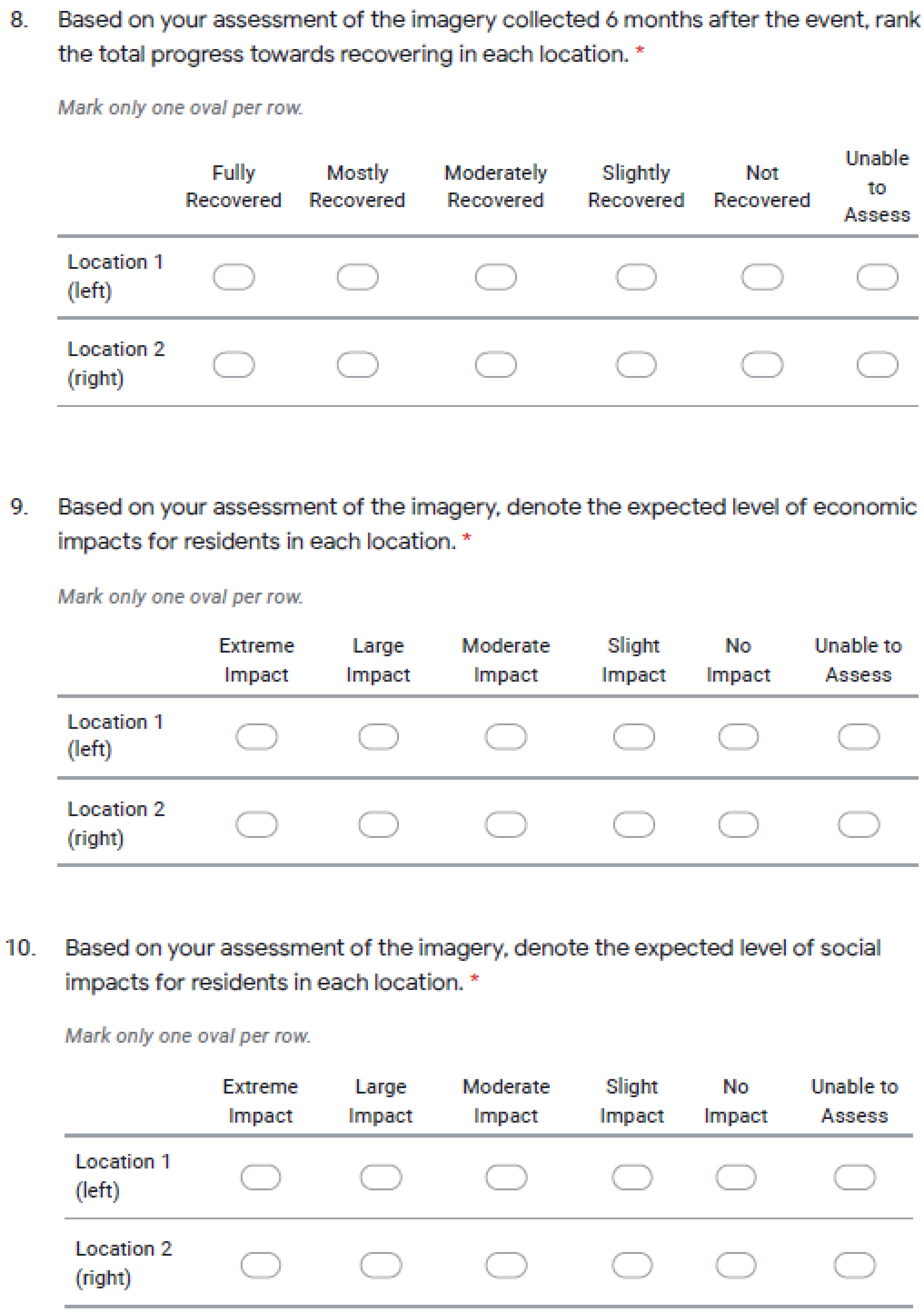
Mark only one oval.

○ less than 30 seconds
○ less than 1 minute
○ less than 2 minutes
○ more than 2 minutes

7. Based on your assessment of the imagery, select which location is closer to recovering at each date. *

Mark only one oval per row.

	Location 1 (left)	Location 2 (right)
March 13th (1 week)	○	○
June 12th (3 months)	○	○
September 4th (6 months)	○	○



8. Based on your assessment of the imagery collected 6 months after the event, rank the total progress towards recovering in each location. *

Mark only one oval per row.

	Fully Recovered	Mostly Recovered	Moderately Recovered	Slightly Recovered	Not Recovered	Unable to Assess
Location 1 (left)	○	○	○	○	○	○
Location 2 (right)	○	○	○	○	○	○

9. Based on your assessment of the imagery, denote the expected level of economic impacts for residents in each location. *

Mark only one oval per row.

	Extreme Impact	Large Impact	Moderate Impact	Slight Impact	No Impact	Unable to Assess
Location 1 (left)	○	○	○	○	○	○
Location 2 (right)	○	○	○	○	○	○

10. Based on your assessment of the imagery, denote the expected level of social impacts for residents in each location. *

Mark only one oval per row.

	Extreme Impact	Large Impact	Moderate Impact	Slight Impact	No Impact	Unable to Assess
Location 1 (left)	○	○	○	○	○	○
Location 2 (right)	○	○	○	○	○	○

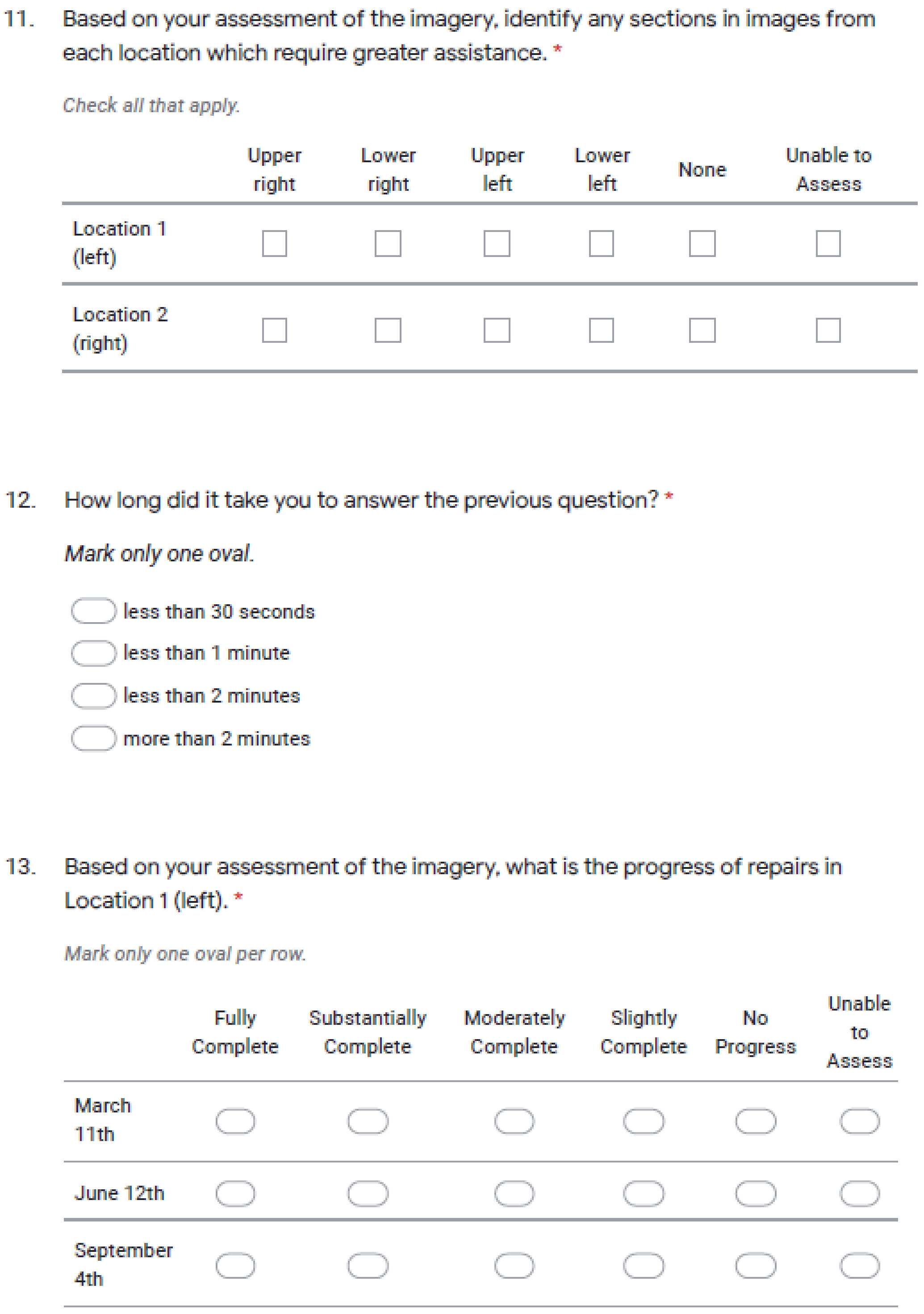
Comparing two different locations, with imagery from three dates spanning 6 months.

Location 1 (left side) Location 2 (right side)

March 11th (1 week after)

June 12th (3 months after)

September 4th (6 months after)



11. Based on your assessment of the imagery, identify any sections in images from each location which require greater assistance. *

Check all that apply.

	Upper right	Lower right	Upper left	Lower left	None	Unable to Assess
Location 1 (left)	☐	☐	☐	☐	☐	☐
Location 2 (right)	☐	☐	☐	☐	☐	☐

12. How long did it take you to answer the previous question? *

Mark only one oval.

○ less than 30 seconds
○ less than 1 minute
○ less than 2 minutes
○ more than 2 minutes

13. Based on your assessment of the imagery, what is the progress of repairs in Location 1 (left). *

Mark only one oval per row.

	Fully Complete	Substantially Complete	Moderately Complete	Slightly Complete	No Progress	Unable to Assess
March 11th	○	○	○	○	○	○
June 12th	○	○	○	○	○	○
September 4th	○	○	○	○	○	○

14. Based on your assessment of the imagery, what is the progress of repairs in Location 2 (right). *

Mark only one oval per row.

	Fully Complete	Substantially Complete	Moderately Complete	Slightly Complete	No Progress	Unable to Assess
March 11th	○	○	○	○	○	○
June 12th	○	○	○	○	○	○
September 4th	○	○	○	○	○	○

Comparing two different locations, with imagery from three dates spanning 1 month.

Location 1 (left side)

Location 2 (right side)

March 13th (1 week after)

March 21th (2 weeks after)

April 4th (1 month after)

15. Based on your assessment of the imagery collected after 1 month, what is the total progress of debris removal in each location pictured? *

Mark only one oval per row.

	Fully Complete	Mostly Complete	Moderately Complete	Slightly Complete	No Progress	Unable to Assess
Location 1 (left)	○	○	○	○	○	○
Location 2 (right)	○	○	○	○	○	○

Supplementary images to show the relative size of debris piles.

16. Based on your opinion and the provided imagery, how important is the removal of rubble/debris towards recovering? *

Mark only one oval.

○ Extremely Important
○ Very Important
○ Moderately Important
○ Slightly Important
○ Not Important