2015

Integrated Sustainability and Resiliency Assessment Methodology for the Design of Single-Family Residential Structures Subject to Wind and Flood Hazards

Elizabeth Chisolm Matthews
Louisiana State University and Agricultural and Mechanical College

Recommended Citation

Matthews, Elizabeth Chisolm, "Integrated Sustainability and Resiliency Assessment Methodology for the Design of Single-Family Residential Structures Subject to Wind and Flood Hazards" (2015). *LSU Doctoral Dissertations*. 3412.
https://repository.lsu.edu/gradschool_dissertations/3412

INTEGRATED SUSTAINABILITY AND RESILIENCY ASSESSMENT METHODOLOGY FOR THE DESIGN OF SINGLE-FAMILY RESIDENTIAL STRUCTURES SUBJECT TO WIND AND FLOOD HAZARDS

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the Degree of
Doctor of Philosophy

in

The Interdepartmental Program in Engineering Science

by
Elizabeth Chisolm Matthews
B.S., Louisiana Tech University, 2005
M.S., Louisiana Tech University, 2007
May 2015

ACKNOWLEDGEMENTS

I would like to thank my committee members collectively and individually: Carol Friedland, John Pardue Ayman Okeil and Craig Colten. They have been instrumental in my graduate education through coursework and helping guide my research. I would also like to thank Meredith Sattler, who was formally a co-chair on my committee and who was a significant participant in my research up until last year. I especially thank my graduate adviser, Carol Friedland, who has been major participant in this research from the beginning and shaped the way in which my research was conducted.

I gratefully acknowledge the Louisiana Board of Regents who supported four years of my research and education with fellowship assistance and the Department of Construction Management at LSU who has provided support in the form of a graduate assistantship in this my last semester. The opportunities afforded to me through this financial support have been invaluable in shaping my education and future.

I am thankful to data provided by Kurtis Gurley at the University of Florida and Jean-Paul Pinelli at the Florida Institute of Technology, which was the basis in the development of the wind model presented in this dissertation. I am deeply thankful for the advice and support I have received from my fellow graduate students and colleagues, Carol Massarra, Shandy Heil, Rehema Monko and Mahtab Orooji. Their support and friendship have meant a great deal as I have progressed through my doctoral education. I especially would like to thank Mahtab Orooji who provided support in the form of Matlab coding and BIM modeling, which was instrumental to the models presented in this dissertation.

Finally, I am thankful to my family which has grown over the four or more years I have been at LSU. My husband, John Matthews, who has been my guiding force throughout and has provided indispensable advice and support as each challenge arose. To my son, Michael Matthews and to my future son Alexander Matthews, who have brought joy and a new meaning to my life. And to my mother, father, brother and sister who have always been there for me when I needed support.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Sustainability and resiliency have become important in shaping the criteria in performance-based design objectives in the recent past and will continue to shape future design as climate change impacts and disasters become more prevalent. While much work has been carried out in developing tools to aid in sustainable and resilient performance-based design there is still much work to be done. It is evident that while sustainability and resiliency have mutual advantages there are also inherent conflicts between the two design approaches. Some of the conflict relates to the robustness required of resilient design, which may have higher environmental impacts than traditional construction. Other conflicts have resulted from addressing these two design goals using separate tools and approaches rather than addressing them simultaneously through an integrated design process.

This means there is the potential today for sustainable buildings to be constructed that are either vulnerable to hazards, which are avoidable, or resilient buildings that could be designed to be more sustainable. Weighing cost and structural performance has been an integral part of engineering design, and in similar ways intersections between environmental impact and structural performance can be addressed. However, sustainable and resilient development principals need to be better integrated together within design process so that intersections between the two can be identified and tradeoffs can be weighed.

The models proposed in this dissertation are potential tools where sustainable and resilient design can be optimized within the context of the design and construction of coastal, single-family residential (SFR) structures subject to wind and flood hazards. Optimization is accomplished through the consideration of the environmental impacts of SFR buildings and by comparing alternate designs with varying levels of resilience. The comparison is based on multiple environmental impact metrics which are measured for key phases of the building’s life-cycle. Identifying the optimal design aides the designer in making objective, performance-based design decisions.

CHAPTER 1: INTRODUCTION

1.1 Background

In the U.S. in 2011 the residential sector consumed 22% of the total energy of all end-use sectors (i.e. residential, commercial, industrial and transportation) (US EIA, 2013) and produced approximately 21% of the carbon dioxide emissions associated with energy consumption for all major energy sources (i.e. coal, natural gas, petroleum, retail electricity). About 71% of those emissions were associated with electricity use. The increased demand for electricity has contributed to an estimated 21% increase in carbon dioxide emissions between 1990 and 2011 (US EPA, 2013). The connection between emissions of greenhouse gases, such as carbon dioxide; and global warming and its impacts (e.g. sea level rise) has been well established (NRC, 2010).

Almost 40% of the U.S. Population in 2010 lived in counties or parishes which make up the shoreline of the country (10% of the total U.S. land area) (NOAA, 2013). NOAA has estimated that of 5,886 miles of Atlantic coast, 27% and 22% are at very high risk and high risk to future sea level rise, respectively (Thieler & Hammar-Klose, 1999). Of the 2,478 miles of Pacific Coast, 27% and 22% are at very high risk and high risk, respectively (Thieler & Hammar-Klose, 2000a), and 5,007 miles of Gulf Coast shoreline, 42% and 13% are at very high risk and high risk, respectively (Thieler & Hammar-Klose, 2000b). One of the highest measured relative sea level rise rates in the U.S. is in Grand Isle, Louisiana (NOAA, 2014).

Compounded with sea level rise, recurring natural hazard events are expected to cause future damage. In the U.S., flooding is associated with a large proportion (90% in 2005) of natural hazard occurrences (US GAO, 2005). While flood-associated events are more common, wind events (e.g. tornadoes and thunderstorms) and combined wind and flood events (e.g. hurricanes and tropical cyclones) have caused the largest proportion of insured losses in the U.S.in the last twenty years (Hartwig & Weisbart, 2012).

The aim of both sustainable and resilient development is to improve the performance of structures and communities beyond current benchmarks. Benchmarks are set by adopted codes and regulations and should be the minimum to which structures are designed. However, code does not take into account long term coastal processes (e.g., global sea level rise, subsidence), which can significantly decrease the resilience of a residential structure over its lifespan (Bohn & Friedland, 2013). To fill this gap, voluntary code-plus guides and programs for residential construction (e.g. FEMA, 2011; Malik et al., 2012) have been developed which do consider these processes in their design guidance.

Additionally, there are resilience tools that determine the vulnerability of structures and communities to hazards (e.g. Ettouney et al., 2011; Renschler et al., 2010; ICA, 2013). These tools consider multiple hazards, building types and levels of assessment. While these tools are useful in measuring resilience they can only be applied to structures that already exist. In many cases, retrofitting structures is more difficult and expensive than incorporating resilient strategies into a design before a structure is even constructed. These tools would be more beneficial to newer constructions if their concepts were applied in the design process rather than the use-phase of the building's lifecycle.

Building codes also do not address issues targeted by sustainable development (e.g., climate change, land conservation and excessive resource consumption). Sustainable development issues are instead being incorporated into the design of residential buildings and neighborhoods through sustainable development tools and principles (e.g. LEED® for Homes, LEED® ND, & New Urbanism). While these tools and principles have been adopted worldwide, it is yet to be proven if they have achieved their intended purpose in all case study applications of these tools. Research (e.g. Menassa et al., 2012; Newsham et al., 2009; Scofield, 2009) has indicated that there are buildings designed with LEED® that do not meet sustainable performance goals (e.g. energy consumption reduction) while other buildings do.

There is also evidence that there are gaps in the design frameworks of sustainable development tools that have the potential to result in sustainable residential structures and communities that are vulnerable to hazards (e.g. FEMA, 2010; Stevens et al., 2010). Conflicts are expected when using code and sustainability tools concurrently for residential design, since the guidance for both have different agendas and neither considers tradeoffs with the other. Weighing cost and structural performance has been an integral part of engineering design, and in similar ways intersections between environmental impact and structural performance can be addressed. However, sustainable and resilient development principals need to be better integrated together within design process so that intersections between the two can be identified and tradeoffs can be weighed.

1.2 Problem Statement

Intersections between resilience and sustainability need to be better addressed when designing single family residential (SFR) structures in coastal areas. Currently no tools or methodologies exist that adequately integrate sustainable and resilient development of SFR structures so that design conflicts and synergies can be identified within the design process. The incorporation of sustainable development into the design process of coastal SFR structures using current tools has the potential to result in SFR structure designs that are vulnerable to the impacts of extreme events. New models need to be developed for integrating the concepts of sustainable and resilient development of coastal SFR structures.

1.3 Goals and Objectives

The main goal of this proposed dissertation research is to integrate the concepts of sustainability and resiliency to improve the design and construction of single-family residential (SFR) structures so that these buildings are environmentally friendly and resistant to wind and flood hazards. In order to achieve the aims of the main goal, four specific objectives are identified.

1) Examine existing sustainability and resiliency tools related to structural design in order to summarize and analyze the current state-of-the-art in sustainability and resiliency design assessment tools, and identify opportunities for the integration of sustainability and resiliency assessment methodologies within coastal residential construction design practice.

Current state-of-the-art in sustainability and resiliency tools relating to structural design and construction are investigated with the objective of identifying opportunities for integrating the two development concepts into a single assessment methodology for structures subject to wind and flood hazards. Studying existing tools allows comparison of the most influential tools to date in order to best understand current methodology and identify gaps where improvement in design assessment can be made. Comparison of these tools also helps to provide a basis for developing an integrated methodology that focuses on optimization and trade-offs, which is key to the structural design decision making process.

2) Develop a set of component-based flood depth-damage curves for single-family residential structures to support Objective 3.

In order to build the model in Objective 3, a set of discrete, component-level depth-damage functions was developed. The functions are customizable to different wood-frame, single-family residential structure designs. The curves are designed to output the percent damage to material damage quantities over a range of flood depths.

3) Develop an integrated sustainability and resiliency design assessment model for flood hazard, with the objective of maximizing performance of residential structures subject to flood loading, but also minimizing environmental impacts of flood-resistant SFR construction through reductions in energy consumption, carbon emissions and water consumption for key phases of the structure’s life-cycle.

Analytical, structural and objective approaches for quantifying sustainability and flood resiliency performance are investigated with the objective of developing an integrated sustainability and flood resiliency design assessment model for SFR structures subject to flood hazards. The most appropriate approaches are selected and data from those approaches are compiled. An integrated design assessment model for sustainable and resilient SFR structures subject to flood hazard is developed that will focus on optimization and trade-offs between environmental impacts and flood-hazard resistant construction.

4) Develop an integrated sustainability and resiliency design assessment model for wind hazard, with the objective of maximizing performance of residential structures subject to high wind loading, but also minimizing environmental impacts of wind-resistant SFR construction through reductions in energy consumption, carbon emissions and water consumption for key phases of the structure's life-cycle.

Analytical, structural and objective approaches for quantifying sustainability and wind-resiliency performance are investigated with the intent of developing an integrated sustainability and wind resiliency design assessment model for SFR structures subject to wind hazards. The most appropriate approaches are selected and data from those approaches are compiled. An integrated design assessment model for sustainable and resilient SFR structures subject to wind hazard is developed that will focus on optimization and trade-offs between environmental impacts and wind-hazard resistant construction.

1.4 Scope of Study

Other than the comparative analysis presented in Chapter 2, the scope of the study is limited to single-family residential construction. The geographical focus of the study will be SFR structures in coastal areas subject to tropical cyclones. Coastal areas are defined according to the National Oceanic and Atmospheric Administration's definition of coastal zones (see Section 1.9). The resilience portion of the study is limited to flood and wind type hazards.

1.5 Limitations of the Study

There are many ways to define and measure the sustainability and resiliency of structural development; however, the methodologies developed in this study are limited to the units of measure chosen within the study. The study is all limited to level of accuracy associated with the data (e.g. embodied energy & global warming potential) collected from the analytical, numerical-based approaches chosen from literature. The methodologies developed in this study mainly focus on geographical areas subject to tropical cyclones, but they may also be applicable in other areas subject to wind and flood hazard. The data associated with the methodologies may need to be recalibrated in order to be applicable in other geographical regions. While the focus is on both wind and flood hazards, this dissertation study does not take into account the combined effect of wind and flood impacts.

1.6 Organization of the Dissertation

This dissertation is organized by the objective topics. Chapter 1 provides an introduction, background for the presented problem, scope of study, limitations of the study and some definition of terms. Chapter 2 reviews current state-of-the-art in sustainability and resiliency tools and methodology and provides a comparison analysis of eleven sustainability assessment frameworks. Chapters 3 presents the development of set of component-based flood depth-damage curves for single-family residential structure. Chapter 4 presents the development of an integrated sustainability and resiliency assessment model for flood hazard. Chapter 5 presents the development of an integrated sustainability and resiliency assessment model for flood hazard. Chapter 6 presents the conclusion and recommendations for the dissertation.

1.7 Definition of Terms

The following are terminology associated with the study and are defined according to accepted definitions within the literature.

Sustainable Development - "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987, pp 41).

Resilience - The Department of Homeland Security (DHS) defines resilience as the "ability to resist, absorb, recover from or successfully adapt to adversity or a change in conditions" (DHS, 2009). Concepts associated with resilience include robustness (i.e., operational durability of systems), redundancy (i.e., presence of backup systems), rapidity (i.e., speed of response), resourcefulness (i.e., ability to plan for or react to disasters), and recovery (i.e., returning to a pre-disaster state) (Bruneau et al., 2003; Ettouney, et al., 2011). Risk is also a key concept associated with resilience, which incorporates elements such as vulnerability, threats, and consequences (Ettouney, et al., 2011).

Mitigation - Actions taken to prevent damaging environmental changes on the global scale (e.g., reducing greenhouse gas emissions (GHG)) (McEvoy et al., 2006; Tol, 2005).

Adaptation - Reacting to environmental changes, predominately at a local scale (e.g., evacuation planning, disaster preparedness, response and recovery planning) (McEvoy, et al., 2006).

Hazard-resistance - Hardening structures and infrastructure so that they are able to resist a specific hazard level (e.g., category 3 hurricane), or designing or siting structures and infrastructure so they are not exposed to hazard forces (e.g., pier foundations) (FEMA, 2011).

Coastal Areas – Areas have historically been or are at risk from future exposure to the impacts of tropical systems related surge flooding and wind hazards. For flood hazards, this includes areas subject to surge flooding, which could include inland areas adjacent to waterways subject to surge flooding as defined by Federal Emergency Management Agency flood insurance rate study documents. However, this does not include areas subject to riverine flooding associated with tropical cyclone events. For wind hazards, this includes areas subject to the risk of tropical cyclone winds as defined by the Applied Technology Council's published wind maps and data.

CHAPTER 2: RESILIENCE ANALYSIS OF SUSTAINABILITY ASSESSMENT FRAMEWORKS

2.1 Introduction

Currently, sustainable development focuses on mitigating damaging environmental changes through reductions in the anthropogenic drivers of degradation (e.g., pollution). Examples of damaging environmental changes include depletion of vital resources (e.g., potable water, rare earth metals, and arable land) and increases in extreme weather events (e.g., extreme temperatures, droughts, flooding, and hurricanes). While sustainable development concentrates on addressing anthropogenic drivers, the practice does little to mitigate the impacts of future environmental change (McEvoy, et al., 2006). Resilience has recently come to the forefront of research and policy as a means to address the impacts of future risks on the built environment due to climate change and other environmental and societal hazards (e.g., natural disasters, terrorism) (Bruneau, et al., 2003; Tol, 2005).

In design, sustainable development has largely been realized through the creation of sustainability development tools. These tools equip designers, builders, owners, and end users with design strategies that reduce the environmental impact of developments (Reeder, 2010). Currently, hundreds of these tools have been developed and they vary in complexity, level of application, and geographical suitability (i.e., internationally versus location specific). Sustainability Assessment Frameworks (SAFs) are one such group of tools that are used by practitioners of sustainable development (e.g. LEED$^{®}$).

Many SAFs incorporate some level of resilience-related issues (e.g., limiting construction in flood prone areas, planning for climate change, and ensuring operational reliability of structures during disasters); however, what is not apparent is the extent to which resilience-related issues are covered and how multiple SAFs compare in terms of their level of integration of hazard resistant design and hazard mitigation measures. Identifying the extent to which resilience is incorporated in SAFs and understanding conflicts between sustainability and resilience criteria is important for designers and other practitioners to understand, especially when developing in hazard prone areas.

Comparisons of SAFs have been made focusing on the various components and functional aspects of tools from a sustainability perspective. Haapio and Viitaniemi (2008); Vijayan and Kumar (2005); and Ding (2008) review

This chapter previously appeared Matthews, E., Sattler, M., & Friedland, C., "A critical analysis of hazard resilience measures within sustainability assessment frameworks," *Environmental Impact Assessment Review*, Vol 49, pp 59-69, 2014. It is reprinted from "A critical analysis of hazard resilience measures within sustainability assessment frameworks, Vol 49, Matthews, E., Sattler, M., & Friedland, C., *Environmental Impact Assessment Review*, pp 59-69, 2014 with permission from Elsevier by permission of Elsevier. See Appendix A for license agreement.

SAFs along with other tool types. Fowler and Rauch (2006), Berardi (2012) and Todd et al. (2001) review building level SAFs. Sharifi and Murayama (2013), Sharifi and Murayama (2014a), Haapio (2012), Sharifi and Murayama (2014b) and Hurley and Horne (2006) discuss community level SAFs. These and other studies have analyzed SAFs primarily to categorize, summarize or compare existing tools for their applicability, scoring, coverage of the core areas of sustainability, and other characteristics (e.g. Fowler & Rauch, 2006; Haapio & Viitaniemi, 2008; Sharifi & Murayama, 2013).

Few studies have investigated resilience in SAFs. While Sharifi and Murayama (2014a) point to the differences in resilience coverage of three community level SAFs, resilience is not the prominent focus of this study and the level of detail of the comparison between the tools for resilience is limited. Gordon (2010) analyzed LEED® ND in more detail for its inclusion of hazard mitigation design measures focusing on fire and earthquakes. The Federal Emergency Management Agency has also identified conflicts between sustainability design strategies and building and community resilience focusing its analysis on International Green Construction Code standards (FEMA, 2010). However, neither Gordon (2010) nor FEMA (2010) compare SAFs to investigate differences in the integration of resilience across multiple frameworks.

2.2 Aim

The aim of Chapter 2 is to compare SAFs to determine the extent to which they integrate resilient design strategies and whether weaknesses in resilience coverage exist that have the potential to lead to the design of structures and communities that are vulnerable to the impacts of extreme events. Through understanding the level of resilience coverage of SAFs, practitioners of sustainable development will be able to make informed decisions when selecting which SAFs to utilize on projects in hazard prone areas and whether additional design and planning effort is needed to address the inherent vulnerabilities of conflicts between sustainable design measures and resilience.

A multi-level analysis (macro, meso, micro) was utilized to make this comparison between 11 SAFs, selected among the most commonly used and recently emerging frameworks. The selection of SAFs also cover multiple scales of application (i.e., building, site and community). The macro-level analysis compares the number and relative frequency of measures within each SAF that address resilience and sustainability. In order to quantify resilience and sustainability measures, a taxonomy of measures was created and used to perform a matrix-based comparison of the SAFs. The taxonomy was developed using guide documents for the selected SAFs, in addition to technical manuals for tools used to assess the resilience of buildings and communities. Sustainability measures are included in the taxonomy to: (1) make relative comparisons between the ratio of resilience and sustainability measures for each SAF and (2) investigate measures commonly considered to benefit sustainable development but that may also inadvertently impact resilience either negatively or positively.

The meso-level analysis compares the coverage of hazard types within SAFs (e.g. flood, fire) and the micro-level analysis provides an in-depth comparison of SAF measures connected to flood-related hazard resilience. With an understanding of the extent to which SAFs address resilience, designers and researchers can better understand the limitations of SAFs from a hazard resistance and mitigation perspective, opening up avenues for future research in integrating resilience with sustainable development practices, and informing designers of the importance of identifying possible conflicts between resilient and sustainable design.

2.2.1 Definitions

SAFs, like other sustainability tools, seek to guide designers in the development of more sustainable buildings and environments. In general, the ultimate goal of specific criteria within SAFs is to create sustainable development, which is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987, pp 41). Quantifying and applying this concept in real world situations has been interpreted, measured, and employed in varying approaches globally. SAFs cover multiple sustainability issues (Trusty, 2000), such as reducing greenhouse gases (GHGs), other pollutants and the consumption of limited resources; protecting and conserving the natural environment; and improving quality of life (e.g., improved indoor air quality).

The specific definition for SAFs, which are the focus of this study, was derived from a previously defined classification system for sustainability tools created by the Athena Institute (Trusty, 2000). This classification system describes one group of tools, "whole building assessment frameworks" (Trusty, 2000, pp 1), which are tools such as LEED® and BREEAM®. Some SAF tools incorporate only one framework (e.g., Envision™), while other tools include a system of multiple assessment frameworks (LEED®). Sharifi & Murayama (2013, pp 73) describe assessment framework tools targeting projects beyond the building level (e.g. LEED® ND) in the definition of "neighborhood sustainability assessment tools" and the definition for SAFs in this study extend to building (e.g. school), site and supporting infrastructure, and community scales. Some SAF tools incorporate only one framework (e.g. Envision ™), while other tools include a system of multiple assessment frameworks applicable to specific scales (e.g. LEED® NC). To understand the overarching incorporation of resilience concepts within SAFs, this study analyzes SAFs across multiple scales of assessment.

Similar to sustainability, resilience has been interpreted in multiple ways. The Department of Homeland Security (DHS) defines resilience as the "ability to resist, absorb, recover from or successfully adapt to adversity or a change in conditions" (DHS, 2009). In social and ecological fields, definitions of resilience center on the idea that systems are in flux and that to survive, systems adapt or transform to accommodate shocks or changes in variables (Friedland & Gall, 2012). "As such, resilience focuses on persistence through continuous development, innovation, and transformation to attain new and better-adapted configurations" (Friedland & Gall, 2012, pp 141). Contrarily, engineering definitions of resilience tend to be more static in nature and focus on measuring the vulnerability of buildings or communities at single points in time and describe resilience in terms of recovery or a "return to a pre-event status" rather than capturing the adaptive or transformative aspects of resilience (Friedland & Gall, 2012, pp 141).

Hazard mitigation is also considered an integral part of resilience. Hazard mitigation not only aims to lessen the physical damage to the natural and built environment during hazard events, but also includes actions taken to reduce impacts on the social and economic networks of a community (Gordon, 2010). A fundamental part of hazard mitigation is hazard resistant design, which primarily focuses on the performance of buildings and community level structures (e.g. flood control, utility and transportation systems) under hazard loading conditions. Performance-based design, rather than prescriptive design, is often used for scoping hazard resistant design projects. Performance-based design requires that designers evaluate a building as a system of components which work together to achieve a specified level of performance.

For the purpose of this study, resilience encompasses both hazard resistant design and hazard mitigation actions. These can include any measures taken to prevent physical damage to the built infrastructure or environment, such as designing buildings or communities to withstand hazard loads or avoid hazards. It also includes any actions taken to prevent damage to social or economic networks (e.g. preventing loss of life by providing evacuation routes).

2.3 Sustainability Assessment Framework Implementation

The first SAF tool released for commercial use was the Building Research Establishment Environmental Assessment Method (BREEAM®) in 1990 in the United Kingdom. Green Globes in Canada and the Leadership in Energy and Environmental Design (LEED®) in the U.S. are two early examples of SAF tool developed after BREEAM® in the 1990s (Reeder, 2010). An extensive literature search found 62 SAF tools, but BREEAM® and

LEED® are the most commonly implemented worldwide and have been used on a significant number of projects (e.g. BRE, 2012; USGBC, 2012).

SAFs tools are used to assess either building(s), site(s), and supporting infrastructure or community-scale projects based on multiple measures associated with the three core areas of sustainable development (i.e., economic, environment, and social). These measures are designed to address environmental impacts (e.g., pollution, global warming), resource consumption (e.g., water, fossil fuels), quality of life (e.g., air quality, security), and economy. Measures are either performance-based (e.g. reduce building energy below certain level) or prescriptive (e.g. install Energy Star equipment). SAFs tools also rely on combinations of subjective and objective data (Trusty, 2000) and are best employed early in the design process to ensure sustainable development goals are met after project completion. Table 2-1 describes scales of SAF tool application and provides example SAFs for each scale from the literature. See Appendix B for a full background description of SAFs and other types of sustainability tools.

Table 2-1: SAFs by Scale

Scale of Application	Application Description	Example Projects	Example Tools
Building	New construction or renovation of buildings	Residential Buildings, Commercial Buildings	LEED® New Construction, Homes (USGBC, 2008, 2009a) Living Building Challenge™ (ILFI, 2010) BREEAM® (BRE, 2011b)
Site & Supporting Infrastructure	Single sites or projects that fall outside of building footprints	Green Spaces, Utility Projects, Roads	Sustainable Sites Initiative™ (SSI, 2009) Envision™ 2.0 (ISI, 2012)
Community	Multiple buildings, supporting infrastructure and space around buildings	Neighborhoods, Towns, Cities	LEED® Neighborhood Development (USGBC, 2009b) BREEAM® for Communities (BRE, 2011a)

2.4 Analytical Comparison of SAFs

Although two SAFs are predominately used worldwide, four other SAF tools were evaluated to broaden the applicability of this research. The selected frameworks were chosen based on a number of factors. First, to ensure multiple scales were considered, SAFs for buildings, sites, and neighborhood/communities were categorized for selection. Second, to ensure global applicability and investigate variations in the coverage of resilience among tools worldwide, SAFs were categorized by location of development as either developed in the U.S. or outside the U.S. (e.g. CASBEE®, BREEAM®), along with the country of origin. Third, to ensure a mixture of more established and newly developed SAFs, the year each SAF was established was recorded, since newer SAFs (e.g. Envision™) might differ in their approach to sustainable development when compared to older, more established SAFs. Priority was given to tools that have the greatest impact (i.e. largest utilization in industry) on sustainable development (e.g. LEED® and BREEAM®) for inclusion in the analysis. The selection of tools also gave preference to countries subject to multiple hazards. Given these considerations, the eleven SAFs taken from the six SAF tools selected for the analysis are provided in Table 2-2, sorted by scale of application, location and year established.

Table 2-2: SAFs Selected for Analysis

Assessment Framework	Scale	Application Location	Year First Released
LEED® for New Construction (NC)	Building	United States	1998
LEED® for Homes		United States	2007
CASBEE® for New Construction (NC)		Japan	2003
CASBEE® for Home (Detached House)		Japan	2007
BREEAM® New Construction (NC)		United Kingdom	2011
Living Building Challenge™		International	2006
Sustainable Sites Initiative™	Site	United States	2009
Envision™ 2.0		United States	2012
LEED® for Neighborhood Development (ND)	Community	United States	2007
CASBEE® for Urban Development (UD)		Japan	2007
BREEAM® Communities		United Kingdom	2011

To determine the extent to which the SAFs integrate resilience strategies, a multi-level procedure was undertaken, including three levels of analysis: (1) macro-level,(2) meso-level; and (3) micro-level, as discussed above.

2.4.2 Macro-Level Analysis: Resilience versus Sustainability

To quantify SAF resilience and sustainability measures, a taxonomy of measures was developed. To derive these measures, guide documents and technical manuals from the selected SAF tools were analyzed. Additionally, guide documents and technical manuals for three building and community resilience tools were evaluated to extract resilience criteria. Of the resilience tools, two tools are used to assess the resilience of communities for structural, societal, and economic vulnerabilities to hazards (Renschler, et al., 2010; Sempier et al., 2010) while the third tool is used to assess building resilience and focuses on specific structural design elements and configurations (e.g., columns, connections, windows, walls, location of entrances) that have the potential to impact the vulnerability of a building or infrastructure given exposure to specific hazards (Ettouney, et al., 2011). For a more in depth discussion of resilience tools see Appendix B.

In total, 97 resilience measures and 162 sustainability measures were defined within the taxonomy. The measures were organized into two main categories (i.e., resilience and sustainability) and 10 subcategories (Table 2-3). Resilience subcategories were defined by the scale of application (i.e., structural & community). Sustainability subcategories were adopted from overarching themes defined in existing SAF criteria, which commonly group criteria into categories (e.g., Energy, Water). Selecting subcategories similar to SAF criteria categories facilitated the organization of sustainability measures within the taxonomy. Sustainability subcategories were also grouped according to the three pillars of sustainability (i.e. environment, social and economic) in order to investigate overall sustainability coverage in relation to resilience. Table A-1 in Appendix A provides a comprehensive listing of the taxonomy of measures used in the analysis grouped by subcategory and category.

Although subcategories were chosen to align with SAF categories, there were cases where individual sustainability measures with multiple intents (e.g., improving quality of life and decreasing GHG) could be placed in multiple categories. However, to avoid duplication, sustainability measures were placed within a single subcategory based on the subcategory description in Table 2-3 that best matched the measure being considered.

Table 2-3: Organization of Taxonomy

Category	Group	Subcategory	Subcategory Description
Resilience		Community	Hazard resistant design or hazard mitigation strategies that are applied at a community level.
		Structural	Hazard resistant design or hazard mitigation strategies that are applied at a building level.
Sustainability	Environmental	Energy	Strategies associated with improving energy efficiency or reducing energy consumption.
		Water	Strategies associated with reducing potable water consumption or preventing actions that may impact the quality of water resources (e.g., preventing pollution of runoff waters).
		Land/Site	Strategies that involve choosing or developing a site in such a way that habitats are preserved or improved or valuable land is conserved. These are actions directly associated with the site itself.
		Materials	Strategies for selecting building materials considering the environmental impacts of material selections or actions taken to promote reduction in material consumption (e.g. recycling).
		Environmental Loads	Strategies taken to monitor, measure, or reduce environmental load sources (e.g., GHG emission, light pollution, solid waste disposal).
	Social	Quality of Life	Strategies related to the well-being or health of occupants or end users.
	Economic	Economy	Strategies that support the surrounding economy or investment in future developments.
	Other	Other	Other strategies that are not associated with the other sustainability categories. These are actions associated with general design (e.g. incorporating best practices, community involvement) or with education.

There were also cases where measures could also have an influence on both sustainability and resilience (e.g. reducing stormwater runoff from site). In these cases the measure was included as a resilience measure if the description of the measure specifically identified that its intent was either partially or entirely meant to address hazard mitigation or resistance. The rationale for this differentiation and for including these measures under resilience was to capture the maximum extent of measures where SAFs specifically incorporate resilience.

To analyze the SAFs, the taxonomy of resilience and sustainability measures was applied to each SAF, and the resilience and sustainability measures within each subcategory were itemized and summarized. The summary matrix (Table 2-4) presents the total number of resilience and sustainability measures for each SAF. The relative frequency of measures corresponding to each subcategory was calculated and summed to derive the total percentage of resilience and sustainability measures, which is a measure of the emphasis each SAF places on each subcategory. The sum of all subcategory relative frequencies for resilience and sustainability equals 100%.

Overall, selected SAFs vary in the number of measures that address resilience. From Table 2-4, the relative frequency of measures associated with resilience range between 3.3 to 17.9%, while the majority of measures (relative frequency between 82.1 and 96.7%) have a sustainability focus. Of the resilience subcategories, structural measures are slightly more common on average than community measures (relative frequency of 5.2% versus 4.2%). CASBEE® NC, CASBEE® for Home, Envision™, and CASBEE® UD are the only SAFs with over 10% of measures related to resilience. Five SAFs have between 5 and 10% and two have less than 5% of measures related to resilience. Five of eleven SAFs have an even split between community and structural resilience measures. Of the remaining six, except for Envision™, community-level SAFs have more community resilience measures and structural- and site-level SAFs have more structural resilience measures. Envision™ is unique in that the majority of its measures are classified under the community subcategory even though it is applied at a site-level scale.

Of the sustainability subcategories, the average relative frequency of the environmental subcategories energy, water, materials, and environmental loads are in a similar range (from 10.1% to 11.8%), with standard deviation of measures ranging from 3.0 to 5.4. The environmental subcategory land/site has the highest average relative frequency of the environmental subcategories (20.7%) and the highest variability among the measures, with relative frequencies ranging from 10.4% to 52.2% and a standard deviation of 11.7%. The total average relative frequency of all environmental subcategories ranges from 50% to 86.9% and has a standard deviation of 10.1%.

Table 2-4: Summary Matrix

SAF	Scale*	Resilience Subcategories				Sustainability Subcategories										
		Total # Resilience Measures	Community (%)	Structural (%)	% Resilience of All Measures	Total # Sustainability Measures	Energy (%)	Water (%)	Land/Site (%)	Materials (%)	Envir. Loads (%)	% Environmental of All Measures	Quality of Life (%)	Economy (%)	Other (%)	% Sustainability of All Measures
LEED® NC (USGBC, 2009b)	B	2	1.6	1.6	3.3	59	9.8	11.5	19.7	13.1	18.0	72.1	19.7	0.0	4.9	96.7
LEED® for Homes (USGBC, 2008)	B	2	1.8	1.8	3.6	54	17.9	8.9	19.6	14.3	12.5	73.2	21.4	0.0	1.8	96.4
CASBEE® NC (IBEC, 2008)	B	8	1.3	9.1	10.4	69	14.3	7.8	10.4	10.4	14.3	57.2	28.6	0.0	3.9	89.6
CASBEE® for Home (Detached House) (IBEC, 2007a)	B	7	1.8	10.7	12.5	49	19.6	8.9	10.7	16.1	8.9	64.2	19.6	0.0	3.6	87.5
BREEAM® NC (BRE, 2011b)	B	6	4.2	4.2	8.5	65	8.5	11.3	16.9	15.5	12.7	64.9	19.7	1.4	5.6	91.5
Living Building Challenge™ (ILFI, 2010)	B	2	4.3	4.3	8.7	21	4.3	17.4	52.2	0.0	13.0	86.9	4.3	0.0	0.0	91.3
Sustainable Sites Initiative™ (SSI, 2009)	S	6	2.6	5.3	7.9	70	5.3	11.8	22.4	11.8	10.5	61.8	17.1	5.3	7.9	92.1
Envision™ 2.0 (ISI, 2012)	S	14	11.5	6.4	17.9	64	3.8	10.3	17.9	10.3	7.7	50	20.5	2.6	9.0	82.1
LEED® ND (USGBC, 2009a)	C	5	4.5	3.0	7.6	61	13.6	9.1	28.8	7.6	7.6	66.7	18.2	3.0	4.5	92.4
CASBEE® UD (IBEC, 2007b)	C	14	7.8	7.8	15.6	76	10.0	6.7	16.7	11.1	14.4	58.9	18.9	1.1	5.6	84.4
BREEAM® Communities (BRE, 2011a)	C	5	4.3	2.9	7.1	65	14.3	7.1	12.9	11.4	10.0	55.7	21.4	7.1	8.6	92.9
*SAF Scales C = Community B = Building S = Site	Minimum	2	1.3	1.6	3.3	21	3.8	6.7	10.4	0.0	7.6	50	4.3	0.0	0.0	82.1
	Maximum	14	11.5	10.7	17.9	76	19.6	17.4	52.2	16.1	18.0	86.9	28.6	7.1	9.0	96.7
	Average	6.5	4.2	5.2	9.4	59.4	11.0	10.1	20.7	11.1	11.8	64.7	19.0	1.9	5.0	90.6
	Standard Deviation	4.3	3.1	3.0	4.5	14.8	5.4	3.0	11.7	4.4	3.2	10.1	5.7	2.4	2.8	4.5

The environmental subcategories have the largest proportion of all measures across all tools, which indicate that the environmental aspect of sustainability figures significantly in the intent of the SAFs. This result is supported by other studies which also found that environmental issues do dominate a significant proportion of the criteria within SAFs (Retzlaff, 2008; Sharifi & Murayama, 2013, 2014a). It has been noted that ecological indicators (e.g. wetlands growth or loss, biodiversity) are connected to the resilience of communities (Cutter et al., 2008). This is especially true in the case of measures, such as those found in the land/site subcategory, that are designed to protect local habitats and lands that may serve as buffers against the forces of some hazards (e.g. wetlands, beach dunes and barrier islands in the case of hurricanes). And even on the global level mitigating climate change through reductions in pollution could contribute to lessening the impact of future climate change impacts.

The social subcategory quality of life has an average relative frequency of 19%. These measures include steps to improve the overall health of occupants, but also include strategies for building the foundation for social networks. Measures such as providing connectivity between community structures, promoting mixed use neighborhoods, encouraging inclusivity through providing low income housing, and building social networks among neighboring communities all help to build social capital. Communities that have strong social capital and networking are found to be more resilient and have more avenues in place through which recovery can be spring boarded (Murphy, 2007; Renschler, et al., 2010). While the inclusion of measures such as these within SAFs can provide benefit to the overall resilience of a community, some studies have found that some of the social aspects of SAFs (e.g. inclusivity and providing low income housing) are ignored within some SAF criteria (Sharifi & Murayama, 2013) or are not included in real world design case studies (Sharifi & Murayama, 2014a, 2014b).

The sustainability subcategory economy and other have the lowest average relative frequencies, 1.9% and 5%, respectively. Notably, the minimum relative frequency for the economy subcategory is 0, corresponding to five separate SAFs – LEED® NC, LEED® for Homes, CASBEE® NC, CASBEE® for Home, and Living Building Challenge™. While some tools incorporate economic measures, it is evident that economic measures are not consistently incorporated across all tools and less emphasis has been placed on economy. This result is supported by Sharifi and Murayama (2013) who found similar results in their analysis of neighborhood level SAFs. However, economy is one of the pillars of sustainable development and it has been found that economic health, resources, diversity, and investment in local economic development have an impact on the resilience of a community (Radloff, 2006). Thus, although this analysis treats resilience and sustainability as separate categories, further exploration of the connections between resilience and sustainability measures is warranted to investigate sustainable development measures that may also negatively or positively impact resilience.

2.4.3 Meso-Level Analysis: Hazards Coverage

To quantify the breadth of hazards covered by SAFs, the hazards explicitly included in the eleven SAFs were identified. Fifteen hazards were identified through evaluating the criteria within the eleven SAFs and three resilience tools. Once all SAFs were examined for incorporation of measures addressing each hazard, a hazard table was created

(Table 2-5) showing the hazard coverage of the SAFs. It should be noted that an SAF was considered to have incorporated the hazard if there were design measures directly addressing that hazard. Design measures addressing disasters in general were not considered as incorporating any specific hazard if a hazard was not explicitly listed.

When comparing hazards covered by the SAFs (Table 2-5) it can be seen that eight of the eleven frameworks include design measures for multiple hazards (i.e. two or more). CASBEE® UD and Envision™ 2.0 incorporate the most hazards, 7 and 13, respectively. In fact, of all the SAFs, only LEED® NC, LEED® for Homes, and Living Building Challenge™ include criteria for only one hazard, flooding.

Across all SAFs, flooding is the most incorporated of all the hazards, with all eleven SAFs addressing flooding. Fire, earthquakes and surge are the second most included hazards, incorporated in five, four and four of the eleven SAFs, respectively. All other hazards are covered by three or fewer SAFs. Some of the limitations in hazard coverage can be explained by the geographic specificity of some tools (e.g. CASBEE® was developed for Japan); however, other tools that are designed to be standardized across varying geographies (e.g. LEED®) also cover a limited number of hazards.

Table 2-5: Tool by Hazard

SAF	H	Fl	SG	F	W	E	Ts	T	M	HS	Ex	At	CA	S	SL	Total
LEED® NC		■														1
LEED® for Homes		■														1
CASBEE® NC		■		■	■	■										4
CASBEE® for Home (Detached House)		■		■		■										3
BREEAM® NC		■	■												■	3
Living Building Challenge™		■														1
Sustainable Sites Initiative™		■		■												2
Envision™ 2.0	■	■	■	■	■	■	■	■	■	■	■	■			■	13
LEED® ND		■	■													2
CASBEE® UD		■		■		■			■		■		■	■		7
BREEAM® Communities		■	■												■	3
Total	1	11	4	5	2	4	1	1	2	1	2	1	1	1	3	40

Hazard Key:

H = Hurricane
Fl = Flood
SG = Surge
F = Fire
W = Wind
E = Earthquake
Ts = Tsunami
T = Tornado
M = Mudslide or Landslide
HS = Hazardous Material Spill
Ex = Explosion
At = Biological, Chemical or Radiological Attack
CA = Cyber Attack
S = Subsidence
SL = Sea Level Rise or Climate Change

2.4.4 Micro-Level Analysis: Flood-Related Resilience Measures

Based on the results of the meso-level hazards analysis, flooding was found to be the hazard most often incorporated in the SAFs analyzed. In order to understand the full extent of resilience coverage for flooding, the SAFs were analyzed by reviewing the criteria within SAF guide documents and technical manuals for specific measures that may limit or conflict with the flood resilience of a building or community. Other flood-related hazards (e.g. sea level rise) were also considered in this analysis.

Table 2-6 presents the flood-related resilience measures included in the eleven SAFs. Six of the eleven SAFs incorporate two or fewer flood-related resilience. Envision^{TM} includes all six measures, while the four remaining SAFs address three to five measures.

Table 2-6: Flood-Related Resilience Measures

SAF	Hazard Avoidance (Build Outside Flood Hazard Areas)	Reduce Flood Damage Risk (Flood Proofing or Elevation)	Reduce Stormwater Runoff from Site	Develop Floodplain without Increasing Flood Risk	Evaluate Flood Hazard Risk & Considered in Design	Climate Impacts Considered in Design	Total
LEED® NC	■		■				2
LEED® for Homes	■		■				2
CASBEE® NC			■				1
CASBEE® for Home (Detached House)			■				1
BREEAM® NC		■	■	■	■	■	5
Living Building Challenge^{TM}	■		■				2
Sustainable Sites Initiative™	■	■	■	■			4
Envision^{TM} 2.0	■	■	■	■	■	■	6
LEED® ND			■		■		2
CASBEE® UD	■	■	■				3
BREEAM® Communities		■	■	■	■	■	5
Total	6	5	11	4	4	3	11

LEED® NC, LEED® for Homes, Living Building Challenge^{TM}, Sustainable Sites Initiative^{TM} Envision^{TM}, and LEED® ND encourage avoiding development in certain flood hazard areas (ILFI, 2010; ISI, 2012; SSI, 2009; USGBC, 2008, 2009a, 2009b). In spite of this, projects can still be developed in accordance with all analyzed SAFs within flood hazard areas. LEED® NC, Sustainable Sites Initiative^{TM}, and LEED® ND provide some exceptions for certain land types (e.g. brownfields, greyfields, infill lots) and LEED® for Homes provides credit points in its rating system for building outside the 100-year floodplain, but does not require it (SSI, 2009; USGBC, 2008, 2009a, 2009b). Living Building Challenge™ provides exceptions for specific types of projects (e.g. docks and landscaping) (ILFI, 2010).

While building outside of flood hazard areas could result in more resilient structures and communities, the reality is that the footprints of many communities already exist within these areas. Given this fact, it is advantageous for SAFs to go beyond simple encouragement of flood hazard avoidance. For building designs where avoiding floodplains is impossible, measures aimed at flood-resistant design are more beneficial. However, not all SAFs include flood-resistant design measures for buildings inside floodplains. Only BREEAM® NC, Sustainable Sites Initiative™, Envision™, LEED® ND, and BREEAM® Communities include criteria for reducing flood damage risk to developments within flood hazard areas .

SAFs encourage compact development, which has sustainability benefits such as land conservation and air pollution reduction (Emerine et al., 2006; USGBC, 2009a). However, McEvoy, et al. (2006) and Pauleit et al. (2005) have shown that densification programs can also lead to the loss of green space in cities, increasing the percentage of impervious surfaces over the same land area. Watersheds that lose pervious surfaces no longer absorb as much water, which in turn leads to an increase in the amount of runoff water during rain events (McEvoy, et al., 2006; Pauleit, et al., 2005). Coupling increases in runoff with older drainage networks that are designed for lower flood flow capacities, the chance of urban flooding problems increases (Ana & Bauwens, 2010; Konrad, 2003).

All eleven SAFs have accounted in part for some of these issues by encouraging projects to reduce stormwater runoff from the development sites through various techniques (e.g. retention ponds, pervious pavements); however, this measure's sole purpose is not to combat urban flooding, but also to reduce pollution and sustain hydrologic conditions in the natural environment. Furthermore, reducing stormwater runoff does not ensure that the structure will have no impact on the flood risk of surrounding developments. For example, in the case of surge flooding, a site designed to capture one hundred percent of its stormwater runoff can still displace a significant volume of floodwater by the physical presence of buildings on that site, thereby increasing the flood risk to the site and surrounding buildings. As Table 2-6 shows, some SAFs go one step further and include measures requiring that projects developed in floodplains do not increase the flood risk to other areas of the floodplain (e.g. BRE, 2011a; BRE, 2011b; ISI, 2012; SSI, 2009).

Compact developments are still at greater risk of more severe damage when impacted by hazard events. In dense developments, infrastructure and building assets cover a smaller area and can incur more damage than typical low density developments (Stevens, et al., 2010). Hurricane Sandy is one of the more recent examples of the level of damage that can occur when disasters impact densely developed areas. Also, for buildings subject to surge and high velocity flooding, the development of any site could lead to structure or infrastructure damage if vulnerabilities to hazards such as subsidence and erosion are not identified (FEMA, 2010). Careful consideration should be given when constructing on lots that might be vulnerable to concentrated flood flows, surge flooding, and flood-borne debris.

Climate change is another issue closely tied to flooding, which is especially important to consider in long term planning and design projects. Avoiding flood hazard areas or designing to prevent flood damage may not prevent future flood damage if climate change impacts are not considered. Due to the variable nature of floodplains, land categorized within the 500-year floodplain today may be within the 100-year floodplain in the future due to sea level rise, erosion, subsidence and other geomorphic processes. This is why considering relative sea level (RSLR) rise in design can be crucial for structures within the proximity of 100-year and 500-year floodplains. Relative sea level rise also has a significant impact on the severity of hurricane surge flooding in multiple respects. In addition to increasing storm surge inundation height and extent, RSLR exacerbates the erosion of natural flood-protective structures such as wetlands and barrier islands (Smith et al., 2010). Only four of the eleven SAFs incorporate the consideration of sea level rise or climate change impacts within design - BREEAM® NC, Envision™, LEED® ND, and BREEAM® Communities.

2.5 Discussion

The results of the study indicate that hazard resilience is not strongly incorporated into existing SAFs. Although some SAFs do incorporate resilience measures more extensively than others, a systematic integration of resilience throughout all sustainability measures would allow tradeoffs between resilience and sustainability to be better identified. While it is expected that SAFs focus primarily on sustainability issues, concentrating efforts towards mitigating climate change while simultaneously failing to adequately address hazards and climate change impacts leads to developments vulnerable to hazards.

Some design measures may be beneficial from a sustainability perspective, but may simultaneously lessen the reliability of buildings and infrastructure when exposed to hazards. As demonstrated by the flood micro-level analysis, some current sustainable development practices such as utilizing infill and previously developed lots help conserve land, but these lands may require further investigation in order to determine if the site is vulnerable hazards. For example, if a site is located in area that is historically vulnerable to subsidence, erosion, and high RSLR rates, all these conditions should be considered in the design and development of the site.

Providing mechanisms or criteria for incorporating resilience in sustainable design is important if buildings are expected to survive throughout their life-cycle and communities are able to recover from disaster. Sustainable developments such as communities designed around the principles of New Urbanism have been shown to be more resistant to flood hazards when community involvement and coordination with municipal officials is present in the development process. However, when communities are not involved, there is no mechanism for building hazard resistance into design (Stevens, et al., 2010). Gordon (2010) found that LEED® ND does not provide adequate measures to address mitigation of earthquake and fire damage. At the time of the study, half of certified LEED® ND neighborhoods were exposed to earthquake or fire hazards, some of which are located in areas that do not have a rigorous earthquake code (Gordon, 2010).

SAFs that do not already incorporate sea level rise and other climate change impacts need to consider including these issues. NOAA (2013) estimates that almost 40% of the U.S. Population in 2010 lived in counties or parishes which make up the shoreline of the country (10% of the total U.S. land area). NOAA has also estimated 27% and 22% of 5,886 miles of Atlantic coast, 27% and 22% of 2,478 miles Pacific coast and 42% and 13% of 5,007 miles of Gulf coast are at very high risk and high risk to future sea level rise, respectively (Thieler & Hammar-Klose, 1999, 2000a, 2000b). This includes densely populated cities and areas such as San Francisco, San Diego, the Chesapeake Bay, New Jersey, the east coast of Florida, New Orleans and Galveston.

Further, SAFs need to better incorporate the economic aspects of sustainable development, especially those measures which can improve the resilience of a community. SAFs that include measures for fostering growth in local economy can not only improve community resilience, but also encourage sustainable development. Diversifying businesses and labor force and investing in resilient buildings, utilities, transportation networks, and other infrastructure are all measures that can contribute to building a resilient community.

Until fully integrated sustainability and resilience design frameworks are developed, designers should carefully consider which SAF tools they will deploy on projects and how measures within tools may conflict with the specific design requirements and conditions present in hazard prone areas. Numerous sustainability and resiliency factors impact the level of performance of the end product and are important to consider, but ultimately it is the engineer's or architect's design and the building user's decisions that will determine the performance of the structure. Voluntary code-plus program and guidelines for hazard resistant construction do exist (e.g. Malik et al., 2012.; FEMA, 2011) and could be utilized in sustainable development projects as resources for identifying conflicts between resilient and sustainable designs.

Additional analysis of the potential for integrating sustainability and resilience practice in multiple geographical areas with varying hazard conditions would be beneficial. Future work also needs to focus on integrating sustainability and resilience measures into a framework that could be used for planning, design, and construction projects. A systematic, performance-based approach which analyzes the sustainability and resilience of key structural components of a building over its lifespan would be beneficial.

Whether through the refinement of current SAFs or the development of new SAF approaches, there are benefits to incorporating resilient design into the practice of sustainable development. Protecting sustainable buildings from hazards serves to (1) conserve future resources, (2) protect investment in sustainable structures and infrastructure, (3) ensure that sustainable buildings continue to function for their design life and continue to reap the benefits of sustainable design, and (4) preserve the stability of social and economic networks within communities.

2.6 Summary

The purpose of Chapter 2 was to understand the extent to which current SAFs incorporate resilience and to determine if weaknesses in resilience coverage exist that have the potential to lead to the design of structures and communities that are vulnerable to the impacts of extreme events. This study was accomplished through comparison of 11 SAFs. A multi-level analysis (macro, meso, micro) was utilized to make this comparison between 11 SAFs, selected among the most commonly used and recently emerging frameworks. The selection of SAFs also cover multiple scales of application (i.e., building, site and community). While the comparative analysis presented in this chapter included multiple scales and applications of tools, the scope of the remainder of this dissertation is limited to single-family residential construction. The following chapters propose the development of models that integrate the concepts of sustainable and resilient development of coastal, wind- and flood-SFR structures.

CHAPTER 3: COMPONENT-BASED FLOOD DEPTH-DAMAGE FUNCTIONS FOR INDIVIDUAL SINGLE-FAMILY, WOOD-FRAME RESIDENTIAL BUILDINGS

3.1 Introduction

Flood damage or loss functions are often used to estimate the impact of flood events on the built environment. These functions are often used to determine the feasibility of flood control structures and flood-proofing projects, or as a tool for assessing the need for changes in policy or building code requirements. Measures of “damage” or “loss” provided by these functions can indicate the level of resilience of structures and within a limited extent be used to indicate the potential performance of structures under hazard conditions.

Flood damage functions for single-family residential (SFR) buildings are typically categorized by physical features (e.g. number of stories, foundation type, material type). SFR curves can also be characterized by the hazards considered (e.g. inundation, velocity, wave action, salt or fresh water), building elements considered (e.g. structure, contents, combined), mathematical function type (e.g. continuous, discrete), and units of measure (e.g. percent, absolute repair costs). The characteristics of SFR curves are generally dependent on the purpose or need being met by the damage functions (Friedland, 2009),.

Two primary approaches are used to create flood damage functions for residential buildings: (1) historical method and (2) synthetic method. The historical method involves averaging historical damage or loss data, whereas the synthetic method derives damage or loss data using expert opinion or theoretical analysis (Freidland, 2009). Historical SFR curves (e.g. USACE, 2000, 2003) represent average or expected damage, therefore significant error can be incurred when applying these curves to individual structures. Synthetic curves (e.g. GEC, 1996, 1997, 2006) are developed based on an assumed model structure, which can also lead to error in estimating damage when applied to alternate designs. Therefore, existing SFR curves have limitations in their application to individual buildings since curves lack the flexibility to be applied across a range of individual building designs without incurring significant error. Typically, synthetic depth-damage functions are developed using a component based approach; however, the curves are developed to describe damage to stocks of buildings using functions describing aggregated damage per building type (e.g. GEC, 1996, 1997, 2006). Although, a component-based approach is taken to develop these curves, component-level depth-damage curves are rarely presented in literature.

There is a need for flood depth-damage set of curves that can help quantify life-cycle damage for a range of individual SFR building designs. Damage curves that are flexible to building design are achievable by developing synthetic curves at the component level, which can be adjust for a specific design. A set of customizable component curves would aid in life-cycle cost (LCC) analysis studies for individual SFR buildings, which aim to capture the costs, including construction, repairs and disposal, associated with individual buildings. Furthermore, these curves can be used to develop a more accurate database of building damage in GIS-based, community or area-wide benefit-cost analysis studies.

3.1.1 Aim

The aim of Chapter 3 is to develop a set of component-level, synthetic depth-damage curves for single family residential (SFR) type structures, which are flexible in their application to individual SFR building designs. The curves are designed to output the percent damage to material quantities over a range of flood depths. Because the conventional method for building new SFR structures in the U.S. is onsite, wood-frame construction, the curves presented in the chapter target this type of construction. Inundation-only, non-velocity flooding is considered in the development of these curves. The curves are applicable to both one-story and two-story SFR building designs, and flexible to account for variations in most SFR designs (e.g. different flooring types and foundation types). While the focus is on the most conventional SFR structure type, it is possible to expand the curves to include less popular construction types (e.g. reinforced concrete, masonry and timber-frame). A case study for a wood-frame SFR building design typical of the coastal, southeastern United States is presented to demonstrate how the component-level, depth-damage curves can be utilized for a unique design.

3.1.2 Definitions

Single-family residential (SFR) homes include residential buildings which are detached from other building types (e.g. commercial), and consist of one-family unit. SFR structures do not include duplexes, town homes, or other types of multifamily structures. SFR structures also do not include previous SFR structures which have been remodeled to accommodate multiple family units (e.g. basement or garage apartments).

Within the context of flood depth-damage curves, references to “damage” in this chapter refer to direct physical damage to a structure while loss indicates the economic loss associated with that damage. Inundation flooding is flooding which rises slowly without notable velocity flow or wave action, the latter flood actions would typically impart other forces on building aside from hydrostatic pressure forces.

Wood-frame construction refers to the traditional home construction method of building homes onsite using dimensioned lumber (e.g. 2×4 lumber). There are standard building practices for building wood-frame SFR structures, which consist of building sheathed wall and roof frames on top of a foundation and finishing the frames with plumbing, mechanical, electrical, water proofing and thermal barriers, and exterior and interior finishes.

3.2 Component Level Analysis

This study develops depth-damage curves adaptable to individual SFR building designs using a component-level approach allows for individualize material damage to calculated. Gulf Engineers & Consultants, Inc (GEC) developed synthetic, depth-loss relationships for five residential structure types for the New Orleans District of USACE (GEC, 2006). Within GEC (2006), there are a set of eighteen tables presenting component-level damage dollar estimates for five residential building types (one-story on piers, one-story on slab, two-story on piers, two – story on slab and mobile home) for three flood conditions (short-duration: freshwater and saltwater; long-duration: saltwater; and long-duration: freshwater). A model design is assumed for each building type and damage were estimated using opinions from a panel of experts (GEC, 2006).

The flood levels included in the tables are relative to the top of the first floor level. Component level damage at each flood level are based on the estimated repair or replacement cost of each component. The damage are itemized across all components for each flood level and the overall percent building damage is calculated as the total repair or replacement cost divided by the total new item value. There is also a set of building damage assumptions developed by the expert panel (GEC, 2006).

Another source of descriptions of damage at the component level for particular flood depths is the “Substantial Damage Estimator (SDE) User Manual and Workbook” (FEMA, 2014). FEMA (2014) provides guidance on assigning percent damage for building components while using the SDE to estimate damage to residential buildings. The guidance includes a table of component-level damage descriptions which are associated with ranges of percent damage and flood depths (FEMA, 2014). The descriptions are organized according the eleven major categories: foundation, superstructure, roof covering, exterior finish, interior finish, doors and windows, cabinets and countertops, floor finish, plumbing, electrical, appliances and HVAC.

3.3 Development of Depth-Damage Curves

GEC (2006) and FEMA (2014) were utilized to develop the set of customizable component-level, SFR depth-damage functions curves proposed in this Chapter. GEC (2006) and FEMA (2014) were used to first develop a list of building components categories. In total, 25 component categories were selected from the GEC(2006) and FEMA (2014) tables, of which seven categories (i.e., electrical, windows, doors, finished flooring, built-in appliances, roof and HVAC) were subdivided further into more detailed components.

In order to develop the depth-damage curves for each component, two sets of assumptions were made. The first set includes general building assumptions. These assumptions are listed in Table 3-1. The second set of assumptions relate to the damage sustained by each component relative to flood depth (Table 3-2). The majority of these assumptions were adapted from assumptions and descriptions provided in GEC (2006) and FEMA (2014), information regarding the source of the assumptions is provided in Table 3-2.

Table 3-1: Building Configuration Assumptions

Building Configuration Assumptions
Floor to ceiling height is 8 feet.
There is a 1 foot gap between the first and second stories.
There is no HVAC or built in appliance equipment below the first floor level (this does not include ductwork).
There is no basement (i.e. no finishes below the first floor).
Any plumbing or electrical extending beyond where utilities connect to the building (i.e. service lines) are not considered.
Only simple roof shapes are considered (hip or gable) with no dormers, cupolas or other structures extending off the main roof.

The component-level, depth-damage functions were then developed based on the component-level damage assumptions. For the components with assumptions sourced from the GEC (2006) tables (exterior siding, foundation, structural frame, roof, stairs, and fireplace), the component percent damage at each flood depth was calculated as the repair or replacement cost provided in the residential depth-damage estimate tables in GEC (2006) divided by the new item value for the component in question. Also for these component curves, where multiple curves were calculated based on the building type and flood duration, curves that were similar were averaged to reduce the number of curves per component and streamline the damage estimation process.

It should be noted that in developing the damage assumptions, thought was given not just to the actual direct physical damage, but also to actions taken by construction professionals while restoring damaged homes. For example, if only a portion of a roof were flooded, it is more likely that all the shingles would be replaced rather than just the damaged portion so that all shingles would match. Also in cases were removing one item lead to the removal of another item (e.g. kitchen cabinets and countertops), both items were assumed to be completely damaged simultaneously even when one item might not be flooded.

Table 3-2: Component-level Damage Assumptions

	Component	Assumptions	Source
1	Sheetrock		
	Wall Paper-Faced	25% damage at 0 feet to 1.5 feet; 50% damage at 2 feet; 100% damage at 4 feet.	GEC, 2006
	Wall or Ceiling, Non-paper-faced	No damage.	*
	Ceiling Paper-Faced	100% damage at 8 feet.	**
2	Bottom Cabinets	All cabinets are particle board cabinets. Damaged as soon as flooded.	GEC, 2006
3	Upper Cabinets	All cabinets are particle board cabinets. Replace at 4 feet flood water.	FEMA, 2014
4	Countertops	Replace when bottom cabinets are replaced.	GEC, 2006
5	Water Heater	Water heater is on first floor level. Replace water heater at 0 feet of water.	GEC, 2006
6	Insulation		
	Floor Insulation	Completely damaged at -1.0 feet of water.	GEC, 2006
	Wall Insulation	25% damage at 0 feet to 1.5 feet; 50% damage at 2 feet; 100% damage at 4 feet Exception for Closed-cell foam insulation which is waterproof. Closed-cell foam assumed to have 0% damage at all depths.	GEC, 2006 FEMA, 2008
	Ceiling Insulation	100% damage at 8 feet. Exception for Closed-cell foam insulation which is waterproof. Closed-cell foam assumed to have 0% damage at all depths.	*** FEMA, 2008
7	Subflooring	Warps at 0 feet. Needs to be replaced when warped.	GEC, 2006
8	Exterior Siding and Sheathing (All siding materials except brick or stone)		
	One-story, Short Duration	Average of GEC exterior siding curves for one-story, short duration flooding.	GEC, 2006
	One-story, Long Duration	Average of GEC exterior siding curves for one-story, long duration flooding.	GEC, 2006
	Two-story, Short Duration	Average of GEC exterior siding curves for two-story, short duration flooding.	GEC, 2006
	Two-story, Long Duration	Average of GEC exterior siding curves for two-story, long duration flooding.	GEC, 2006: Tables
9	Brick or Stone Siding Materials	No damage sustained. Siding remains adhered and requires only cleaning and drying.	GEC, 2006 FEMA, 2014
10	Base Molding	Totally damaged at 0 feet of water.	GEC, 2006
11	Interior Paint/ Wallpaper	At 0 feet, entire wall covering will need to be replaced because of color matching.	GEC, 2006
12	Exterior Paint	At 0.5 feet, entire wall covering will need to be replaced because of color matching.	GEC, 2006
13	Wainscoting	Graduate Rate from 0 to 4 feet, cut and replace.	GEC, 2006
14	Electrical		
	Floor Receptacles	Destroyed at zero feet. Wiring with wet ends replaced.	GEC, 2006
	Wall Receptacles	Destroyed at 0.5 feet. Wiring with wet ends replaced.	FEMA, 2014
	Switches	Destroyed at 5 feet. Wiring with wet ends replaced.	GEC, 2006
	Fixtures	Destroyed at 5 feet. Wiring with wet ends replaced.	GEC, 2006
15	Built-in Appliances		
	Dishwasher	Replace at 0 feet.	GEC, 2006
	Clothes Dryer	Replace at 0.5 feet.	FEMA, 2014
	Clothes Washer	Replace at 4 feet.	FEMA, 2014
	Hood	Replace at 4 feet.	GEC, 2006

Table 3-2: Component-level Damage Assumptions (Continued)

	Component	Assumptions	Source
16	Foundation		
	Pier	Average of GEC foundation curves for pier buildings.	GEC, 2006
	Slab	Average of GEC foundation curves for slab buildings.	GEC, 2006
17	Structural Frame	Average of GEC all structural frame curves.	GEC, 2006
18	Windows		
	Floor Level	Replace at 0.5 feet.	FEMA, 2014
	Sill Height	Replace at 1.5 feet.	FEMA, 2014
	High Windows	Replace at 5 feet (assumed based on 0.5 feet above bottom of a window 4 feet from floor)	FEMA, 2014
19	Doors		
	Interior	Replace at 1 foot.	FEMA, 2014
	Exterior	Replace at 1.5 feet.	FEMA, 2014
20	Finish Flooring		
	All (Wood Substrate)	Replace at 0 feet.	FEMA, 2014
	Vinyl, Carpet, Wood on Slab	Replace at 0 feet.	FEMA, 2014
	Ceramic on Slab	No damage.	FEMA, 2014
21	Roof		
	Covering	Replace at 7+ foot of water or when any portion inundated.	GEC, 2006
	Sheathing	Replace inundated portions.	****
	Soffits, One-story	Average of GEC soffit curves for one-story buildings.	GEC, 2006
	Soffits, Two-story	Average of GEC soffit curves for two-story buildings.	GEC, 2006
22	Condenser Unit	Replace at 1 foot of flooding. Condenser unit assumed to be at first floor level.	FEMA, 2014
23	Heating		
	Heating Unit (1st Floor Level)	Assumed to be gas or oil fired. Replaced when unit is flooded with 12 inches.	FEMA, 2014
	Ductwork (Below 1st)	Totally damaged when flooded. Assumed to be flooded at -1.0 foot.	FEMA, 2014
	Heating Unit (2nd Floor Level)	Assumed to be gas or oil fired. Replaced when unit is flooded with 12 inches.	FEMA, 2014
	Ductwork (2nd Flood Level)	Totally damaged when flooded. Assumed to be flooded at 9 feet.	FEMA, 2014
	Ductwork (3rd Floor Level)	Totally damaged when flooded. Assumed to be at 18 feet.	FEMA, 2014
24	Stairs		
	Pier Foundation	Average of GEC stair curves for pier foundation	GEC, 2006
	Slab Foundation	Average of GEC stair curves for slab foundation	GEC, 2006
25	Fireplace		
	Two-story, Short Duration	Average of GEC fireplace curves for short duration flooding.	GEC, 2006
	Two-story, Long Duration	Average of GEC fireplace curves for long duration flooding.	GEC, 2006

* Non paper faced sheetrock is a material used for wet flood proofing, which can stay in place and dry after flooding See (FEMA, 2008).

** Assumed to be completely damaged once water reaches ceiling height.

*** Insulation (other than closed-cell foam) assumed to be damage 100% when water touches insulation, which is assumed to occur at ceiling height of 8 feet.

**** Assumed to need replacement as inundated, since typical sheathing material warps when soaked with water.

For one component, roof sheathing, there was not enough description from GEC (2006) or FEMA (2014) to determine the percent damage. While GEC provides damage estimates for the roof from which curves could be developed, it was determined that because GEC (2006) had to assume a roof configuration to make the estimates, the results from these curves might not match other roof configurations. It was decided that roof damage would be calculated based on the assumption that only inundated sheathing would require replacement. In order to determine the percent of roof sheathing that would need to be replaced Equation 3-1 was utilized.

$$\%\ \text{Damaged Sheathing} = \frac{\text{Area of Inundated Sheathing}}{\text{Total Area of Sheathing}} * 100 \qquad \text{Equation 3-1}$$

Also, to account for variation in the design of components at the first-, second- and third-story level (i.e. attic of a two-story) of a SFR building, all components except for six were separated into two sets of depth-damage curves for the first, second and third floors levels. Only exterior siding, foundation, structural frame, roof, stairs, and fireplace depth damage curves include all the floors combined. These components were not separated by story because there was not enough information from GEC (2006) and FEMA (2014) to split damage percentage by building level. The first-floor, second-floor, third-floor level and combined depth-damage functions can be found in Appendix C (Tables C-1 through C-4).

3.4 Case Study

The following case study illustrates how the component depth-damage curves can be utilized for an individual building design. Figure 3-1 shows the design floor plan. The building model being assessed is a one-story, slab-on-grade, wood-framed, hipped roof SFR structure with three bedrooms and two baths typical of coastal southeastern United States. The location of the home is in Saint Petersburg, Florida. Flooding was assumed to be of short-duration, fresh or saltwater flooding. Table 3-3 shows the material quantities, total new cost, and total replacement cost of the design components within the case study house. The total new cost and total replacement cost of each component is based on RS Means online costing data (i.e. Gordian, 2015). Total replacement cost includes demolition and replacement of existing damage components. Using all the curves in Tables C-1 through C-6 which are applicable to this design and the information in Table 3-3, the damage in dollar values for each component were calculated over a range of flood depths (-1 to 20 feet) by multiplying the percent damage at each flood depth by the total replacement cost for each component. These calculations are shown in Tables C-5 and C-6 in Appendix C.

The total repair cost and percent damage at each flood depth was calculated. Other costs considered include permitting and mold remediation. The percent damage for each flood depth was calculated by dividing the total repair cost by the total new cost value for the whole building (Equation 3-2).

$$\text{Percent Damage} = \frac{\text{Total Repair Cost}}{\text{Total New Cost}} \qquad \text{Equation 3-2}$$

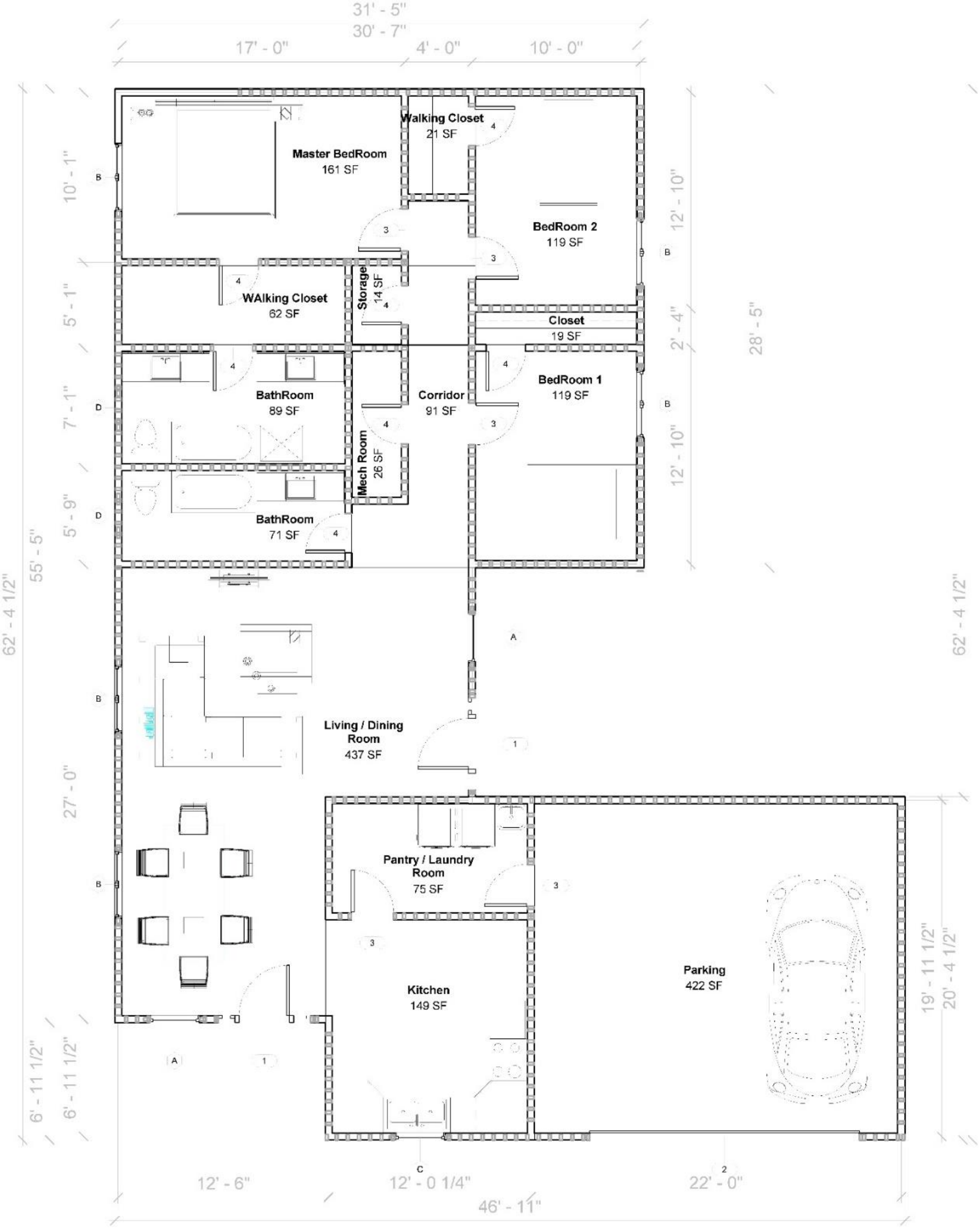


Figure 3-1: Case Study SFR Building Floor Plan

Table 3-3: Material Quantities

	Possible Design Components	Units	Quantity Design 1	TNC*	TRC*
Site	AC Condensing Unit	Each	1	1400.00	1706.60
Foundation	Slab	Sq. Ft.	1735.73	5450.19	6526.34
Structure Framing	Wall & Roof Framing	Sq. Ft.	17029.65	37535..43	40212.17
Roof Covering	Roof Membrane & Cover	Sq. Ft.	3142.1	14987.82	17030.18
	Fascia/Soffits	L. Ft.	230.7	258.35	348.31
	Sheathing	Sq. Ft.	3142.1	5498.68	6441.31
Exterior Walls	Wall Sheathing	Sq. Ft.	1579.38	2763.92	3332.49
	Siding	Sq. Ft.	1579.38	10976.69	11861.14
	Windows	Sq. Ft.	133	3808.44	3928.44
	Exterior Doors	Sq. Ft.	153	575.89	590.81
	Insulation - Walls	Sq. Ft.	1579.38	900.25	979.22
	Insulation - Ceiling	Sq. Ft.	2056.41	280.19	429.62
Interiors	Cabinets - Upper	L. Ft.	24	1575.21	1689.42
	Cabinets - Lower	L. Ft.	23.5	2412.96	2529.60
	Countertops	Sq. Ft.	98	4900.00	5059.74
	Wood Flooring	Sq. Ft.	529.9	3688.73	4102.12
	Carpet	Sq. Ft.	541.1	2286.32	2394.54
	Ceramic Flooring	Sq. Ft.	385.5	2937.51	3164.96
	Interior Sheathing - Walls	Sq. Ft.	3916.2	3602.90	4386.14
	Interior Sheathing - Ceiling	Sq. Ft.	2056.41	2097.54	2508.82
	Paint/Wall Coverings	Sq. Ft.	4426.3	2169.16	2169.16
	Base Molding	Sq. Ft.	142.3	223.60	365.50
	Interior Doors	Sq. Ft.	116.7	2121.86	2275.91
	Hot Water Heater	Each	1	549.79	599.79
	Dishwasher	Each	1	360.88	410.88
	Clothes Washer	Each	1	636.58	666.58
	Clothes Dryer	Each	1	655.54	685.54
	Electrical Outlets	Each	24	1050.96	1163.04
	Electrical Switches	Each	19	788.12	876.85
	Electrical Fixtures	Each	26	2360.25	2799.25
	Kitchen Hood	Each	1	148.37	198.37
	Heating Unit	Each	1	5489.70	5746.66
	Ductwork	Per Story	1	2654.17	2723.17

* TNC = total new item cost of the component. TRC = total replacement cost of the component, which includes demolition and replacement of existing damaged component. Based on RSMeans online costing data (Gordian, 2015).

3.5 Comparison between Customized and Existing Curves

The mean percent damage for the case study building is shown in comparison with similar curves from three other GEC studies in Figure 3-2. For most flood depths, the mean percent damage varies between all the curves, with the least variation between GEC (1996) and GEC (2006). The Saint Petersburg case study curve, has the lowest mean percent damage of all the curves for most of the lower flood depths (0.5 – 7 feet). For flood depths 8 feet or greater, the case study curve has higher mean percent damage values than the GEC (1997) curve, but lower values than the GEC (1996) and GEC (2006) curves.

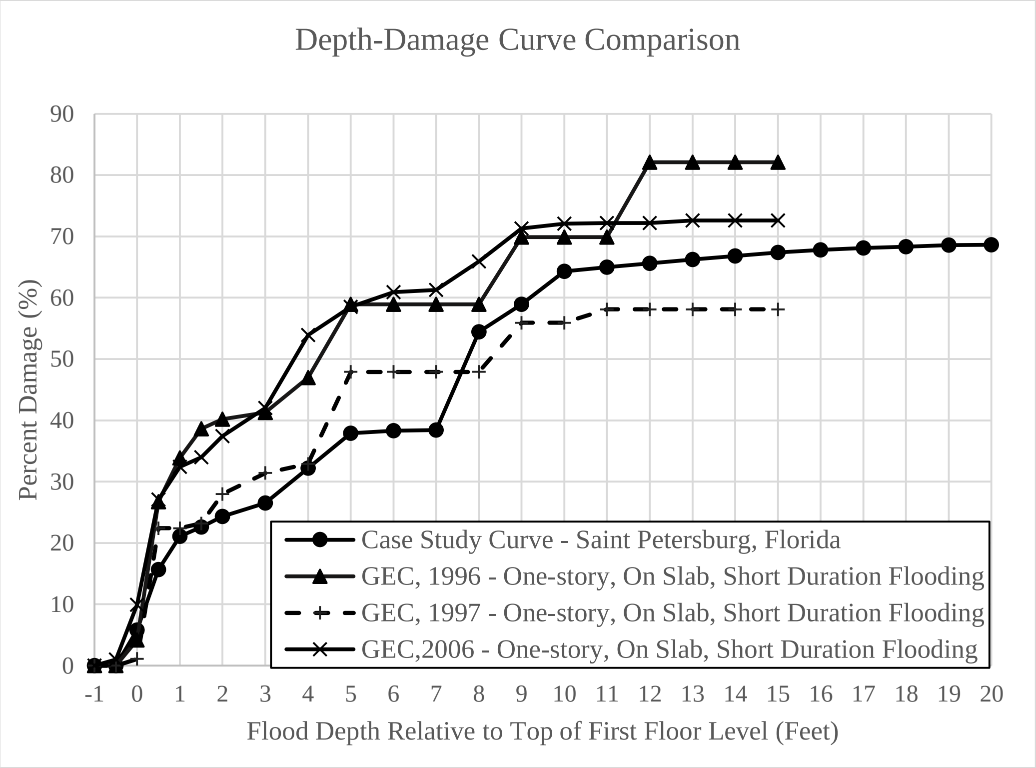


Figure 3-2: Depth-Damage Curve Comparison

Considering that damage assumptions, building designs and cost assumptions differ from one study to another, the variation in curves is expected. Although similar assumptions were made in the structural damage assumptions listed in GEC (2006) study when creating the new curves, the Saint Petersburg case study curve is lower than the GEC (2006). This is in part attributed to the expanded breakdown of components and additional assumptions made based on FEMA (2014). There are also differences in estimates of new and repair costs between the development of the case study curve and GEC (2006) because each curve was based on different costing data sources. Assumptions about the design most likely also differ. The Saint Petersburg is 1736 square feet, which is almost 100 square feet more than the house design in GEC (2006). The only assumption presented in GEC (2006) were the number of stories and foundation type, other design differences are unknown.

3.6 Summary

In this chapter, a set of component-level, synthetic depth-damage curves for single family residential (SFR) type structures was developed, which are flexible in their application to individual SFR building designs. The curves are designed to output the percent damaged material quantities over a range of flood depths. The curves presented in the chapter target the most conventional type of SFR construction (i.e. wood-framed). Inundation-only, non-velocity flooding is considered in the development of these curves. The curves are applicable to both one-story and two-story SFR building designs, and flexible enough to account for variations in most SFR designs. A case study for a wood-frame SFR building design typical of coastal, southeastern United States was presented to demonstrate how the component-level, depth-damage curves could be utilized for a unique design.

The variations between curves from other studies and the case study curve demonstrate that synthetic curves can vary. Even with a similar structure type, there are many factors that can impact the final depth-damage curve, including individual building design characteristics and assumptions related to damage and cost. When estimating damage at the building level, developing curves tailored to the specific building in question helps to reduce estimate errors. The customizable component curves presented in this chapter serve as a tool for creating curves specific to individual building designs.

CHAPTER 4: FLOOD RESILIENCE AND ENVIRONMENTAL IMPACT MATERIAL OPTIMIZATION MODEL FOR COASTAL, SINGLE-FAMILY, RESIDENTIAL (SFR) BUILDING DESIGNS

Methodologies that analyze intersections between flood resilience and sustainability over a building's life-cycle are important to consider within the context of performance-based design. Life-cycle analysis often incorporates regular building maintenance as part of use-phase environmental impacts; however, repairs made to structures required by hazard damage are largely ignored. Additionally, sustainable design strategies can in the case of flood-prone structures, lead to more damage and higher life-cycle impacts if the materials are less flood resistant. To address these issues, Chapter 4 presents a flood resilience and environmental impact material optimization model for coastal, single-family residential (SFR) building designs. The model incorporates (1) a probabilistic procedure for determining flood-related repairs during the useful life of the building (2) a life-cycle assessment based method for measuring the environmental impact of the building, including its initial construction and flood-related repairs. The integrative model provides the basis for a tool with which design professionals can weigh the performance of residential structure designs subject to flood hazards against environmental impacts (i.e., energy consumption, carbon dioxide footprint and water consumption) within coastal areas.

4.1 Introduction

Performance-based design is a common engineering approach to designing buildings subject to natural hazards. Flood design has focused primarily on either resisting or avoiding damage associated with flood depths of a specific exceedance level (e.g., 1% annual exceedance or 100-year flood). For single-family residential structures, the focus is generally on avoiding flood damage, so most structures are elevated above the target design flood level. Similarly, in sustainable design, a common practice in attaining a certain level of sustainable performance is to stipulate that residential buildings meet a specified sustainability certification (e.g. LEED® Gold). Sustainable design objectives typically target the three main pillars of sustainability: social, economic, and environment. While both hazard-resistant and sustainable design have benefits independently, studies have shown incompatibility between resilience and sustainability strategies that can lead to weaknesses in the overall performance over a building's life (FEMA, 2010; Gordon, 2010; Matthews et al., 2014). Therefore, there is a need for models or procedures for evaluating sustainable design performance objectives while considering hazard-resistant building designs.

Several studies and models have used life-cycle cost (LCC) analysis to quantify the performance of structures to define the initial cost of construction plus costs accumulated during the life of the structure. While not all LCC studies account for hazard-related costs, some do (e.g. Chang & Shinozuka, 1996; Fragiadakis et al., 2006; Kang & Wen, 2000; Liu et al., 2003; Liu et al., 2004; Padgett et al., 2010). These studies are limited to bridges and building designs typical of commercial or multi-family residential construction rather than single-family buildings. Noshadravan et al, 2014 compared life-cycle costs for two wood-framed, SFR buildings exposed to hazards (i.e. one to earthquakes and one to hurricanes). While this study included life-time energy consumption costs, the costs were related to operational energy. Furthermore, while these studies consider monetary losses associated with hazard-related damage, other aspects of sustainability are not considered.

Contrary to LCC studies, life-cycle assessment (LCA) investigates the environmental impacts of products or processes. Appendix B provides of full description of the types of LCA methodologies. Studies have utilized process-based LCA to estimate the environmental impacts of multi-family and single-family residential buildings (Table 4-1 lists example LCA studies for residential buildings). While most of these residential LCA studies do consider maintenance a building's useful life, the type of maintenance considered is either unspecified (e.g. Blengini, 2009; Peuportier, 2001) or limited to the regular replacement of materials (e.g. Mithraratne & Vale, 2004). Keoleian et al. (2000) does include unplanned maintenance (e.g. broken windows) in addition to regular maintenance; however, hazard damage repairs are not addressed. Asif et al. (2005), Hammond and Jones (2008), and Zabalza Bribián et al. (2009) do not include maintenance and Rossi et al. (2012) assumes only a per decade percent increase in embodied carbon and energy to account for maintenance.

Table 4-1: Residential LCA Studies

Residential LCA Study	Type of Building	Country
Keoleian, et al. (2000)	1 Standard Home, 1 Energy Efficient Home	U.S.
Peuportier (2001)	3 Homes	France
Mithraratne and Vale (2004)	Building Industry Advisory Council (BIAC) standard house	New Zealand
Asif, et al. (2005)	Semi-detached Home (Condo)	Scotland
Hammond and Jones (2008)	8 Standard Homes, 1 Energy Efficient Homes, 3 Standard Apartments, 2 Energy Efficient Apartments	England
Blengini, 2009	Apartment	Italy
Zabalza Bribián, et al. (2009)	1 home	Spain
Rossi, et al. (2012)	1 Steel Home & 1 Masonry Home (Brussels); 3 Steel Homes (One in Each Location)	Belgium, Portugal, Sweden

More recent studies (e.g. Arroyo et al., 2014; Court et al., 2012; Feese et al., 2014; Hossain & Gencturk, 2014; Sarkisian, 2014) have addressed the development of models for quantifying environmental impacts from earthquake-induced repairs. In case studies, multi-story reinforced concrete and steel structures in general are considered, which are more typical of commercial or multi-family residential construction, but not single-family residential buildings. Dong et al. (2013) developed a framework for assessing social, environmental, and economic impacts associated with seismic and flood induced damage of reinforced concrete bridges, while Padgett and Tapia (2013) presented a model for assessing environmental impacts associated with damage from multiple hazards to bridges. Plumblee and Klotz (2014) compared the environmental impacts of wind damage related to the use of standard windows versus hazard-resistant windows. While these studies begin to weigh sustainable performance design objectives against hazard-resistant building designs, flooding and other hazards still need to be addressed within the context of single-family residential buildings.

4.1.2 Aim

The aim of Chapter 4 is to present an integrated sustainability and resilience assessment (ISRA-F) model for optimizing flood resilience and environmental impact of single-family residential building designs in coastal geographies. Life-cycle assessment techniques are utilized to measure energy consumption, carbon dioxide footprint, and water consumption related to initial construction and flood-induced repairs incurred over a building's useful life. A probabilistic methodology utilizing Monte Carlo techniques is used to simulate flood losses. To demonstrate the capability of the model for optimizing performance-based design for flood hazards, the methodology is applied to a one-story home in Saint Petersburg, Florida.

4.2 Model Overview

The ISRA-F model is designed to compare multiple designs to identify optimal performance, where building performance is assessed within the framework of the ISRA-F model using two modules (Figure 4-1): (1) Flood Resilience Assessment (FRA) and (2) Environmental Impact Assessment (EIA). Matlab and Microsoft Excel were utilized to program the model.

Within the FRA module, the building flood performance is assessed using the Lifecycle Material Damage Estimator. The estimator simulates flood events over a building's design life, N, for K iterations and then calculates expected mean repair for each material. The main input parameters for the estimator include site and design specific parameters. Site specific parameters include the probability of extreme flood events, sea level rise rate, and ground elevation; and design specific parameters include the building elevation and component depth-damage curves that provide a measure of damage over a range of flood depths.

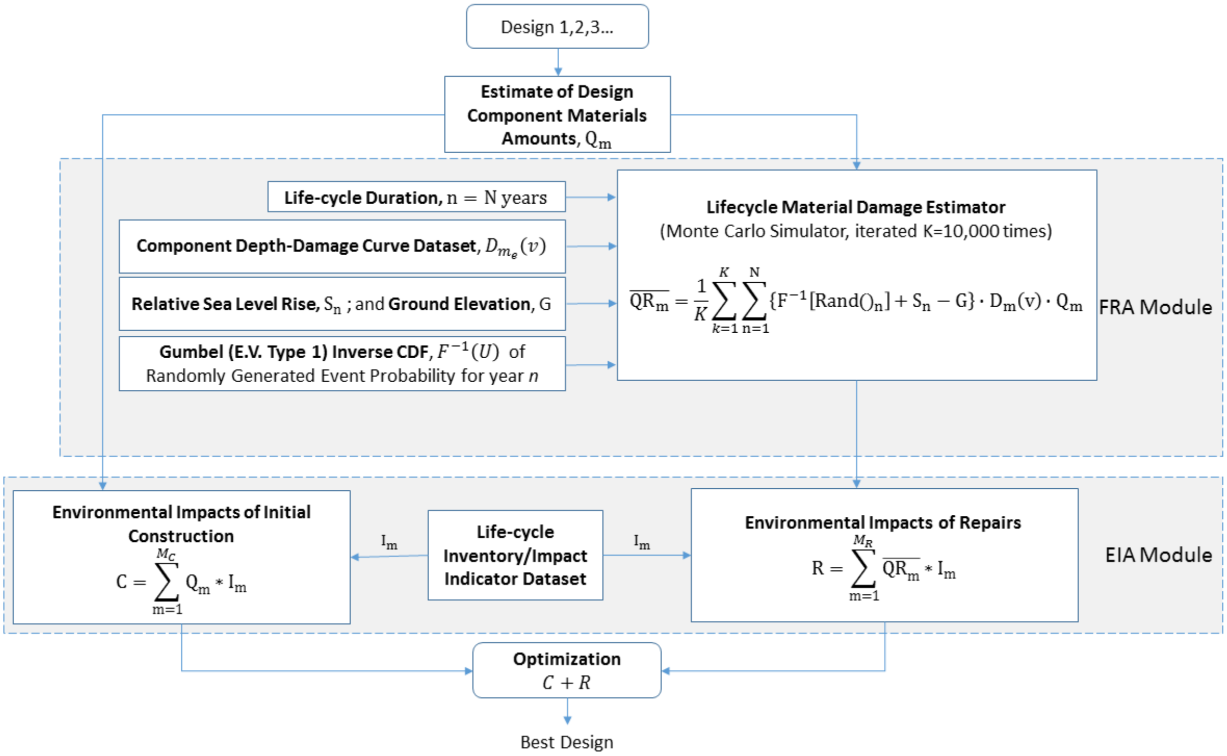


Figure 4-1: IRSA-F Model Framework

For the EIA Module, the environmental impact is measured by calculating the embodied energy, CO2 footprint, and water consumption for initial construction and flood-induced repairs using a life-cycle inventory database. Both the FRA and EIA modules depend on a quantity estimate of the materials for all building design components. The output of the optimization model is the selection of the design with the lowest total environmental impacts associated with the initial construction and repairs for the design in question.

4.2.2 Flood Resilience Assessment Module (FRA)

The FRA module determines damage as the failure of materials through a process of convolving a set of probable flood depths and the damage associated with those flood depths (Equation 4-1),

$$E(D) = \int_0^{\infty} D(v) \cdot p_f(v) \cdot dv \qquad \text{Equation 4-1}$$

where $E(D)$ is the expected damage, $D(v)$ is the relationship between flood depth, v, and damage and $p_f(v)$ is the probability density function (PDF) for flood depth. The convolution method has been used to determine component failure probabilities in reliability-type studies of residential buildings for other types of hazards, where inherent uncertainties in the hazard occurrence and performance of structural components to hazard loading are considered (e.g. Li & Ellingwood, 2006). It has also been utilized in benefit-cost analyses to compare the cost of damage-mitigation alternatives (e.g. Amoroso, 2009).

The discrete depth-damage curves, developed in Chapter 3, were utilized to define D(v). The PDF, $p_f(v)$, is assumed to follow an Extreme Value Type 1 (Gumbel) distribution, which has been used to model extreme rain and flood events (e.g. DOC, 1961). While the Gumbel distribution has been shown to underestimate flood and rainfall events for long return periods (Needham et al., 2012; Wilks, 1993), any estimate errors for the longer return periods would be present in both designs being compared; therefore, the comparison between designs is still valid.

The inverse cumulative distribution function for the Gumbel distribution is shown in Equation 4-2,

$$F^{-1}(U) = u + a\{-\log_e[-\log_e(F(U))]\} \qquad \text{Equation 4-2}$$

where $F^{-1}(U)$ is the inverse cumulative distribution function for the Gumbel distribution, $F(U)$ is the cumulative distribution function for the Gumbel distribution, u is the location parameter, and a is the scale factor.

In order to utilize the inverse CDF for Monte Carlo simulations, u and a must first be derived for the specific location being considered. The return period, R, is defined as the inverse of the probability of exceedance [1-F(U)], Equation 4-3. Therefore, $F^{-1}(U)$, can be written in terms of the return period, R, for the annual extreme flood depth using Equation 4-4.

$$R = \frac{1}{\text{Probability of exceedance}} = \frac{1}{1-F(U)} \qquad \text{Equation 4-3}$$

The inverse cumulative distribution function becomes:

$$F^{-1}(U) = y = u + a\left\{-\log_e\left[-\log_e\left(1-\frac{1}{R}\right)\right]\right\} \qquad \text{Equation 4-4}$$

For large values of R, Equation 4-4 simplifies to a logarithmic equation (Equation 4-5),

$$y = u + a\log_e(R) \qquad \text{Equation 4-5}$$

where, scale factor, a, and location parameter, u, are derived by fitting a logarithmic trendline to a set of given extreme flood events for the site and correspond to the slope and y-intercept, respectively. The flood depth for extreme events (10 year, 50 year, 100 year and 500 year) are published in FEMA Flood Insurance Study (FIS) reports. Figure 4-2 shows the logarithmic trendline for the case study in Saint Petersburg, Florida presented in Section 4.3. The 10 year, 50 year, 100 year and 500 year stillwater elevations (i.e. 4.1 feet, 7.0 feet, 8.3 feet and 11.1 feet) were taken from FEMA (2009), which correspond to the nearest location to the case study site (i.e. South Yacht Basin).

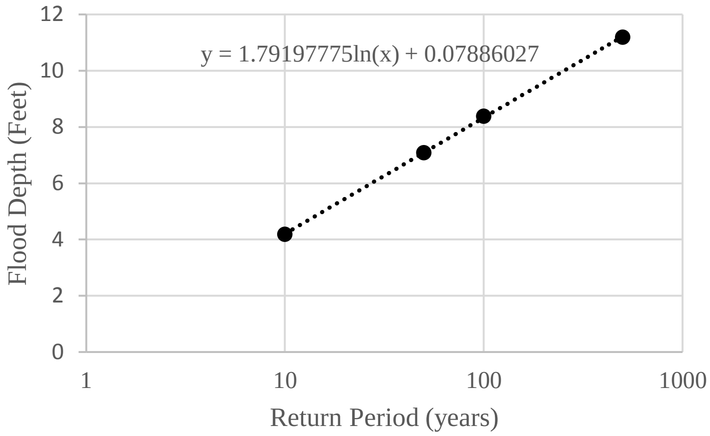


Figure 4-2: Logarithmic Trend Line for Case Study in Saint Petersburg, Florida

Damage analysis in the FRA module is carried out at the component level (e.g. roof cover, floor finishes, insulation, etc.) over the life of the building using Equation 4-6, where

$$\overline{\mathrm{QR_m}} = \frac{1}{K}\sum_{k=1}^{K}\sum_{\mathrm{n}=1}^{\mathrm{N}}\{\mathrm{F}^{-1}[\mathrm{Rand}()_\mathrm{n}] + \mathrm{S_n} - \mathrm{G}\} \cdot \mathrm{D_m}(\mathrm{v}) \cdot \mathrm{Q_m} \qquad \text{Equation 4-6}$$

$\overline{\mathrm{QR_m}}$ is the average of K iterations of cumulative damage for component, m, over building life N, $\mathrm{F}^{-1}[\quad]$ is the inverse of the cumulative Gumbel distribution, $\mathrm{Rand}()_\mathrm{n}$ is a uniformly distributed random variable between 0 and 1 for each year n, $\mathrm{S_n}$ is the increase in relative sea level rise at the site for year n, G is the ground elevation, $\mathrm{D_m}(\mathrm{v})$ is functional relationship between flood damage to component m and flood depth (i.e. depth-damage function), and Q_m is the total material quantity for component m.

Relative sea-level rise (RSLR) and the elevation of the building relative to ground are important to consider for coastal buildings since these factors can have a significant impact on the vulnerability of a building to hazards. RSLR, which typically accounts for ground settlement or subsidence, is assumed to increase at a constant rate following historical trends.

The damage analysis defined by Equation 4-6 is carried out using Monte Carlo simulations. The annual maximum flood depth for each year of the building's life is sampled using the Gumbel distribution and the component damage associated with each event is determined by the discrete component depth-damage curves. The cumulative flood damage over the building's life is then calculated by aggregating the yearly damage from n=1 to N. The process is iterated K times, where K= 10,000, and the expected cumulative damage over the building's life, $\overline{\mathrm{QR_{m,J}}}$, is calculated by averaging the cumulative damage from K=1 to 10,000.

The number of iterations was selected based on the number of iterations at which point the expected damage converged. Figure 4-3 shows three sample simulation results for damage to interior sheathing at year one of the building life for the Saint Petersburg case study presented in 4.3. Around 10,000 iterations the expected damage begins to converge.

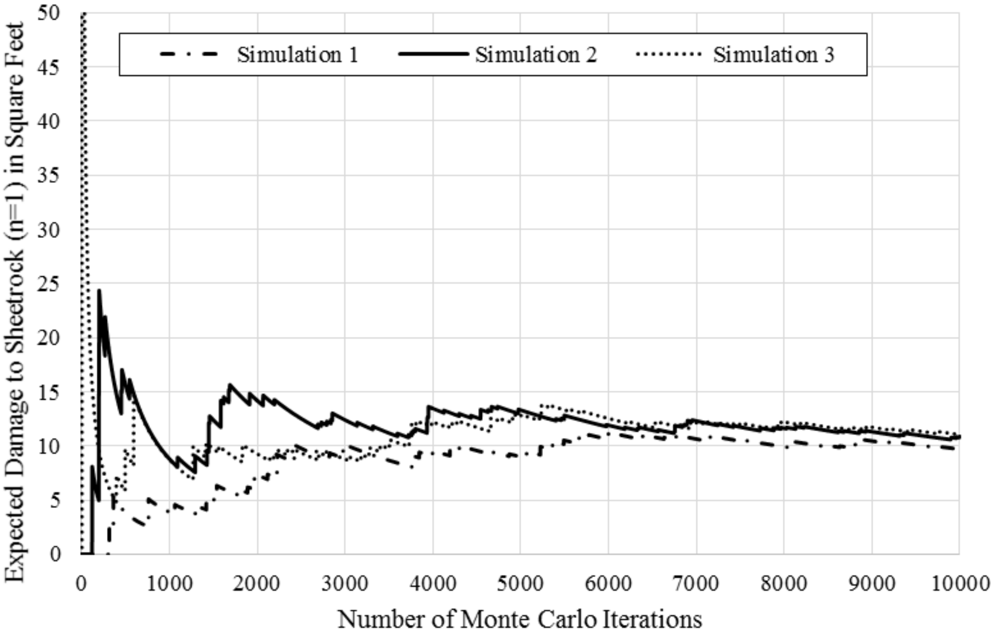


Figure 4-3: Convergence of Monte Carlo of Expected Damage to Wall Sheathing (n=1)

4.2.3 Environmental Impact Assessment (EIA) Module

The EIA module includes calculating the environmental impacts of initial construction plus flood-induced life-cycle repairs. For this model, environmental impacts include those associated with extraction, manufacturing and transportation of materials to the building site. Where impact data are available for the construction and installation of building materials, these were also included. Removal of damaged materials was not considered in this model. The two main data components in the EIA module include (1) the impacts of initial construction and (2) the impacts of flood-induced repairs.

For initial construction, the environmental impact is calculated with Equation 4-7, where

$$\mathrm{C} = \sum_{\mathrm{m}=1}^{\mathrm{M}_C} \mathrm{Q}_{\mathrm{m}} * \mathrm{I}_{\mathrm{m}} \qquad \text{Equation 4-7}$$

C is the cumulative environmental impact (Embodied Energy, CO_2 Footprint and Water Consumption) for all materials, M_C, used in the initial construction of the SFR building, Q_{m} is the quantity of material used in the initial construction, m, and I_{m} is the environmental impact per unit of material, m.

The environmental impact of repairs is essentially calculated the same as initial construction; however, the focus is on the replacement of damaged materials. In FRA module, the output of the Material Damage Estimator for each component is averaged and used to calculate the environmental impact of repairs (Equation 4-8), where,

$$\mathrm{R} = \sum_{\mathrm{m}=1}^{M_R} \overline{\mathrm{QR_m}} * \mathrm{I_m} \qquad \text{Equation 4-8}$$

R is the cumulative environmental impact (Embodied Energy, CO_2 Footprint and Water Consumption) for all materials repairs, M_R, to the SFR building over its useful life, $\overline{\mathrm{QR_m}}$ is the expected cumulative damage/repair quantity for material, m.

The life-cycle inventory (LCI) dataset, which provides the environmental impact per unit of material, is a significant part of the EIA module, as the output by the EIA module is very sensitive to the inventory data utilized, especially for materials that have a higher environmental impact in proportion to the rest of the materials in the structure. While LCI data can vary over time and from one location to another, uncertainty in LCI data is outside the scope of this study and was not considered in the proposed model. Effort was taken, however, to utilize LCI data from the United States, where data were available. Two main sources were utilized for LCI inventory data, (1) National Institute of Standards and Technology's online tool BEES (NIST, 2015) and (2) Ashby (2009). A full list of sources for component-level LCI data is provided in Table D-1 in the Appendix D.

4.2.4 Estimation of Material Component Quantities

The estimate of all materials used to initially construct the building was needed for each design being considered as initial input for both the FRA and EIA modules. The estimate includes (1) determining the list of materials associated with all components of interest for the designs being analyzed, and (2) estimating the quantity of materials for all components. Ideally, a list of materials associated with all possible design-specific building components needs to be developed. A general list of components for a coastal SFR building is provided in Table 4-2.

Effort was made to include as many materials as possible; however, for some components, it was difficult to pinpoint every material quantity. For example, the quantity of materials for the majority of built-in appliances was not readily available so only the materials that constituted a large proposition of the components by weight were included and these quantities were assumed based on quantities presented in literature (see Table D-1). When calculating the list of materials for life-cycle repairs, the list of damaged materials is limited to the material components covered by the flood damage curves. After the list of materials is compiled, then the quantity of materials is calculated. There are multiple units by which a material can be quantified (e.g. weight, area, length or volume). While there is no distinct measure for quantifying materials, the life-cycle inventory data collected for the EIA module will have a specific set of units that may require conversion depending on how the material quantities are defined.

Table 4-2: General Component Breakdown for a SFR Building

	Possible Design Components	Typical Materials
Site	Land	Soil, Vegetation
	Utilities	Polymers, Steel, Clay, Concrete
Foundation	Footings	Concrete, Steel, Brick
	Foundation Walls	Concrete, Steel, Brick
	Slabs	Concrete, Steel
	Piers	Concrete, Steel
	Piles	Woods, Polymer Composites, Concrete, Steel, Chemicals
Below First Level	Mechanical Equipment	Steel, Aluminum, Copper
	Stairways	Woods, Chemical Agents
	Parking Pads/Driveways	Concrete, Asphalt
	Breakaway Flood Walls	Wood, Gypsum/Cement Composites, Polymers, or Brick
Structure Framing	Members/Studs	Wood
	Beams/Plates	Wood
	Connections	Coated, Galvanized or Stainless Steels
Roof Covering	Roof Membrane	Asphalt Composites
	Roof Covers	Asphalt Composites, Clay, Concrete, Wood, Coated or Galvanized Steels
	Flashing	Galvanized Steels
	Attic Venting	Galvanized Steels
Roof Framing	Trusses	Woods
	Rafters	Woods
	Sheathing	Wood Composites
Exterior Walls	Wall Cladding/Covering	Gypsum/Cement Composites, Woods, Polymers, or Brick
	Windows	Glass, Steel, Aluminum and Polymers
	Exterior Doors	Fiberglass Composites, Wood, Glass
	Insulation	Polymers, Natural Fibers, Fiberglass
	Mechanical	Polymers or Copper
	Electrical	Copper, Aluminum, Polymers
Interiors	Interior Wall and Floor Framing	Woods
	Cabinets, Countertops and Shelving	Wood, Stone, Ceramic, Glass
	Interior Sheathing	Gypsum/Cement Composites, Wood
	Paint/Wall Coverings	Polymers, Paper
	Mechanical	Steel, Aluminum, Polymers, Rubber, Copper
	Electrical	Copper, Aluminum, Polymers,

4.3 Case Study

4.3.1 Case Study Location and Design Model

To provide a demonstration of the ISRA-F model, a case study is presented (Table 4-3). The building model being assessed is a one-story, slab-on-grade, wood-framed, hipped roof SFR structure with same layout as case study house in Chapter 3.

Table 4-3: Case Study Location Details

General Location	Saint Petersburg, Florida	Source
Exact Location (Lat/Lon)	27°45'14.4"N 82°37'51.6"W	-
Approximate Ground Elevation	7 feet	FDEM (2015)
Flood Zone	AE EL 8	FEMA (2015)
Freeboard	1 foot	-
Historic Relative Sea Level Rise Trend	2.36 mm/year	NOAA (2014)

Two designs for the SFR building were evaluated within the ISRA-F model. The first (Design 1) represents typical construction materials and installations, while the second (Design 2) uses more flood-resistant materials and installations (Table 4-4) and follows design recommendations described in FEMA (2008) for wet floodproofing. These recommendations include using non-paper faced gypsum instead of paper-faced gypsum wallboard on all interior walls and ceilings; installing closed-cell spray foam insulation instead of fiberglass batt insulation; elevating the hot water heater, washer and dryer; and using ceramic tile for all flooring instead of mixed flooring types. For the elements of the design that were elevated the discrete depth-damage curves developed in Chapter 3 were adjusted to account for the change in elevation. The depth-damage curves for Design 1 and Design 2 can be found in Tables D-2 through D-9 in Appendix D.

Table 4-4: Case Study Design Considerations

Design 1 - Typical	Design 2 – Flood Resistant
Paper-faced gypsum wallboard	Non-paper-faced gypsum wallboard
Fiberglass batt insulation	Closed-cell spray foam insulation
Hot water heater located on first floor	Hot water heater in attic
Flooring types: wood, ceramic & carpet	All ceramic flooring
Electrical outlets at 1.5 feet	Electrical outlets elevated to 4 feet
Washer & dryer set on first floor level	Washer & dryer elevated 1 foot

4.3.2 Bill of Materials and LCI Inventory

The bill of materials which include all material quantities for the components in Design 1 and Design 2 are shown in Table 4-5. The table is organized according to major component categories (e.g. site, structure) and each major category is broken down to individual design components. The materials units used for each component are also shown. Finally the quantities of each design component are shown. Where the quantities were the same for both designs, the value is provided once in the table

Table 4-5: Case Study Bill of Materials

	Design Components	Units	Quantity Design 1	Quantity Design 2
Site	AC Condensing Unit	Each	1	
Structure	Slab	Sq. Ft.	1736	
	Stud Framing	Pounds	17030	
Roof Covering	Roof Membrane & Cover	Sq. Ft.	3142	
	Fascia	Sq. Ft.	115	
	Soffits	Sq. Ft.	574	
	Roof Sheathing	Sq. Ft.	3142	
Exterior Walls	Wall Sheathing/Covering	Sq. Ft.	1579	
	Windows	Sq. Ft.	133	
	Exterior Doors	Sq. Ft.	153	
	Insulation - Walls	Sq. Ft.	1579	
	Insulation - Ceiling	Sq. Ft.	2056	
Interiors	Cabinets - Upper	L. Ft.	24	
	Cabinets - Lower	L. Ft.	23.5	
	Countertops	Sq. Ft.	98	
	Wood Flooring	Sq. Ft.	530	0
	Carpet	Sq. Ft.	541	0
	Ceramic Flooring	Sq. Ft.	386	1457
	Interior Sheathing - Walls	Sq. Ft.	3916	
	Interior Sheathing - Ceiling	Sq. Ft.	2056	
	Paint/Wall Coverings	Sq. Ft.	4426	
	Base Molding	Sq. Ft.	142	
	Interior Doors	Sq. Ft.	117	
	Hot Water Heater	Each	1	
	Dishwasher	Each	1	
	Clothes Washer	Each	1	
	Clothes Dryer	Each	1	
	Electrical Outlets	Each	24	
	Electrical Switches	Each	19	
	Furnace	Each	1	
	Fan Coil Unit	Each	1	
	Ductwork	Per Story	1	

4.3.3 Environmental Impact Initial Construction

The environmental impacts of initial construction output by the ISRA-F model for Design 1 and Design 2 are shown in Table 4-6. The environmental impacts are embodied energy (EE), carbon footprint (CO_2) and water consumption. The units of measure for the environmental impacts are mega joules, kilograms CO_2 equivalent and cubic meters for EE, CO2 and water, respectively.

Design 2 has a slightly higher embodied energy (+ 2.3%), however the increase is not large. There is also a small decrease in carbon footprint (-0.4%) and water consumption (-5.1%) when comparing Design 2 to Design 1.

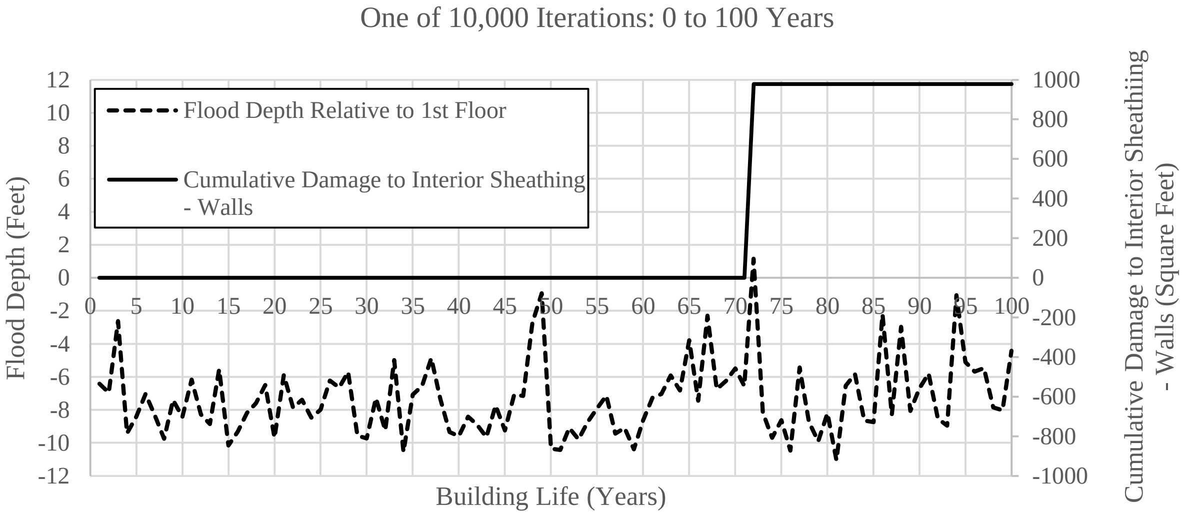
Since the differences for all three impact categories are small, it is assumed that there is no difference in the environment impact of initial construction when comparing Design 1 to Design 2.

Table 4-6: Environmental Impacts of Initial Construction

Design components	Design 1			Design 2		
	EE (MJ)	CO$_2$ (Kg CO$_2$ Eq.)	Water (M^3)	EE	CO$_2$	Water
AC Condensing Unit	10134.1	687.7	16.0	10134.1	687.7	16.0
Slab	96680.2	6955.9	10.2	96680.2	6955.9	10.2
Stud Framing	77197.2	12600.3	5310.6	77197.2	12600.3	5310.6
Roof Membrane & Cover	230682.6	4515.3	17.6	230682.6	4515.3	17.6
Fascia	1029.6	63.0	73.0	922.7	55.4	73.0
Soffits	1797.5	110.9	121.1	1531.3	91.9	121.1
Roof Sheathing	57200.3	1281.3	0.8	57200.3	1281.3	0.8
Exterior Wall Sheathing	28751.8	644.0	0.4	28751.8	644.0	0.4
Exterior Siding	69390.4	335.1	12.7	69390.4	335.1	12.7
Windows	9640.7	482.7	4.6	9640.7	482.7	4.6
Exterior Doors	1748.7	120.1	2.3	1748.7	120.1	2.3
Insulation - Walls	3645.2	152.7	0.0	12354.1	442.4	66.9
Insulation - Ceiling	5311.4	382.6	0.0	32171.0	1152.2	174.2
Cabinets - Upper	1723.3	213.3	230.6	1723.3	213.3	230.6
Cabinets - Lower	2486.6	307.7	332.8	2486.6	307.7	332.8
Countertops	3709.1	118.4	2.2	3709.1	118.4	2.2
Wood Flooring	6846.2	408.5	815.6	0.0	0.0	0.0
Carpet	76525.0	3211.0	235.4	0.0	0.0	0.0
Ceramic Flooring	15282.6	1088.8	2.3	57743.4	4113.8	8.6
Interior Sheathing - Walls	142615.3	8266.6	4.4	175880.4	7724.0	4.4
Interior Sheathing - Ceiling	74887.8	4340.8	2.3	92355.4	4055.9	2.3
Paint/Wall Coverings	22025.0	983.9	5.4	22025.0	983.9	5.4
Base Molding	1715.9	102.2	203.8	1715.9	102.2	203.8
Interior Doors	2455.5	72.3	0.2	2455.5	72.3	0.2
Hot Water Heater	1601.4	125.5	4.2	1601.4	125.5	4.2
Dishwasher	5599.0	264.5	291.8	5599.0	264.5	291.8
Clothes Washer	6040.0	360.4	293.4	6040.0	360.4	293.4
Clothes Dryer	5279.4	317.8	291.9	5279.4	317.8	291.9
Electrical Outlets	55.0	3.0	0.1	55.0	3.0	0.1
Electrical Switches	124.3	6.7	0.3	124.3	6.7	0.3
Furnace	4049.5	295.6	7.0	4049.5	295.6	7.0
Fan Coil Unit	3131.1	243.4	4.4	3131.1	243.4	4.4
Ductwork	6073.9	441.2	6.7	6073.9	441.2	6.7
Total	975435.5	49503.2	8304.2	1020826.3	49140.4	7500.5
% Increase				2.3	-0.4	-5.1

4.3.4 Environmental Impact Initial Construction and Repairs

An example output of the ISRA-F model for one of ten thousand iterations computed within the Monte Carlo simulation for repairs to interior wall sheathing for Design 1 is shown in Figure 4-4. The flood depth relative to the first floor level is also shown. When the flood depth rises above 0 feet at 72 years, damage occurs to a portion of the sheetrock (25% as defined by the depth-damage curves). Since no other flood damage events occurs at 100-years, the cumulative damage is equal to the damage sustained during the single flood event. The embodied energy, CO^2 footprint and water consumption of repairs at 100-year building life are 35652 MJ, 2067 kg CO^2 equivalent, 1.1 m^3, respectively.



100 Year Buiding Life: EE = 35652 MJ, C02 = 2067 KG CO2 Equivalent, Water = 1.1 M^3

Figure 4-4: One of Ten Thousand Iterations Showing Repairs to Interior Wall Sheathing

When expected cumulative damage/repairs over the life of the building are added to initial construction (C+R), the environment impact differences between Design 1 and Design 2 are larger especially for longer building life spans. Figures 4-5, 4-6 and 4-7 show the combined C+R embodied energy, CO_2 footprint, and water consumption, respectively, over a range of building lives. Figure 4-8 shows the percent increase in the combined C+R impacts when comparing the typical design to the flood-resistant design for selected building lives.

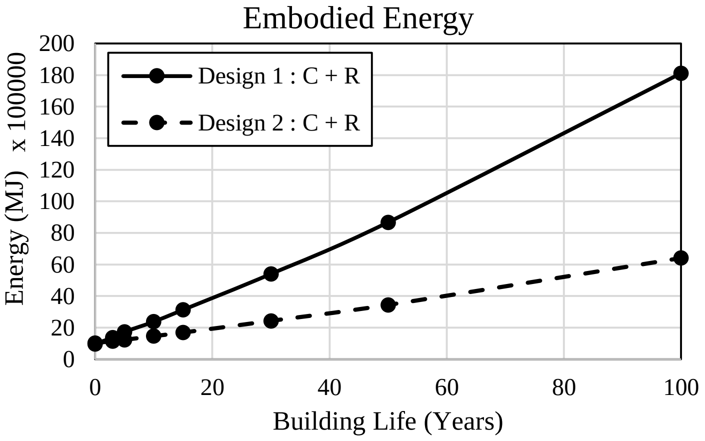


Figure 4-5: Design 1 versus Design 2 Embodied Energy (C+R)

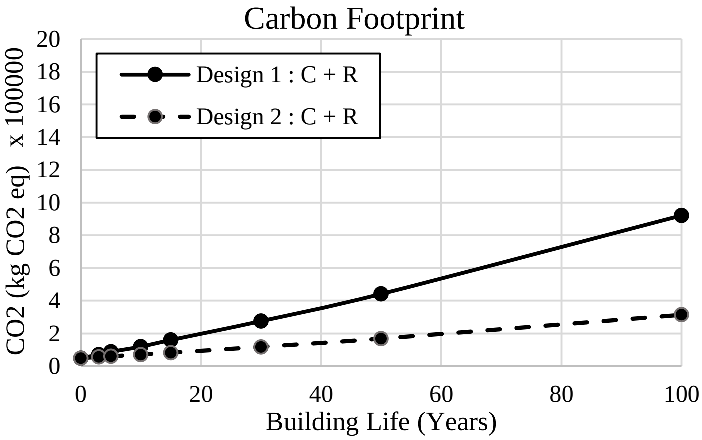


Figure 4-6: Design 1 versus Design 2 Carbon Footprint (C+R)

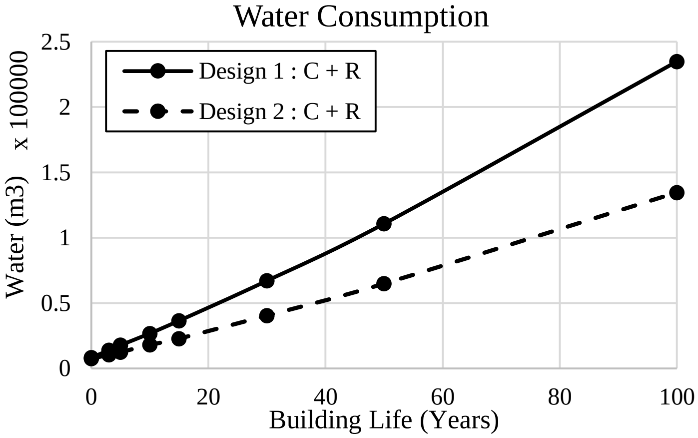


Figure 4-7: Design 1 versus Design 2 Water Consumption (C+R)

Overall, embodied energy and carbon footprint show the greatest difference of all three impact factors. While a difference is reported in the model for water consumption, the difference between Design 1 and Design 2 is not as large at the other two impact factors except when the building life is short (5 years or less). At a life span of 5 years, the embodied energy, carbon footprint and water consumption are almost 20%, 26% and 32% higher, respectively, for Design 1 than Design 2. For a typical 30 year mortgage, the difference is even greater, with a 127.6%, 134.1% and 65.6% increase in embodied energy, carbon footprint, and water consumption, respectively. By the time the building life reaches 100 years, the embodied energy, carbon footprint, and water consumption for Design 1 is 2.91, 2.94 and 1.74 times higher than Design 2, respectively. These results are similar to other studies where increases in environmental impact due to hazard-related repairs were observed over time for non-SFR structures (e.g. Arroyo, et al., 2014; Dong, et al., 2013).

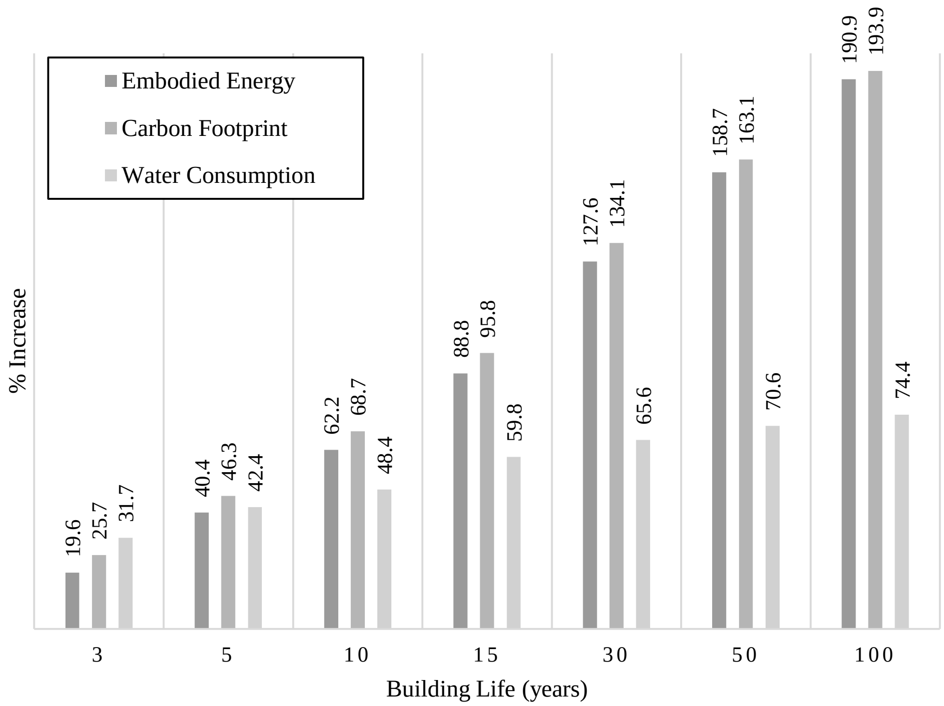


Figure 4-8: Design 1 Percent Increase Over Design 2 (C+R)

4.3.5 Optimization of Design

The model indicates that for initial construction, the more flood-resistant design does not differ from Design 1; however, the environmental performance of Design 2 is significantly better when hazard-related repairs over the life of the building are considered. If sustainability is an important design factor, the ISRA-F model indicates that flood-resistant design would be better choice. To determine which individual component design choices have the greatest impact on the results of the model, a sensitivity analysis of the case study was conducted on individual design choices. The results of the sensitivity analysis are shown in Table 4-7 for a building life of 50 years.

Based on the results in Table 4-7, two design alternatives have the greatest impact on the results: (1) mixed flooring versus ceramic flooring and (2) paper-faced versus non-paper-faced gypsum wall board. In the case of flooring, choosing the typical design results in a much higher embodied energy, carbon footprint, and water consumption than the more flood resistant option. When choosing paper-faced over non-paper-faced gypsum board, Design 1 yields a higher embodied energy and carbon footprint than design two with similar water consumption. When optimizing the design for the Saint Petersburg SFR building, choosing ceramic flooring and non-paper-faced gypsum wallboard are the best options for reducing environmental impact over the life of the structure; however, it should be noted that flood-resistant insulation should also be used in combination with the non-paper-faced gypsum board since the wallboard would have to be replaced to remove and replace the flooded fiberglass bat insulation.

Table 4-7: Sensitivity Analysis Results for 50 year Building Life

Design Alternatives												% Increase C+R (50yr)		
PF	NPF	F	CL	HW1	HW2	FM	FC	E1	E2	WD1	WD2	EE	CO2	Water
X*		X		X		X		X		X		0	0	0
	X	X		X		X		X		X		29.8	38.3	0.1
X			X	X		X		X		X		0.2	0.3	-0.2
X		X			X	X		X		X		0.7	1.1	0.1
X		X		X			X	X		X		58.0	46.8	60.5
X		X		X		X			X	X		0.7	0.9	3.3
X		X		X		X		X			X	0.1	0.2	0.5

PF = Paper-faced gypsum
NPF = Non-paper-faced gypsum
F = Fiberglass Batt Insulation
CL = Closed-cell Foam Insulation
HW1 = Hot Water Heater on 1st Floor
HW2 = Hot Water Heater on 2nd Floor
FM = Flooring Mixed
FC = Flooring Ceramic
E1 = Electrical Outlets at 1.5 feet
E2 = Electrical Outlets at 4 feet
WD1 = Washer/Dryer Not Elevated
WD2 = Washer/Dryer Elevated

* X indicates the design option chosen.

4.4 Summary

Methodologies that analyze intersections between flood resilience and sustainability over a building's lifecycle are important to consider within the context of performance-based design of flood-prone buildings. While both hazard-resistant and sustainable design have benefits independently, some design strategies can conflict, which in the case of flood-prone, single-family residential building structures can lead to more damage and higher life-cycle impacts if materials utilized are less flood resistant. Chapter 4 presented a flood resilience and environmental impact material optimization model for coastal, single-family, residential (SFR) building designs. The model incorporates (1) a probabilistic procedure for determining flood-related repairs during the useful life of the building, and (2) a life cycle assessment-based method for measuring the environmental impact of the building, including initial construction and flood repairs.

To demonstrate the capability of the model to optimize flood performance-based designs for environmental impact, the methodology was applied to an example case study, which compared two design alternatives for a one-story home in Saint Petersburg, Florida. Design 1 utilized traditional construction materials that are less flood resistant and require replacement when damaged. Design 2 used wet floodproofing techniques and included alternative materials that are flood resistant. Little difference in initial construction environmental impacts was found between Design 1 and 2; however, the environmental impacts of Design 2 are less when hazard-related repairs over the life of the building are considered. For a 30 year building life, the typical design has more than two times the embodied energy and carbon footprint of initial construction and flood repairs combined and 1.7 times the water consumption. The difference is greater at a 100 year building life where the embodied energy, carbon footprint, and water consumption for Design 1 are 2.91, 2.94 and 1.74 times higher, respectively, than Design 2. The results of the case study demonstrate how the model provides the basis for a tool by which the performance of residential building designs subject to flood hazards can be evaluated against environmental impacts (i.e., energy consumption, carbon dioxide footprint, and water consumption) within coastal areas.

CHAPTER 5: WIND RESILIENCE AND ENVIRONMENTAL IMPACT MATERIAL OPTIMIZATION MODEL FOR COASTAL, SINGLE-FAMILY, RESIDENTIAL (SFR) BUILDING DESIGNS

Chapter 5 presents a wind resilience and environmental impact material optimization model for coastal, single-family residential (SFR) building designs, similar to the flood model presented in Chapter 4. The model incorporates (1) a probabilistic procedure for determining wind damage-related repairs during the useful life of the building (2) a life cycle assessment-based method for measuring the environmental impact of the building, including its initial construction and wind-damage repairs. The integrative model provides the basis for a tool with which design professionals can weigh the performance of residential structure designs subject to wind hazards against environmental impacts (i.e., energy consumption, carbon dioxide footprint and water consumption) within coastal areas.

5.1 Introduction

Wind design has focused primarily on resisting damage associated with wind speeds of a specific exceedance level (e.g., 0.2% or 500-year wind speed). For single-family residential structures, the focus is generally on resisting wind forces through the use of wind resistant materials and design strategies (e.g. hurricane straps and clips, opening protection, wind-rated windows, doors and claddings). Similar to performance-based design for flooding, there is a need for models or procedures that evaluate sustainable design performance objectives against wind hazard-resistant building designs. Plumblee and Klotz (2014) compared the environmental impacts of wind damage standard windows versus hazard-resistant windows, however the analysis focused on one building component, While this study begins to weigh sustainable performance design objectives against hazard-resistant building designs, wind-hazards still need to be addressed within the context multiple components and single-family residential buildings.

5.1.1 Aim

The aim of Chapter 5 is to present an integrated sustainability and resilience assessment model for wind hazards (ISRA-W) to optimize wind resilience and environmental impact of single-family residential building designs in coastal geographies. Similar to Chapter 4, life-cycle assessment techniques are utilized to measure energy consumption, carbon dioxide footprint, and water consumption resulting from initial construction and wind damage repairs incurred over the building’s useful life. A probabilistic methodology utilizing Monte Carlo techniques is used to simulate wind losses. To demonstrate the capability of the model for optimizing wind performance-based designs, the methodology is applied to the same case study home used in Chapter 4.

5.2 Model Overview

The ISRA-W model is designed to compare multiple designs to identify the design with optimal performance, where building performance is assessed within the framework of the ISRA-W model using two modules (Figure 5-1): (1) Wind Resilience Assessment (WRA) and (2) Environmental Impact Assessment (EIA). Microsoft Excel was utilized to program the model.

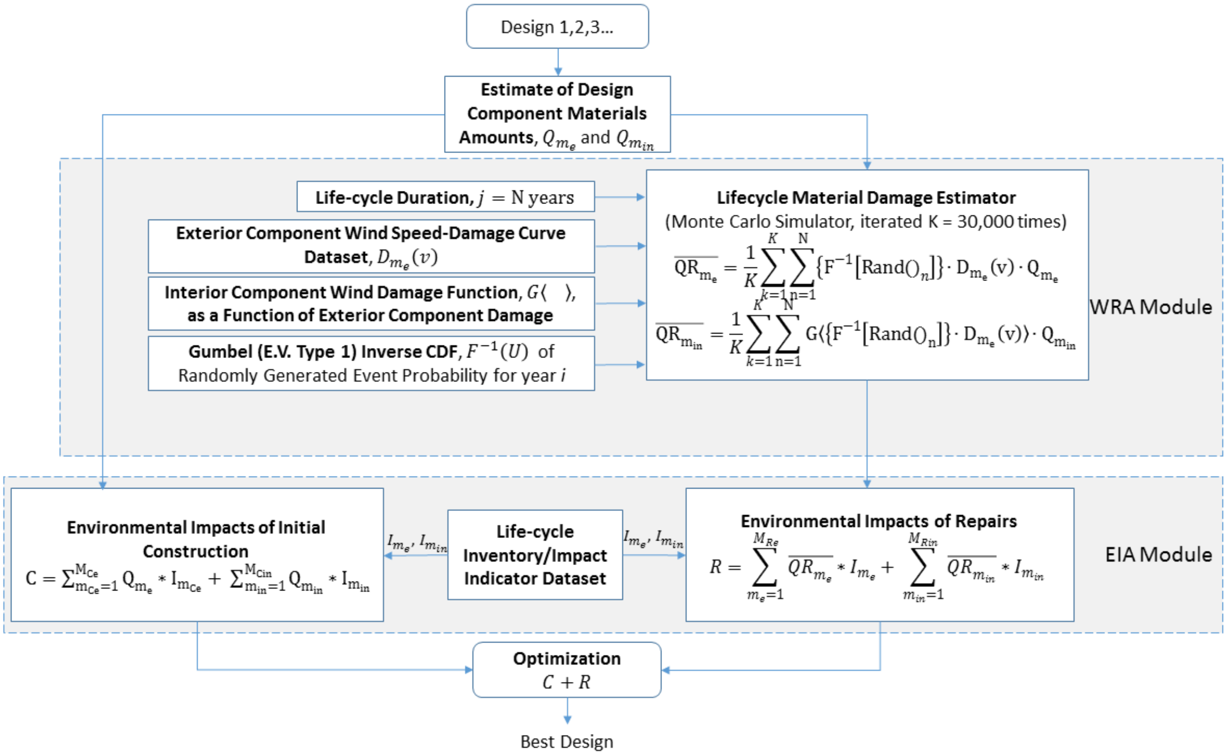


Figure 5-1: IRSA-W Model Framework

Within the WRA module, the wind performance of the building is assessed using the Lifecycle Material Damage Estimator. The estimator simulates annual wind events over the building's life, N, for K iterations and then calculate the expected mean repair for exterior and interior materials. The main input parameters for the estimator include site and design specific parameters. Site specific parameters include the probability of extreme wind events and design specific parameters including exterior building component wind-damage curves that provide a measure of damage over a range of wind speeds and interior building component wind-damage curves which relate interior component damage to exterior component damage.

For the EIA Module, the environmental impact is measured by calculating the embodied energy, CO_2 footprint, and water consumption of the initial construction and repairs to life-cycle damage using a life-cycle inventory database. Both the WRA and EIA modules depend on a quantity estimate of the materials for all building design components. The output of the optimization model is the summation of environment impacts associated with the initial construction and repairs for the design in question.

5.2.2 Wind Resilience Assessment Module (WRA)

The WRA module determines damage due the failure of materials through a process of convolving a set of probable wind speeds and the damage associated with those wind speeds (Equation 5-1),

$$\mathrm{E(D)} = \int_0^\infty \mathrm{D(v)} \cdot \mathrm{p_f(v)} \cdot \mathrm{dv} \qquad \text{Equation 5-1}$$

where, $\mathrm{E(D)}$ is the expected damage, $\mathrm{D(v)}$ is the relationship between wind speed and damage and $\mathrm{p_f(v)}$ is the probability density function (PDF) for wind speed. The convolution method has been used to determine component failure probabilities in reliability-type studies of residential buildings for wind hazards, where inherent uncertainties in the hazard occurrence and performance of structural components to hazard loading are considered (e.g. Li & Ellingwood, 2006). It has also been utilized in benefit-cost analysis to compare the cost of wind damage-mitigation alternatives (e.g. Amoroso, 2009).

$\mathrm{D(v)}$ is defined by wind speed-damage curves. FEMA's Hazus® Hurricane model (FEMA, 2012) and the Florida Public Hurricane Loss Model (FPHLM) (Zhang, 2003; Cope, 2004; Murphree, 2004; Hamid et al, 2010; Pinelli et al., 2011; Hamid et al., 2011) are two examples of models that incorporate wind speed-damage curves to estimate damage due to wind hazard. Component-level wind-damage functions were needed so that individual material damage could be converted to environmental impacts in the EIA module. FPHLM functions were used within the model as a component-level approach is needed to calculate material damage (Cope, 2004). Hazus® does provide a methodology for determining sub-assembly damage; however, the breakdown is not sufficient enough to determine component level damage.

A portion of the curves that have been used in prior versions of the FPHLM are provided in literature, which show the mean expected wind damage curves for four types of residential buildings: concrete block gable and hip roof (CBG and CGH) and wood frame gable and hip roof buildings (WG and WH). The curves show the mean damage to key exterior structural components for wind speeds ranging from 50 to 250 mph for southern Florida (Cope, 2004). Murphree (2004) provides some interior damage ratios based on the percentage of the damage to six exterior structural components. Interior damage is attributed to the intrusion of water and wind into the building due to the damage to exterior structural components (Murphree, 2004).

Table 5-1 shows the coverage of exterior components for each structure. Some general building configuration assumptions were made in the development of these curves which are listed in Table 5-2. Other building assumptions not listed in Table 5-2 include the square footage of each modeled building type; placement of openings (i.e. windows and doors); and the mean, distribution and COV's of the wind resistance capacities of the exterior structural components shown in Table 5-1 (Zhang, 2003; Cope, 2004).

Table 5-1: FLPM Component Wind Damage Curve Coverage

		Concrete Block, Gable (CBG)	Concrete Block, Hip (CBH)	Wood, Gable (WG)	Wood, Hip (WH)
Exterior Structural Components	walls	X	X	X	X
	windows	X	X	X	X
	exterior doors	X	X	X	X
	garage door	X	X	X	X
	gable end	X		X	
	roof sheathing	X	X	X	X
	connections	X	X	X	X
	roof cover	X	X	X	X

Table 5-2: Building Configuration Assumptions

General Building Configuration Assumptions (Gurley, et al., 2005b)
Floor to ceiling height is 10 feet.
Building shape is rectangular and consists of only one story.
There are 15 windows, two exterior doors and one double garage door.
Truss spacing of 2 feet on center.
There is no basement.
Roof eave overhang is 2 feet.
Only basic simple roof shapes are considered (hip or gable) with no dormers, cupolas or other structures extending off the main roof.
Roof slope is 5" on 12" ≈ 23º

Since some of the structural components include multiple material components (e.g. wall, gable end), these components were broken down further so that individual material damage could be captured by the WRA module. Table 5-3 shows the expanded component list. The specific FPHLM exterior component damage curves utilized in the WRA module for analyzing the case-study building were provided by the authors of the FPHLM model (Gurley & Pinelli, 2015). To use the exterior component damage curves in the WRA model, polynomial trendlines were fit to the curve dataset provided from the FPHLM model so that the damage could be calculated for every sampled wind speed within the life-cycle material damage estimator.

The interior damage relationships published in Murphree (2004) were also used to estimate interior component damage. The interior damage associated with all exterior structural components were determined based on these relationships; however, to avoid double counting and overestimation of interior damage only the largest set of interior damage per exterior component was utilized in calculating the environmental impacts of life-cycle repairs to the structure. For example, if loss of roof sheathing resulted in the greatest life-cycle damage to interior walls in comparison to other exterior components, the interior damage associated with this component sheathing was included in the estimation of life-cycle repairs to interior walls. While failure of multiple exterior components impacts interior damage, including all interior damage relating to failures of all exterior component could yield more than 100% damage to interior materials for any one event.

Table 5-3: FLPM Components Expanded

		CBG	CBH	WG	WH
Structural Components	wall				
	exterior sheathing			X	X
	exterior finish	X	X	X	X
	exterior wall framing			X	X
	windows	X	X	X	X
	exterior doors	X	X	X	X
	gable end				
	exterior sheathing			X	
	exterior finish	X		X	
	exterior wall framing			X	
	exterior CMU wall	X			
	roof sheathing	X	X	X	X
	connections	X	X	X	X
	roof covering	X	X	X	X

While considering interior damage relating to one exterior component could also result in an underestimation of interior damage, it was decided that underestimating was preferable to overestimating environmental impacts. Also, for one exterior component, roof covering, it was assumed that for every event instance where greater than 10% damage occurred, the whole roof would be replaced rather than just a portion of the roof. This assumption was based on the assumption that color matching might be difficult when replacing only a portion of the roof. It has also been found that shingle roofs that experience 10% hail damage required more than 40% of the roof covering materials to be replaced and when over 12% damage occurs it is unfeasible to replace only the damaged portions, which can amount to more than 50% replacement (East et al., 2014).

The probability density function (PDF), $p_f(v)$, used to sample wind speeds in the life-cycle material damage estimator, is assumed to follow an Extreme Value Type 1 (Gumbel) distribution, which is commonly used to model annual extreme wind events (Palutikof et al., 1999). The inverse cumulative distribution function for the Gumbel distribution is show in Equation 5-2.

$\mathrm{F}^{-1}(\mathrm{U}) = \mathrm{u} + \mathrm{a}\{-\log_{\mathrm{e}}[-\log_{\mathrm{e}}(\mathrm{F}(\mathrm{U}))]\}$ Equation 5-2

where, $\mathrm{F}^{-1}(\mathrm{U})$ is the inverse cumulative distribution function for the Gumbel distribution (Extreme Value Type 1), $\mathrm{F}(\mathrm{U})$ is the cumulative distribution function for the Gumbel distribution (Extreme Value Type 1), u is the location parameter, and a is the scale factor.

In order to utilize the inverse CDF for Monte Carlo simulations, u and a must first be derived for the specific case study site being consider. The return period, R, is defined as the inverse of the probability of exceedance [1-F(U)], Equation 5-3. The inverse cumulative distribution function, $\mathrm{F}^{-1}(\mathrm{U})$, can be written in terms of the return period, R, for the annual extreme wind speed depth using Equation 5-4.

$\mathrm{R} = \frac{1}{\text{Probility of exceedance}} = \frac{1}{1-\mathrm{F}(\mathrm{U})}$ Equation 5-3

The inverse cumulative distribution function becomes:

$\mathrm{F}^{-1}(\mathrm{U}) = \mathrm{y} = \mathrm{u} + \mathrm{a}\left\{-\log_{\mathrm{e}}\left[-\log_{\mathrm{e}}\left(1 - \frac{1}{\mathrm{R}}\right)\right]\right\}$ Equation 5-4

And for large values of R, Equation 5-4 simplifies to a logarithmic (Equation 5-5),

$y = u + alog_e(R)$ Equation 5-5

where scale factor, a, and location parameter, u, are derived by fitting a logarithmic trendline to a set of given extreme wind speeds for the site and correspond to the slope and y-intercept, respectively. The wind speeds corresponding to the 10, 25, 50, 100, 300, 700, and 1700 year return periods can be found according to geographical location on the Applied Technology Council website (ATC, 2015). The slope and intercept of the logarithmic trend line correspond to *a* and *u*, respectively. Figure 5-2 shows the logarithmic trend line for the case study in Saint Petersburg, Florida presented in Section 5.3.

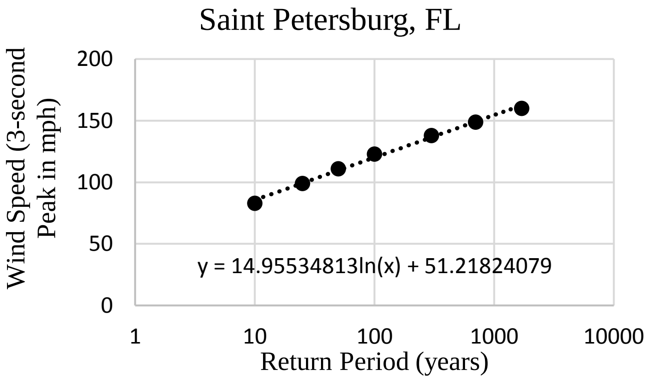


Figure 5-2: Logarithmic Trend Line for Case Study Location

Damage analysis in the WRA module is carried out at the component level (e.g. roof cover, floor finishes, insulation) over the life of the building using Equations 5-6 and 5-7,

$$\overline{QR_{m_e}} = \frac{1}{K}\sum_{k=1}^{K}\sum_{n=1}^{N}\{F^{-1}[Rand()_n]\}\cdot D_{m_e}(v)\cdot Q_{m_e} \qquad \text{Equation 5-6}$$

where, $\overline{QR_{m_e}}$ is the average of K iterations of cumulative damage for exterior component, m_e, over building life, N, $F^{-1}[\quad]$ is the inverse cumulative Gumbel distribution, $Rand()_n$ is a uniformly distributed random variable between 0 and 1 for each year n, $D_{m_e}(v)$ is functional relationship between percent damage to exterior component m_e and wind speed (i.e. wind-damage curves), and Q_{m_e} is the total material quantity for exterior component m_e.

$$\overline{QR_{m_{in}}} = \frac{1}{K}\sum_{k=1}^{K}\sum_{n=1}^{N} G\langle\{F^{-1}[Rand()_n]\}\cdot D_{m_e}(v)\rangle\cdot Q_{m_{in}} \qquad \text{Equation 5-7}$$

Where, $\overline{QR_{m_{in}}}$ is the average of K iterations of cumulative damage for interior component m_{in} over building life, N, $G\langle\quad\rangle$ is the percent interior component damage as a function of the percentage of exterior component damage and $Q_{m_{in}}$ is the total material quantity for interior component m_{in}.

The damage analysis defined by Equations 5-6 and 5-7 is carried out using Monte Carlo simulation. The annual extreme wind speeds for each year are sampled using the Gumbel distribution and the exterior and interior component damage associated with each event is determined by the wind-damage curves. The cumulative wind damage over the building's life is then calculated by aggregating the yearly damage from n=1 to N. The process is iterated K times, where K = 30,000, and the expected cumulative exterior damage, $\overline{QR_{m_e}}$, and interior damage, $\overline{QR_{m_{in}}}$, are calculated by averaging cumulative damage from K = 1 to 30,000. Alternatively, since expected damage for each year of the buildings life is the same, it is also possible to average damage for year one (n=1) from K=1 to 30,000 and then multiple the annual expected damage by the building life, N, in years.

The number of iterations was selected based on the number of iterations at which point the annual expected percent damage converges. Figure 5-3 shows three sample simulation results for expected annual percent damage to roof sheathing for one to 30,000 iterations for the Saint Petersburg case study presents in Section 5.3. Around 30,000 iterations the annual expected damage begins to converge. Based on this assessment the number of iterations was selected to be 30,000.

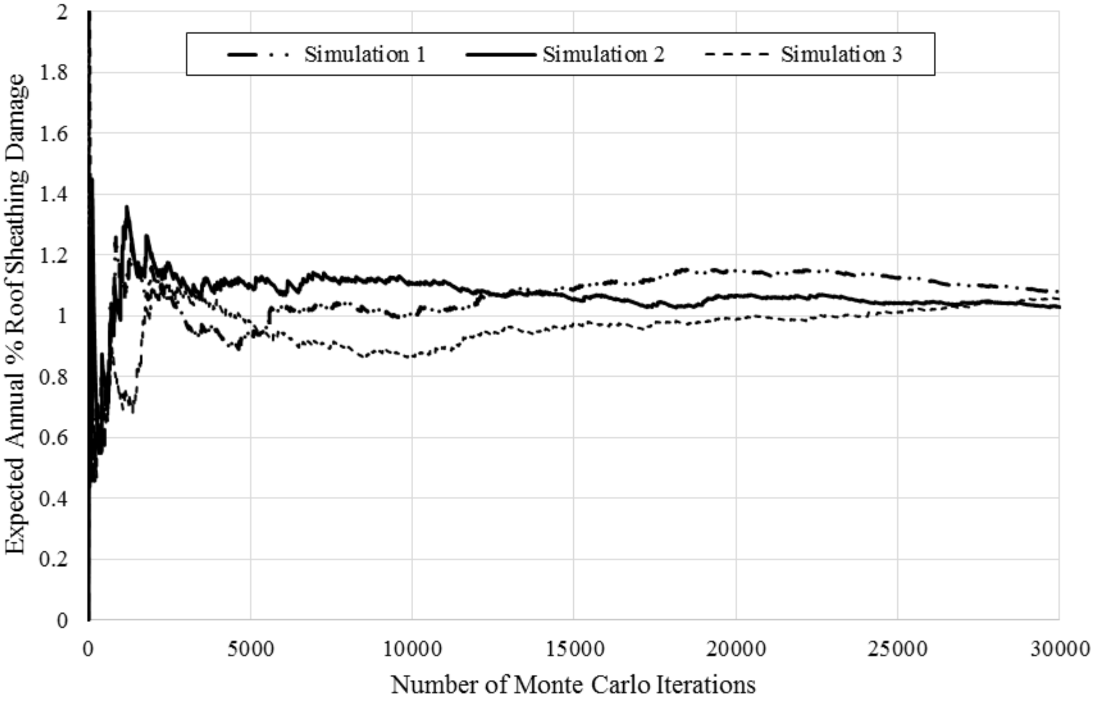


Figure 5-3: Convergence of Monte Carlo of Expected Annual % Damage to Roof Sheathing

5.2.3 Environmental Impact Assessment (EIA) Module

The EIA module includes calculates the environmental impacts of initial construction plus life-cycle repairs. For this module, environmental impacts include those associated with extraction, manufacturing, and transportation of materials to the building site. Where impact data were available for the construction and installation of building materials, these were also included. Removal of damaged materials was not considered in this model. The two main data components in the EIA module include (1) calculating the impacts of initial construction and (2) calculating the impacts of wind damage repairs.

For initial construction, the environmental impact is calculated with Equation 5-8:

$$\mathrm{C} = \sum_{\mathrm{m_e}=1}^{\mathrm{M_{Ce}}} \mathrm{Q_{m_e}} * \mathrm{I_{m_e}} + \sum_{\mathrm{m_{in}}=1}^{\mathrm{M_{Cin}}} \mathrm{Q_{m_{in}}} * \mathrm{I_{m_{in}}} \qquad \text{Equation 5-8}$$

Where, C is the cumulative environmental impact (Embodied Energy, CO_2 Footprint or Water Consumption) for all exterior materials used in the initial construction, M_{Ce} and interior materials used in the initial construction, M_{Cin}, $\mathrm{Q_{m_e}}$ and $\mathrm{Q_{m_{in}}}$ are the quantity of exterior material, m_e, and interior material m_{in}, respectively, and $\mathrm{I_{m_e}}$ and $\mathrm{I_{m_{in}}}$ are the environmental impact per unit of exterior and interior materials, respectively.

The environmental impact of repairs to life-cycle damage are essentially calculated the same as initial construction; however, the focus is on the replacement of damaged materials rather than the building as a whole. In this model, the material damage output of the Material Damage Estimator for each component in the WRA module is averaged and used to calculate the impact of repairs. Equation 5-9 is used to calculate the environmental impact of repairs,

$$\mathrm{R} = \sum_{\mathrm{m_e}=1}^{\mathrm{M_{Re}}} \overline{\mathrm{QR}_{\mathrm{m_e}}} * \mathrm{I}_{\mathrm{m_e}} + \sum_{\mathrm{m_{in}}=1}^{\mathrm{M_{Rin}}} \overline{\mathrm{QR}_{\mathrm{m_{in}}}} * \mathrm{I}_{\mathrm{m_{in}}} \qquad \text{Equation 5-9}$$

where, R is the cumulative environmental impact (Embodied Energy, $\mathrm{CO_2}$ Footprint and Water Consumption) for all exterior material repairs, $\mathrm{M_{Re}}$, and all interior material repairs, $\mathrm{M_{Rin}}$, over the building life, $\overline{\mathrm{QR}_{\mathrm{m_e}}}$ and $\mathrm{I}_{\mathrm{m_e}}$ are the expected cumulative repair quantity and environmental impact for exterior material component, $\mathrm{m_e}$, respectively, and $\overline{\mathrm{QR}_{\mathrm{m_{in}}}}$ and $\mathrm{I}_{\mathrm{m_{in}}}$ are the expected cumulative repair quantity and environmental impact for interior material component, respectively.

The life cycle inventory (LCI) dataset, which provides the environmental impact per unit of material, is a significant part of the EIA module. The impacts output by the EIA module are very sensitive to the inventory data utilized, especially for materials that have higher environmental impact in proportion to the rest of the materials in the structure. While LCI data can vary over time and from one location to another, uncertainty in LCI data was outside the scope of the study and was not considered in the proposed model. Effort was taken, however, to utilize LCI data from the United States, where data were available. Two main sources were utilized for LCI inventory data, (1) National Institute of Standards and Technology (NIST)'s online tool BEES (NIST, 2015) and (2) Ashby (2009). A full list of sources for LCI data are shown in Table E-1 in the Appendix E.

5.2.4 Estimation of Material Component Quantities

Similar to flood model in Chapter 4, the estimate of all materials used to initially construct the building was needed for each design being considered as initial input for both the WRA and EIA modules. The estimate includes (1) determining the list of materials associated with all components of interest for the designs being analyzed and (2) estimating the quantity of the materials for all components in the design being assessed.

Ideally, a list of materials associated with all possible building components needs to be developed, and effort was made to include as many materials as possible; however, for some components, it was difficult to pinpoint every material quantity. For example, the quantity of materials for the majority of the built-in appliances was not readily available so only the materials that constituted a large proposition of the components by weight were included and these quantities were assumed based on quantities presented in literature. Once a list of materials is compiled, the quantity of materials is calculated. There are multiple units by which a material can be quantified (e.g. weight, area, length or volume). While there is no distinct measure for quantifying materials, the life-cycle inventory data collected for the EIA module will have a specific set of units that may require conversion depending on how the material quantities are defined.

5.3 Case Study

5.3.1 Case Study Location and Design Model

To provide a demonstration of the ISRA-W model, a case study is presented. The case study location in Saint Petersburg, Florida is at the same site location as the case study in Chapter 4. The building model being assessed is a one-story, slab-on-grade, hipped roof SFR structure with same layout as case study house in Chapter 3 and 4. Effort was made to model the building layout and configuration to represent typical residential construction in coastal, southeastern United States.

Two designs for the SFR building are proposed for assessment within the ISRA-W model. The first (Design 1) represents weak wind- and water-resistant construction materials and installations, while the second (Design 2) uses more wind- and water-resistant materials and installations (Table 5-4). Design 1 utilizes typical interior construction materials that are not water resistant and does not have strong connections between the roof and walls. Design features strong hurricane strap-type connections between the roof and wall, and water-resistant interior materials which would resistant damage from wind-driven rain. The water-resistant interior materials include paperless gypsum wallboard on interior walls, closed-cell spray foam insulation throughout the house and all ceramic flooring. These materials are classified as flood resistant materials recommended in FEMA (2008) for wet flood proofing.

Table 5-4: Case Study Design Comparison

Design 1 – Weak Wind/Rain-Resistant	Design 2 – Wind/Rain-Resistant
Paper-faced gypsum wallboard on interior walls	Non-paper-faced gypsum wallboard on interior walls
Fiberglass batt insulation	Closed-cell spray foam insulation
Standard wood-frame wall system with no strap roof-wall-connections	Standard wood-frame wall system with strap roof-to-wall connections
Flooring types: wood, ceramic & carpet	All ceramic flooring

5.3.2 Bill of Materials and LCI Inventory

The bill of materials which include all material quantities for the components in Design 1 and Design 2 are shown in Table 5-5. Where the quantities were the same for both designs the value is only shown once in the table. The LCI data utilized in the model were pulled from the LCI data table (Table E-1) in Appendix E. Impacts due to transportation of materials to the building site were also specific to the case study location.

Table 5-5: Case Study Bill of Materials

	Design Components	Units	Quantity Design 1	Quantity Design 2
Site	AC Condensing Unit	Each	1	
Structure	Slab	Sq. Ft.	1736	
	Stud Framing	Pounds	17030	
	Wall to Roof Straps	Each	0	177
Roof Covering	Roof Membrane & Cover	Sq. Ft.	3142	
	Fascia	Sq. Ft.	115	
	Soffits	Sq. Ft.	574	
	Roof Sheathing	Sq. Ft.	3142	
Exterior Walls	Wall Sheathing/Covering	Sq. Ft.	1579	
	Windows	Sq. Ft.	133	
	Exterior Doors	Sq. Ft.	153	
	Insulation - Walls	Sq. Ft.	1579	
	Insulation - Ceiling	Sq. Ft.	2056	
Interiors	Cabinets - Upper	L. Ft.	24	
	Cabinets - Lower	L. Ft.	23.5	
	Countertops	Sq. Ft.	98	
	Wood Flooring	Sq. Ft.	530	0
	Carpet	Sq. Ft.	541	0
	Ceramic Flooring	Sq. Ft.	386	1457
	Interior Sheathing - Walls	Sq. Ft.	3916	
	Interior Sheathing - Ceiling	Sq. Ft.	2056	
	Paint/Wall Coverings	Sq. Ft.	4426	
	Base Molding	Sq. Ft.	142	
	Interior Doors	Sq. Ft.	117	
	Hot Water Heater	Each	1	
	Dishwasher	Each	1	
	Clothes Washer	Each	1	
	Clothes Dryer	Each	1	
	Electrical Outlets	Each	24	
	Electrical Switches	Each	19	
	Furnace	Each	1	
	Fan Coil Unit	Each	1	
	Ductwork	Per Story	1	

5.3.3 Environmental Impact Initial Construction

The environmental impact of initial construction output by the ISRA-W model for Design 1 and Design 2 is shown in in Table 5-6. The environmental impacts are embodied energy (EE), carbon footprint (CO_2) and water consumption. The units of measure for the environmental impacts are mega joules, kilograms CO_2 equivalent and cubic meters for EE, CO2 and water, respectively.

Design 2 has a slightly higher embodied energy (+4.68%), however the increase is not significant. There is also a small decrease in carbon footprint (-0.68%) and water consumption (-9.67%) when comparing Design 2 to Design 1. Since the differences for all three impact categories are not large, it is assumed that there is little difference in the environment impact of initial construction when comparing Design 1 to Design 2.

Table 5-6: Environmental Impacts of Initial Construction

Design Components	Design 1			Design 2		
	EE (MJ)	CO_2 (kg CO_2 Eq.)	Water (M^3)	EE	CO_2	Water
AC Condensing Unit	10134.1	687.7	16.0	10134.1	687.7	16.0
Slab	96680.2	6955.9	10.2	96680.2	6955.9	10.2
Stud Framing	77197.2	12600.3	5310.6	77197.2	12600.3	5310.6
Wall to Roof Straps	0	0	0	282.6	22.1	0.4
Roof Membrane & Cover	230682.6	4515.3	17.6	230682.6	4515.3	17.6
Fascia	1029.6	63.0	73.0	922.7	55.4	73.0
Soffits	1797.5	110.9	121.1	1531.3	91.9	121.1
Roof Sheathing	57200.3	1281.3	0.8	57200.3	1281.3	0.8
Exterior Wall Sheathing	28751.8	644.0	0.4	28751.8	644.0	0.4
Exterior Siding	69390.4	335.1	12.7	69390.4	335.1	12.7
Windows	9640.7	482.7	4.6	9640.7	482.7	4.6
Exterior Doors	1748.7	120.1	2.3	1748.7	120.1	2.3
Insulation - Walls	3645.2	152.7	0.0	12354.1	442.4	66.9
Insulation - Ceiling	5311.4	382.6	0.0	32171.0	1152.2	174.2
Cabinets - Upper	1723.3	213.3	230.6	1723.3	213.3	230.6
Cabinets - Lower	2486.6	307.7	332.8	2486.6	307.7	332.8
Countertops	3709.1	118.4	2.2	3709.1	118.4	2.2
Wood Flooring	6846.2	408.5	815.6	0.0	0.0	0.0
Carpet	76525.0	3211.0	235.4	0.0	0.0	0.0
Ceramic Flooring	15282.6	1088.8	2.3	57743.4	4113.8	8.6
Interior Sheathing - Walls	142615.3	8266.6	4.4	175880.4	7724.0	4.4
Interior Sheathing - Ceiling	74887.8	4340.8	2.3	92355.4	4055.9	2.3
Paint/Wall Coverings	22025.0	983.9	5.4	22025.0	983.9	5.4
Base Molding	1715.9	102.2	203.8	1715.9	102.2	203.8
Interior Doors	2455.5	72.3	0.2	2455.5	72.3	0.2
Hot Water Heater	1601.4	125.5	4.2	1601.4	125.5	4.2
Dishwasher	5599.0	264.5	291.8	5599.0	264.5	291.8
Clothes Washer	6040.0	360.4	293.4	6040.0	360.4	293.4
Clothes Dryer	5279.4	317.8	291.9	5279.4	317.8	291.9
Electrical Outlets	55.0	3.0	0.1	55.0	3.0	0.1
Electrical Switches	124.3	6.7	0.3	124.3	6.7	0.3
Furnace	4049.5	295.6	7.0	4049.5	295.6	7.0
Fan Coil Unit	3131.1	243.4	4.4	3131.1	243.4	4.4
Ductwork	6073.9	441.2	6.7	6073.9	441.2	6.7
Total	975435.5	49503.2	8304.2	1021108.9	49162.5	7500.9
% Increase				4.68	-0.68	-9.67

5.3.4 Environmental Impact Initial Construction and Repairs

The annual expected percent repairs to exterior and interior components, which are used to calculate environmental impacts over the life of the building are shown Tables 5-7 and 5-8, respectively. These annual expected percent repairs are output by the simulation process in the WRA module. Comparing Design 1 and 2, except for connections and walls, the annual expected percent repairs to the exterior components are the same. The largest annual expected percent repairs to the interior components for Design 1 are primarily associated with damage to roof sheathing, except for paint which results from damage to exterior doors. For Design 2, since it was assumed that water resistant materials were used for flooring, ceiling, interior walls and insulation, the only components to result in repairs are the kitchen, paint and interior doors which have the same percent values as Design 1.

Table 5-7: Expected Annual Repairs to Exterior Components

Repairs to Exterior Components (%)											
Design 1						Design 2					
Roof Sheathing	Roof Cover	Windows	Exterior Doors	Connections	Walls	Roof Sheathing	Roof Cover	Windows	Exterior Doors	Connections	Walls
1.05	2.56	0.26	0.89	0.28	0.07	1.05	2.56	0.26	0.89	0.002	0.002

Table 5-8: Expected Annual Repairs to Interior Components

Repairs to Interior Components (%)								
	Exterior Component	Kitchen	Flooring	Interior walls	Ceiling	Paint	Interior Doors	Insulation
Design 1	Roof Sheathing	0.68	2.33	0.80	1.71	1.21	1.13	2.84
	Roof Cover	0.10	0.42	0.30	0.48	0.54	0.12	0.37
	Windows	0.13	1.33	0.47	0.07	0.47	0.75	0.05
	Exterior Doors	0.01	0.63	0.18	0	1.73	0.28	0
	Walls	0.14	0.20	0.14	0.20	0.26	0.20	0.14
Design 2	Roof Sheathing	0.68	0	0	0	1.21	1.13	0
	Roof Cover	0.10	0	0	0	0.54	0.12	0
	Windows	0.13	0	0	0	0.47	0.75	0
	Exterior Doors	0.01	0	0	0	1.73	0.28	0
	Walls	0.004	0	0	0	0.01	0.01	0

When repairs over the life of the building are added to initial construction (C+R), the environment impact differences between Design 1 and Design 2 are larger and generally increase as the building life increases. Figures 5-4, 5-5 and 5-6 show the combined C+R embodied energy, carbon footprint, and water consumption, respectively, over a range of building lives. Figure 5-7 shows the percent increase in the combined C+R impacts when comparing the traditional design to the wind-resistant design for selected building lives.

Overall, carbon footprint and water consumption show the greatest difference of all three impact factors. While a difference is reported in the model for embodied energy, the increase in embodied energy from Design 1 to Design 2 is negative at a building life of 5 years, almost zero at 10 years and smaller than the other two impact factors for a building life of 15 years or greater. At a life span of 5 years, the embodied energy, carbon footprint and water consumption are almost -2%, 3.2% and 12.3% higher, respectively, when comparing Design 1 to Design 2. For a typical 30 year mortgage the difference is even greater, with an 8.0%, 14.4% and 19.7% increase in embodied energy, carbon footprint and water consumption, respectively. By the time the building life reaches 100 years, the embodied energy, carbon footprint and water consumption for Design 1 is 1.25, 1.39 and 1.38 times higher than Design 2, respectively. These results are similar to other studies where increases in environmental impact due to hazard-related repairs were observed over time for non-SFR structures (e.g. Arroyo, et al., 2014; Dong, et al., 2013).

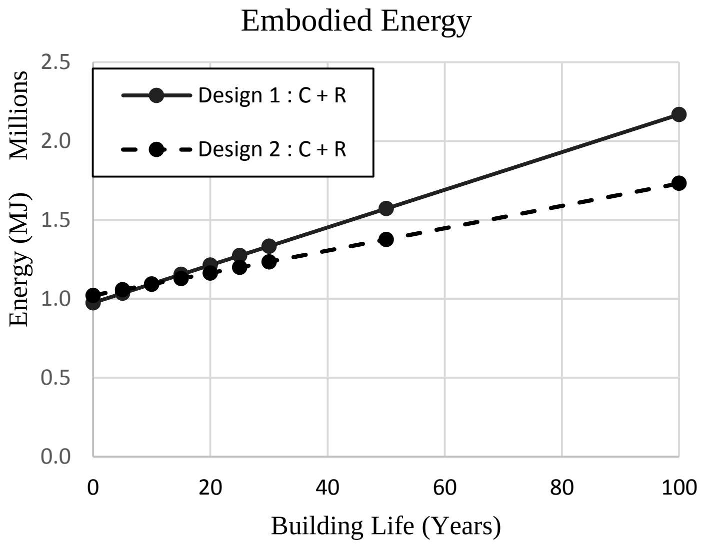


Figure 5-4: Design 1 versus Design 2 Embodied Energy (C+R)

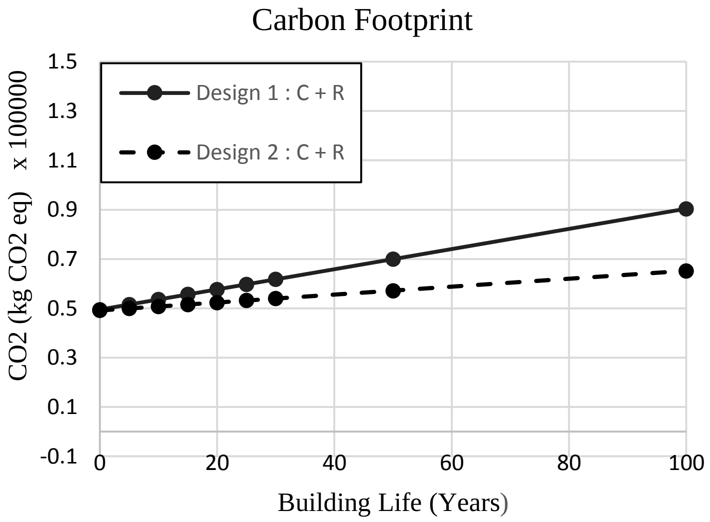


Figure 5-5: Design 1 versus Design 2 Carbon Footprint (C+R)

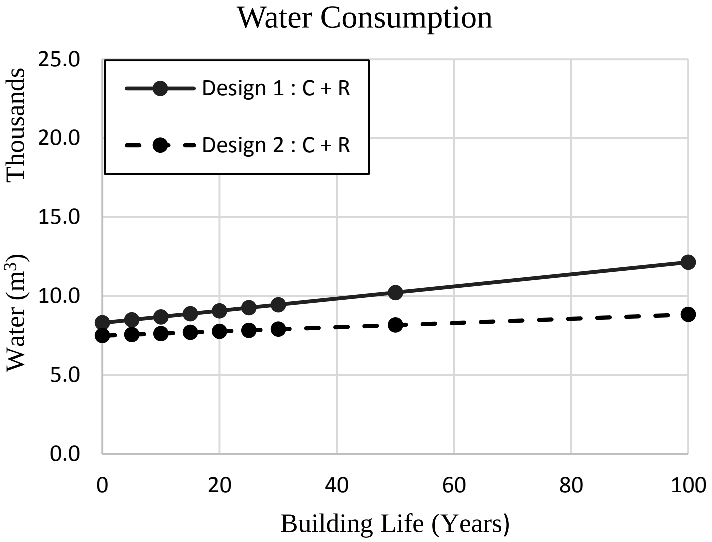


Figure 5-6: Design 1 versus Design 2 Water Consumption (C+R)

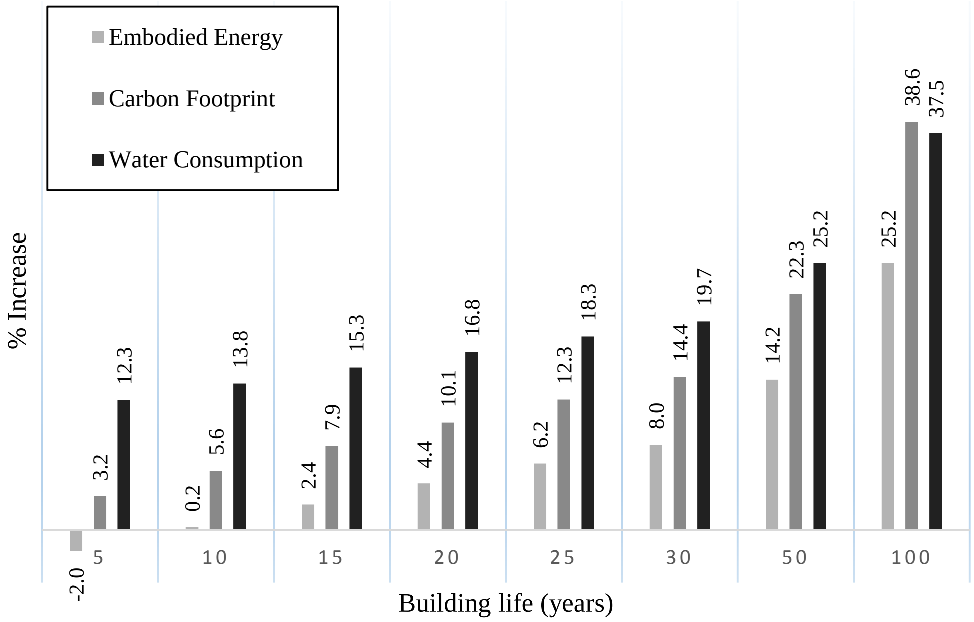


Figure 5-7: Design 1 Percent Increase Over Design 2 (C+R)

5.3.5 Optimization of Design

When comparing between Design 1 and 2, the model indicates that the more wind- and rain-resistant design does not differ from Design 1 when analyzing initial construction, however, the sustainable performance of Design 2 is better when hazard-related repairs over the life of the building are considered. If sustainability is an important design factor, the ISRA-F model indicates that Design 2 would be better choice. To determine which individual component design choices have the greatest impact on the results of the model, a sensitivity analysis was conducted on individual design choices. The results of the sensitivity analysis are shown in Table 5-9 for a building life of 50 years.

Table 5-9: Sensitivity Analysis Results for 50 year building life

Design Alternatives								% Increase C+R (50yr)		
PF	NPF	F	CL	S	NS	FM	FC	EE	CO2	Water
X*		X		X		X		0	0	0
	X	X		X		X		4.96	12.86	-0.65
X			X	X		X		-1.54	-0.65	0.16
X		X			X	X		0.16	-0.001	-0.03
X		X		X			X	9.73	7.28	27.87

PF = Paper-faced gypsum
NPF = Non-paper-faced gypsum
F = Fiberglass Batt Insulation
CL = Closed-cell Foam Insulation
S = Roof to wall straps
NS = No roof to wall straps
FM = Flooring Mixed
FC = Flooring Ceramic

* X indicates the design option chosen.

According to the results of the sensitivity analyses, two design choices have the greatest impact on the results: (1) mixed flooring versus ceramic flooring only and (2) paper-faced versus non-paper-faced gypsum wall board. In the case of flooring, choosing the traditional design options results in a higher embodied energy, carbon footprint and water consumption than the more rain-resistant materials (i.e. ceramic flooring). When choosing paper-faced over non-paper-faced gypsum board, Design 1 yields a higher embodied energy and carbon footprint than design two. When optimizing the design for the Saint Petersburg SFR building, choosing ceramic flooring and non-paper-faced gypsum wallboard would be the best options for reducing environmental impact over the life of the structure, however it should be noted that water-resistant insulation should also be used in combination with the non-paper-faced gypsum board since the wallboard would have to be damaged to remove and replace the fiberglass bat insulation.

5.4 Summary

Methodologies that analyze intersections between wind resilience and sustainability over a building's lifecycle are important to consider within the context of performance-based design of wind damage-prone buildings. While both hazard-resistant and sustainable design have benefits independently, some design strategies can conflict, which in the case of wind damage-prone, single-family residential building structures can lead to more damage and higher life-cycle impacts if materials utilized are less resistant wind-related hazards. Chapter 5 presented a wind resilience and environmental impact material optimization model for coastal, single-family, residential (SFR) building designs. The model incorporates (1) a probabilistic procedure for determining wind-related repairs during the useful life of the building (2) a life cycle assessment-based method for measuring the environmental impact of the building, including its initial construction and wind damage related repairs.

To demonstrate the capability of the model for optimizing wind performance-based designs for environmental impact, the methodology was applied to an example case study, which compared two design alternatives for a one-story home in Saint Petersburg, Florida. Design 1 utilized traditional construction materials which are less resistant wind-related hazards (i.e. extreme wind and wind-driven rain) and require replacement when damaged. Design 2 used wind-resistant roof-to-wall connections and water resistant materials utilized in wet flood proofing techniques. It was found that there was little difference in environmental impacts with the initial construction when comparing Design 1 and 2; however, the environmental impacts of Design 2 are less when hazard-related repairs over the life of the building are considered. For a 30 year building life, the weaker design has 1.08, 1.14 and1.2 times the embodied energy, carbon footprint and water consumption of initial construction and wind-related repairs combined compared to the more hazard-resistant design, respectively. The difference is greater at a 100 year building life where the embodied energy, carbon footprint and water consumption for Design 1 is 1.25, 1.39 and 1.38 times higher, respectively, than Design 2. The results of the case study demonstrate how the model provides the basis for a tool with which design professionals can weigh the performance of residential structure designs subject to wind hazards against environmental impacts (i.e., energy consumption, carbon dioxide footprint and water consumption) within coastal areas.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction

The overarching goal of this dissertation was to integrate the concepts of sustainability and resiliency to improve the design and construction of single-family residential (SFR) structures so that these buildings are environmentally friendly and resistant to wind and flood hazards. In order to achieve the aims of the main goal, four specific objectives are identified. Four primary objectives were completed to accomplish this goal:

1) Examine existing sustainability and resiliency tools related to structural design in order to summarize and analyze the current state-of-the-art in sustainability and resiliency design assessment tools, and identify opportunities for the integration of sustainability and resiliency assessment methodologies within coastal residential construction design practice
2) Develop a set of component-based flood depth-damage curves for single-family residential structures to support Objective 3.
3) Develop an integrated sustainability and resiliency design assessment model for flood hazard, with the objective of maximizing performance of residential structures subject to flood loading, but also minimizing environmental impacts of flood-resistant SFR construction through reductions in energy consumption and carbon emissions for key phases of the structure’s life-cycle.
4) Develop an integrated sustainability and resiliency design assessment model for wind hazard, with the objective of maximizing performance of residential structures subject to high wind loading, but also minimizing environmental impacts of wind-resistant SFR construction through reductions in energy consumption and carbon emissions for key phases of the structure’s life-cycle.

Chapters 2 through 5 described the work accomplished to achieve these objectives and summaries of the work and findings for each of the objectives were presented at the end of each chapter. Chapter 6 discusses conclusions of the four objectives and explains how these objective serve to integrate the concepts of sustainability and resiliency as they relate to the design and construction of single-family residential (SFR) structures and support the development of SFR buildings that are environmentally friendly and resistant to wind and flood hazards.

6.2 Critical Resilience Analysis of Sustainability Assessment Frameworks (SAFs)

The aim of Chapter 2 was to compare SAFs to determine the extent to which they integrate resilient design strategies and whether weaknesses in resilience coverage exist that have the potential to lead to the design of structures and communities that are vulnerable to the impacts of extreme events. Current state-of-the-art in sustainability and resiliency tools relating to structural design and construction were investigated. Studying existing tools allowed for a comparison of the most influential tools to date in order to best understand current methodology and identify gaps where improvement in design assessment can be made. Comparison of these tools also helped to provide a basis for identifying opportunities for integrating sustainable and resilient development concepts into a single assessment methodology for structures subject to wind and flood hazards. Through a multi-level comparison analysis of eleven SAFs, the following conclusions have been derived:

- Although SAFs do incorporate resilience-related measures, resilience is not strongly or systematically integrated throughout SAFs. Envision™ has the best overall coverage of resilience with 17.9% of measures addressing resilience, 13 of 15 identified hazards addressed, and all six flood measures incorporated in its framework. Other tools are much weaker, especially LEED® for Homes and LEED® NC, with less than 5% resilience measures, only one hazard included (flooding) and only two flood measures included in each framework.
- Of the SAFs studied, the coverage of hazards is limited, with 8 of 11 frameworks including design measures for three or fewer hazards. Flooding is the most incorporated hazard (included in all 11 SAFs) and fire, earthquakes and surge are the next most often included hazards (incorporated in five, four and four of the eleven SAFs, respectively). The ten remaining hazards are addressed by three or fewer SAFs.
- Other than using strategies to reduce stormwater runoff, the flood-related measures analyzed in the mico-level analysis are not consistently incorporated across all SAFs.
- Some tools, such as LEED® for Homes and LEED® NC only discourage developing in floodplains. Other tools (e.g. BREEAM® NC, LEED® ND) incorporate additional measures for reducing flood damage risk for buildings developed in floodplains. And only three SAFs include the consideration of climate change impacts in design.
- Weaknesses in resilience coverage within SAFs do exist that have the potential to lead to the design of structures and communities that are vulnerable to the impacts of extreme events. Some sustainably beneficial design measures can result in vulnerable developments if the resilience aspects of design are not considered. Also, SAFs are stronger at addressing environmental issues when compared to the other pillars of sustainable development. This is especially true for the economic pillar of sustainability which received the least amount of inclusion in the frameworks studied. Since economy has shown to be integral to the resilience of buildings and communities the lack of integrating economy into SAFs is consider a weakness in resilience and sustainability coverage.

Furthermore, SAFs that fail to consider climate change impacts and concentrate efforts primarily on mitigating climate change have the potential to lead to developments vulnerable to hazards especially for developments threatened by future sea level rise (Matthews et al., 2014).

6.3 A Component-based Approach to Flood Depth-damage Functions for Individual Single-family, Wood-frame Residential Building Designs

Since resilience was not strongly or systematically integrated throughout through current state-of-the art SAFs, it was determined new models were needed where resilience measures could be weighed against sustainability and optimal designs could be identified. Optimization is a key aspect of a designer's decision-making process, especially within the context of performance-based design. Since the geographical focus of the dissertation is on SFR structures in coastal areas subject to tropical cyclones, a flood model and a wind model were developed. In order to build the flood model outlined in Objective 3, a set of discrete, component-level, synthetic depth-damage curves for single family residential (SFR) type structures were developed, which are flexible in their application to individual SFR building designs.

The curves are designed to output the percent damage to material damage quantities over a range of flood depths. The curves presented in the chapter target the most conventional type of SFR construction (i.e. wood-framed). Inundation-only, non-velocity flooding is considered in the development of these curves. The curves are applicable to both one-story and two-story SFR building designs, and flexible enough to account for variations in most SFR designs. Multiple literatures sources were utilized to develop a list of building components categories and a set of assumptions related to the damage sustained by each component relative to flood depth. Using the component categories and damage assumptions component-level damage functions were created for the first-, second- and third-story level (i.e. attic of a two-story) of an SFR building.

6.4 Flood Resilience and Environmental Impact Material Optimization Model for Coastal, Single-family, Residential Building Designs

The third objective of this dissertation was to develop an integrated sustainability and resilience assessment (ISRA-F) model for optimizing flood resilience and environmental impact of single-family residential building designs in coastal geographies. Life-cycle assessment techniques were utilized to measure energy consumption, carbon dioxide footprint, and water consumption related to initial construction and flood damage repairs incurred over the building's useful life. A probabilistic methodology utilizing Monte Carlo techniques was used for simulating flood losses over a building's life. The ISRA-F model is designed to compare multiple designs to identify the design with optimal performance, where building performance is assessed within the framework of the ISRA-F model using two modules: (1) Flood Resilience Assessment (FRA) and (2) Environmental Impact Assessment (EIA). Matlab and Microsoft Excel were utilized to program the model.

Within the FRA module, the flood-performance of the building is assessed by simulating flood events for a building over its design life and damage associated with the events are aggregated by calculating the expected mean damage statistic. The main input parameters for the estimator include site and design specific parameters. Site specific parameters include the probability of extreme flood events, sea level rise rate and ground elevation; and design specific parameters include the building elevation and component depth-damage curves developed in Chapter 3 that provide a measure of damage over a range of flood depths.

For the EIA Module, the environmental impact is measured by calculating the embodied energy, CO2 footprint, and water consumption of the initial construction and repairs to life-cycle damage using a life-cycle inventory database. Both the FRA and EIA modules depend on a quantity estimate of the materials for all building design components. The output of the optimization model is the summation of environment impacts associated with the initial construction and repairs for the design in question.

To provide a demonstration of the ISRA-F model, a case study is presented. Two designs for an SFR structure located in Saint Petersburg, Florida were assessed using the ISRA-F model. The first (Design 1) represents typical construction materials and installations, while the second (Design 2) uses more flood-resistant materials and installations. When comparing between Design 1 and 2, the model indicates that the more flood-resistant design does not differ from Design 1 when analyzing initial construction, however, the sustainable performance of Design 2 is significantly better when hazard-related repairs over the life of the building are considered. If sustainability is an important design factor, the ISRA-F model indicates that Design 2 would be better choice. To determine which individual component design choices had the greatest impact on the results of the model, a sensitivity analysis was conducted on individual design choices. According to the results of the sensitivity analyses, two design choices have the greatest impact on the results: (1) mixed flooring versus ceramic flooring only and (2) paper-faced versus non-paper-faced gypsum wall board.

6.5 Wind Resilience and Environmental Impact Material Optimization Model for Coastal, Single-family, Residential Building Designs

The fourth objective of this dissertation was to develop an integrated sustainability and resilience assessment (ISRA-W) model for optimizing wind resilience and environmental impact of single-family residential building designs in coastal geographies. Development of the wind model was similar to the approach was taken in the development of the ISRA-W model. Similar to the ISRA-F model, building performance was assessed using two modules: (1) Wind Resilience Assessment (FRA) and (2) Environmental Impact Assessment (EIA). Matlab and Microsoft Excel were utilized to program the model.

Within the WRA module, the wind-performance of the building is assessed by simulating wind events for a building over its design life and damage associated with the wind events are aggregated by calculating the expected mean damage statistic. The main input parameters for the estimator include site and design specific parameters. Site specific parameters include the probability of extreme wind events and design specific parameters include building component wind-damage curves that provide a measure of damage over a range of wind speeds. The wind-damage curves used in this module were provided by the Florida Public Hurricane Loss Model (FPHLM). Both direct damage due to wind and indirect damage due to wind-driven rain were considered.

Similar to the ISRA-F model, the EIA Module in the ISRA-W model was used to calculate the environmental impacts (i.e. embodied energy, CO2 footprint, and water consumption) of the initial construction and repairs to life-cycle damage using a life-cycle inventory database. Also similar to the ISRA-F mode, both the WRA and EIA modules depend on a quantity estimate of the materials for all building design components and the output of the optimization model is the summation of environment impacts associated with the initial construction and repairs for the design in question.

To provide a demonstration of the ISRA-W model, a case study is presented. Two designs for an SFR structure located in Saint Petersburg, Florida were assessed using the ISRA-W model. The first (Design 1) represents a design with weak resistance to wind and wind-driven rain hazards, while the second (Design 2) uses more wind-resistant and water resistant materials and installations. When comparing between Design 1 and 2, the model indicates that the more wind-resistant design does not differ from Design 1 when analyzing initial construction, however, the sustainable performance of Design 2 is better when hazard-related repairs over the life of the building are considered. If sustainability is an important design factor, the ISRA-W model indicates that the wind-resistant design would be better choice. To determine which individual component design choices had the greatest impact on the results of the model, a sensitivity analysis was conducted on individual design choices. According to the results of the sensitivity analyses, two design choices have the greatest impact on the results: (1) mixed flooring versus ceramic flooring only and (2) paper-faced versus non-paper-faced gypsum wall board.

6.6 Final Remarks and Recommendations

The overarching goal of this dissertation was to integrate the concepts of sustainability and resiliency to improve the design and construction of single-family residential (SFR) structures so that these buildings are environmentally friendly and resistant to wind and flood hazards. This was accomplished primarily through the development of two models (i.e. ISRA-F and ISRA-W), which can be utilized to compare multiple designs and determine the optimal design for maximizing the hazard-resistant performance of coastal SFR residential buildings while also minimizing environmental impacts. The preceding sections describe the work accomplished to develop the ISRA-F and ISRA-W models, including all foundational work carried out.

While the research presented in this dissertation does in part accomplish the goal by presenting models that can be used to design and construct SFR structures that are both resilient and minimize impacts on the environment, more work is needed to expand the research into the other area of sustainability (i.e. social, economic). Also, since SFR buildings that are impacted by hurricanes are exposed to both flood and wind hazards simultaneously, it would be beneficial to develop a model that considers life-cycle damage resulting from joint wind and flood hazards. Furthermore, consideration for uncertainty in damage incurred by structures and life-cycle inventory impact data needs to be investigated. Other distributions that better fit extreme events for longer return periods should also be utilized in future versions of this model especially for buildings designed for longer life spans. In future versions of this model it would be beneficial to consider other RSLR scenarios where rates increase over time rather than stay constant. Also, since ground elevation is considered to be a constant in this model there may be factors that exist at particular buildings sites other than subsidence (e.g. coastal erosion) that are ignored. In these cases it is possible for G to be adjusted as a time dependent variable. This research provides the foundation for future models, which can be expanded to other geographies, hazards and building types.

REFERENCES

Amoroso, S. (2009). “Benefit Cost Analysis for Wind Hazard Mitigation.” *Louisiana Civil Engineer*, 17 (3), 6-10.

Ana, E. & Bauwens, W. (2010).“Modeling the structural deterioration of urban drainage pipes: the state-of-the-art in statistical methods.” *Urban Water Journal*, 7(1), 47-59.

Applied Technology Council (ATC). (2015). Windspeed by Location. Retrieved Mar. 4, 2015 from http://windspeed.atcouncil.org/

Arroyo, D., Ordaz, M., & Teran-Gilmore, A. (2014). Seismic Loss Estimation and Environmental Issues. *Earthquake Spectra* In-Press, doi: http://dx.doi.org/10.1193/020713EQS023M.

Athena Sustainable Material Institute (ASMI). (2015). Our Software and Data. Retrieved Mar. 29, 2015 from http://www.athenasmi.org/our-software-data/overview/

Ashby, M.F. (2009). *Materials and the Environment: Eco-Informed Material Choice*. Burlington, MA: Elsevier, Inc.

Asif, M., Muneer, T. & Kelley, R. (2005). "Life cycle assessment: A case study of a dwelling home in Scotland." *Building and Environment*, 42(3), 1391-1394.

Berardi, U. (2012). “Sustainability assessment in the construction sector: rating systems and rated buildings.” *Sustainable Development*, 20(6), 411-424.

Blengini, G. (2009). "Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy." *Building and Environment*, 44(2), 319-330.

Bohn, F. & Friedland, C. (2013). “Why the 100-year Flood?” *Louisiana Civil Engineer*, 21(3), 16-18.

Bole, R. (2006). *Life-cycle optimization of residential clothes washer replacement*, Master’s Thesis, University of Michigan.

Bruneau, M., Chang, S. E., Eguchi, R. T., Lee, G. C., O'Rourke, T. D., Reinhorn, A. M., Shinozuka, M., Tierney, K., Wallace, W. A., & von Winterfeldt, D. (2003). “A framework to quantitatively assess and enhance the seismic resilience of communities.” *Earthquake spectra*, 19(4), 733-752.

Building Research Establishment (BRE) Global Ltd. (2011a). BREEAM for Communities: Stage 2, SD5066 Technical Guidance Manual, Version 1. 498 pp.

Building Research Establishment (BRE) Global Ltd. (2011b). BREEAM for New Construction: Non-Domestic Buildings, Technical Manual SD5073-2.0:2011. 406 pp.

Building Research Establishment (BRE) Global Ltd. (2012). BREEAM® : What is BREEAM. Retrieved Mar. 26, 2012 from www.breeam.org/about.jsp?id=66

Building Research Establishment (BRE) Global Ltd. (2015) Background ot the Green Guide to Specification. Retrieved Mar. 29, 2015 from http://www.bre.co.uk/greenguide/page.jsp?id=2069

Carnegie Mellon University Green Design Institute. (2013a). Economic Input-Output Life Cycle Assessment. Retrieved Aug. 16, 2013 from http://www.eiolca.net/

Carnegie Mellon University Green Design Institute. (2013b). Economic Input-Output Life Cycle Assessment (EIO-LCA) Hybrid Interface (beta). Retrieved Aug. 16, 2013 from http://www.eiolca.net/aurora-hybrid.html

Chang, S. E., & Shinozuka, M. (1996). “Life-cycle cost analysis with natural hazard risk.” *Journal of Infrastructure Systems*, 2(3), 118-126.

Cope, A. (2004). *Predicting the vulnerability of typical residential buildings to hurricane damage.* PhD Dissertation, University of Florida, Department of Civil Engineering.

Court, A., Simonen, K., Webster, M., Trusty, W., & Morris, P. (2012). “Linking Next-Generation Performance-Based Seismic Design Criteria to Environmental Performance (ATC-86 and ATC-58).” Paper presented at the Structures Congress 2012.

Cutter, S. L., Barnes, L., Berry, M., Burton, C., Evans, E., Tate, E., & Webb, J. (2008). “A place-based model for understanding community resilience to natural disasters.” *Global Environmental Change*, 18(4), 598-606.

Department of Commerce (DOC). (1961). Rainfall Frequency Atlas of the United States for Durations from 30 Minutes to 24 Hours and Return Periods from I to 100 Years. Washington D.C.: Department of Commerce.

Department of Homeland Security (DHS). (2009). National Infrastructure Protection Plan: Partnering to enhance protection and resiliency. DHS, Washington, D.C.

Ding, G. K. (2008). Sustainable construction—the role of environmental assessment tools. Journal of environmental management, 86(3), 451-464.

Dixit, M., Fernández-Solís, J., Lavy, S. & Culp, C. (2010). "Identification of parameters for embodied energy measurement: A literature review." *Energy and Buildings*, 42(8), 12381247.

Dixit, M., Fernández-Solís, J., Lavy, S. & Culp, C. (2012). "Need for an embodied energy measurement protocol for buildings: A review paper." *Renewable and Sustainable Energy Reviews*, 16(6), 3730-3743.

Dong, Y., Frangopol, D. M., & Saydam, D. (2013). “Time-variant sustainability assessment of seismically vulnerable bridges subjected to multiple hazards.” *Earthquake Engineering & Structural Dynamics*, 42(10), 1451-1467.

East, B., Lozos, T., Verhulst, C. S., & ME, M. D. (2014). Guidelines to Assess Hail Damage to Shingle Roofs. Retrieved Mar. 30, 2015 from http://www.nelsonforensics.com/Downloads/2012-Guideline_to_Assess_Hail_Damage.pdf

Emerine, D., Shenot, C., Bailey, M., Sobel, L., & Susman, M. (2006). This Is Smart Growth. Smart Growth Network, Retrieved Mar. 25, 2013 from www.epa.gov/smartgrowth/tisg.htm.

Ettouney, M., Schneider, P., Walker, R., & Chipley, M. (2011). Building and Infrastructure Protection Series: Integrated Rapid Visual Screening of Buildings, BIPS 04/September 2011. DHS, Science and Technology Directorate, Infrastructure Protection and Disaster Management Division, Washington, D.C.

Federal Emergency Management Agency (FEMA). (2008). Flood Damage Resistant Materials Requirements for Buildings Located in Special Flood Hazard Areas in accordance with the Nation Flood Insurance Policy, Technical Bulletin 2. Washington, DC: Federal Emergency Management Agency.

Federal Emergency Management Agency (FEMA). (2009). Flood Insuranace Study: Pinellas County, Florida and Incorporated Areas. Washington D.C.: Department of Homeland Security.

Federal Emergency Management Agency (FEMA). (2010). Natural Hazards and Sustainability for Residential Buildings. FEMA P-798, DHS, Washington, D.C.

Federal Emergency Management Agency (FEMA). (2011). Coastal Construction Manual: Principles and Practices of Planning, Siting, Designing, Constructing, and Maintaining Residential Buildings in Coastal Areas (4th ed.). FEMA P-55, Department of Homeland Security, Washington, D.C.

Federal Emergency Management Agency (FEMA). (2014). Substantial Damage Estimator (SDE) User Manual and Workbook. FEMA P-784, Washington D.C.: Department of Homeland Security.

FEMA. (2015). FEMA's Flood Map Service Center Retrieved Feb. 3, 2015, from https://msc.fema.gov/portal

FEMA. (2012). Hazus®–MH 2.1 Technical Manual. Washington D.C.: Department of Homeland Security.

Feese, C., Li, Y., & Bulleit, W. M. (2014). "Assessment of Seismic Damage of Buildings and Related Environmental Impacts." *Journal of Performance of Constructed Facilities* In-Press, doi: 10.1061/(ASCE)CF.1943-5509.0000584

Florida Department of Emergency Management (FDEM). (2015). FloridaDisaster.org Retrieved Feb 3, 2015, from http://www.floridadisaster.org/gis/lidar/

Fowler, K. M., & Rauch, E. M. (2006). Sustainable Building Rating Systems Summary: Pacific Northwest National Laboratory.

Fragiadakis, M., Lagaros, N. D., & Papadrakakis, M. (2006). "Performance-based multiobjective optimum design of steel structures considering life-cycle cost." *Structural and Multidisciplinary Optimization*, 32(1), 1-11.

Friedland, C. J. (2009). *Residential building damage from hurricane storm surge: proposed methodologies to describe, assess and model building damage*, PhD Thesis, Louisiana State University.

Friedland, C. J., & Gall, M. (2012). "True Cost of Hurricanes: Case for a Comprehensive Understanding of Multihazard Building Damage." *Leadership and Management in Engineering*, 12(3), 134-146.

Gilbert, S. (2010). Disaster Resilience: A Guide to the Literature. U.S. Department of Commerce, National Institute of Standards and Technology, Gaithersburg, MD

.

Gordian. (2015). RSMeans Online Retrieved February 17, 2015

Gordon, P. M. (2010). *Sustainable Disaster Resilience: Incorporating Hazard Mitigation Methodologies into LEED for Neighborhood Development*, Master's Thesis, University of Texas at Austin.

Gulf Engineers & Consultants (GEC). (1996). Depth-damage relationships for structures, contents, and vehicles and content-to-structure value ratios (CSVRs) in support of the Jefferson and Orleans flood control feasibility studies, Gulf Engineers & Consultants, Baton Rouge, LA.

Gulf Engineers & Consultants (GEC). (1997). Depth-Damage Relationships for Structures, Contents, and Vehicles and Content-to-Structure Value Ratios (CSVR) in Support of the Lower Atchafalaya Reevaluation and Morganza to the Gulf, Louisiana Feasibility Studies, Gulf Engineers & Consultants, Baton Rouge, LA

Gulf Engineers & Consultants (GEC). (2006). Depth-Damage Relationships for Structures, Contents, and Vehicles and Content-to-Structure Value Ratios (CSVR) in Support of the Donaldsonville to the Gulf, Louisiana, Feasibility Study, Gulf Engineers & Consultants, Baton Rouge, LA

Gurley, K., & Pinelli, J.-P. (2015). Florida Public Hurricane Loss Model Curve Dataset. University of Florida and Florida Institute of Technology.

Haapio, A. (2012). "Towards sustainable urban communities." *Environmental Impact Assessment Review*, 32(1), 165-169.

Haapio, A., & Viitaniemi, P. (2008). "A critical review of building environmental assessment tools." *Environmental Impact Assessment Review*, 28(7), 469-482.

Hammond, G. & Jones, C. (2008). "Embodied energy and carbon in construction materials." Proceedings of the Institution of Civil Engineers-Energy 161(2): 87-98.

Hamid, S., Golam Kibria, B. M., Gulati, S., Powell, M. D., Annane, B., Cocke, S., et al. (2010). Predicting Losses of Residential Structures in the State of Florida by the Public Hurricane Loss Evaluation Models. *Journal of Statistical Methodology*, *7*(5), 552-573.

Hamid, S., Pinelli, J.-P., Chen, S.-C., Gurley, K. (2011). Catastrophe Model Based Assessment of Hurricane Risk and Estimates of Potential Insured Losses for the State of Florida. *ASCE Natural Hazard Review, 12*(4), 171-176.

Hartwig, R. P., & Weisbart, S. N. (2012). Coastal Crossroads: Hurricanes and the Shifting Nature of Catastrophic Loss in the United States. In Insurance Information Institute, 2012 National Hurricane Conference. Retrieved Mar 29. 2015 from http://www.iii.org/presentation/coastal-crossroads-hurricanes-and-the-shifting-nature-of-catastrophic-loss-in-the-united-states-032712.

Hossain, K. A., & Gencturk, B. (2014). "Life-Cycle Environmental Impact Assessment of Reinforced Concrete Buildings Subjected to Natural Hazards." *Journal of Architectural Engineering* In-Press, doi: 10.1061/(ASCE)AE.1943-5568.0000153

Hurley, J., & Horne, R. (2006). "Review and Analysis of Tools for the Implementation and Assessment of Sustainable Urban Development." Paper presented at the In Environmental Institute of Australian and New Zealand National Conference, Adelaide: Environment Institute of Australia and New Zealand

Ingargiola, John and Moline, Jula. (2012). "Flood Damage-Resistant Materials: Research and Evaluation." In C. P. Jones, & L. G. Griffis (Eds.), Advances in Hurricane Engineering: Learning from Our Past. Paper presented in Miami, Fl, 24-26 October, pp. 34-47.

Institute for Building Environment and Energy Conservation (IBEC). (2007a). CASBEE® for Home (Detached House): Comprehensive Assessment System for Building Environmental Efficiency, Technical Manual 2007 Edition. 267 pp.

Institute for Building Environment and Energy Conservation (IBEC). (2007b). CASBEE® for Urban Development: Comprehensive Assessment System for Building Environmental Efficiency, Technical Manual 2007 Edition. 177 pp.

Institute for Building Environment and Energy Conservation (IBEC). (2008). CASBEE® for New Construction: Comprehensive Assessment System for Building Environmental Efficiency, Technical Manual 2008 Edition. 262 pp.

Institute for Sustainable Infrastructure (ISI). (2012). Institute for Sustainable Infrastructure: Envision Tool Portal. Retrieved Feb. 2, 2012 from www.sustainableinfrastructure.org

Insurance Council of Austrailia (ICA). (2013). Building Resilience Rating Tool. Retrieved Mar. 31, 2013 from www.buildingresilience.org.au/building-resilience-rating-tool

International Living Building Institute (ILBI). (2010). Living Building Challenge 2.0. Retrieved Mar. 30, 2015 from https://ilbi.org/lbc/LBC%20Documents/LBC2-0.pdf

Kang, Y.-J., & Wen, Y. (2000). Minimum life-cycle cost structural design against natural hazards: University of Illinois Engineering Experiment Station, College of Engineering, University of Illinois at Urbana-Champaign.

Keoleian, G., Blanchard, S., & Reppe, P. (2000). "Life-Cycle Energy, Costs, and Strategies for Improving a Single-Family House." *Journal of Industrial Ecology*, 4(2), 135-156.

Konrad, C. (2003). Effects of Urban Development on Floods. United States Geological Survey Fact Sheet 076-03, Tacoma, WA.

Lenzen, M., & Treloar, G. (2002). “Embodied energy in buildings: wood versus concrete—reply to Börjesson and Gustavsson.” *Energy Policy*, 30(3), 249-255.

Li, Y., & Ellingwood, B. R. (2006). “Hurricane damage to residential construction in the US: Importance of uncertainty modeling in risk assessment.” *Engineering Structures*, 28(7), 1009-1018.

Liu, M., Burns, S. A., & Wen, Y. (2003). “Optimal seismic design of steel frame buildings based on life cycle cost considerations.” *Earthquake Engineering & Structural Dynamics*, 32(9), 1313-1332.

Liu, M., Wen, Y., & Burns, S. A. (2004). “Life cycle cost oriented seismic design optimization of steel moment frame structures with risk-taking preference.” *Engineering Structures*, 26(10), 1407-1421.

Malik, F., Brown, R. & York, W. (2012).“IBHS FORTIFIED Homes Hurricane; Bronze, Silver and Gold: An incremental, holistic approach to reducing residential property losses in hurricane prone areas.” In C.P. Jones, & L.G. Griffis (Eds.), Advances in Hurricane Engineering: Learning from Our Past. Paper presented in Miami, Fl, 24-26 October, pp. 212-228.

Matthews, E. C., Sattler, M., & Friedland, C. J. (2014). “A critical analysis of hazard resilience measures within sustainability assessment frameworks.” *Environmental Impact Assessment Review*, 49, 59-69.

McEvoy, D., Lindley, S., & Handley, J. (2006). “Adaptation and mitigation in urban areas: synergies and conflicts.” *Proceedings of the Institution of Civil Engineers - Municipal Engineer*, 159(4), 185-191.

Menassa, C., Mangasarian, S., El Asmar, M., & Kirar, C. (2012). “Energy Consumption Evaluation of U.S. Navy LEED-Certified Buildings.” *Journal of Performance of Constructed Facilities*, 26(1), 46-53.

Mithraratne, N., & Vale, B. (2004). “Life cycle analysis model for New Zealand houses.” *Building and Environment*, 39(4), 483-492.

Murphy, B. L. (2007). “Locating social capital in resilient community-level emergency management.” *Natural Hazards*, 41(2), 297-315.

Murphree, J. (2004). *Florida Public Hurricane Loss Projection Model:Development Calibration and Validation of Vulnerability Matrices.* MS Thesis, Florida Institute of Technology, Department of Civil Engineering.

National Institute of Science and Technology (NIST). (2015). BEES Retrieved Jan 13, 2015, from http://www.nist.gov/el/economics/BEESSoftware.cfm

National Oceanic and Atmospheric Administration (NOAA). (2014). Sea Level Trends. Retrieved Aug. 30, 2012 from http://tidesandcurrents.noaa.gov/sltrends/sltrends.shtml

National Oceanic and Atmospheric Administration (NOAA). (2013). NOAA’s State of the Coast. Retrieved Mar. 31, 2013 from http://stateofthecoast.noaa.gov/population/welcome.html

National Oceanic and Atmospheric Administration (NOAA). NOAA Office of Ocean and Coastal Resource Management: Coastal Zone Management Act of 1972. Retrieved Aug. 16, 2013 from http://coastalmanagement.noaa.gov/about/czma.html#section304.

National Research Council (NRC). (2010). Advancing the Science of Climate Change: America's Climate Choices. The National Academies Press, Washington, D.C., USA.

National Renewable Energy Laboratory (NREL). (2013). U.S. Lifecycle Inventory Database. Retrieved Aug. 12, 2013 from http://www.nrel.gov/lci/

Needham, H. F., Keim, B. D., Sathiaraj, D., & Shafer, M. (2012). "Storm surge return periods for the United States Gulf Coast." In C.P. Jones, & L.G. Griffis (Eds.), Advances in Hurricane Engineering: Learning from Our Past. Paper presented in Miami, Fl, 24-26 October, pp. 715-740.

Newsham, Guy R, Mancini, Sandra, & Birt, Benjamin J. (2009). "Do LEED-certified buildings save energy? Yes, but…." *Energy and Buildings*, 41(8), 897-905.

Noshadravan, A., Ghattas, R., Gregory, J. and Kirchain, R. (2014). "Quantifying hazard life-cycle cost." Retrieved Mar. 14, 2014 from https://cshub.mit.edu/news/lca-research-brief-quantifying-hazard-life-cycle-cost.

Padgett, J. E., Dennemann, K., & Ghosh, J. (2010). "Risk-based seismic life-cycle cost–benefit (LCC-B) analysis for bridge retrofit assessment." *Structural Safety*, 32(3), 165-173.

Padgett, J. E., & Tapia, C. (2013). "Sustainability of Natural Hazard Risk Mitigation: Life Cycle Analysis of Environmental Indicators for Bridge Infrastructure." *Journal of Infrastructure Systems*, 19(4), 395-408.

Palutikof, J., Brabson, B., Lister, D., & Adcock, S. (1999). "A review of methods to calculate extreme wind speeds." *Meteorological Applications*, 6(02), 119-132.

Peuportier, B. (2001). "Life cycle assessment applied to the comparative evaluation of single family houses in the French context." *Energy and Buildings*, 33(5), 443-450.

Pinelli, J.-P., Pita, G., Gurley, K., Torkian, B. B., Hamid, S., Subramanian, C. (2011). Damage Characterization: Application to Florida Public Hurricane Loss Model. *ASCE Natural Hazard Review*, *12*(4), 190-195.

Plumblee, J., & Klotz, L. (2014). "Marlo's windows: why it is a mistake to ignore hazard resistance in LCA." *The International Journal of Life Cycle Assessment*, 19(6), 1173-1178.

Pauleit, S., Ennos, R., & Golding, Y. (2005). "Modeling the environmental impacts of urban land use and land cover change – a study in Merseyside, UK." *Landscape and Urban Planning*, 71(2-4), 295-310.

Radloff, K. (2006). Community Resilience, Community Economic Development, and Saskatchewan Economic Developers: Community-University Institute for Social Research.

Reeder, L. (2010). Guide to green building rating systems: understanding LEED, Green Globes, Energy Star, the National Green Building Standard, and more, Vol. 12: John Wiley & Sons.

Renschler, C. Fraizer, A., Arendt, L., Cimellaro, G., Reinhorn, A., & Bruneau, M. (2010). A Framework for Defining and Measuring Resilience at the Community Scale: The PEOPLES Resilience Framework. U.S. Department of Commerce, National Institute of Standards and Technology, Gaithersburg, MD.

Retzlaff, R. C. (2008). "Green building assessment systems: a framework and comparison for planners." *Journal of the American Planning Association*, 74(4), 505-519.

Rossi, B., Marique, A., & Reiter, S. (2012). "Life-cycle assessment of residential buildings in three different European locations, case study." *Building and Environment*, 51, 402-407.

Sarkisian, M. P. (2014). Design of environmentally responsible structures in regions of high seismic risk. Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance, 10(7), 849-864.

Scientific Applications International Corporation (SAIC). (2006). Life cycle Assessment: Principals and Practice. National Risk Management Research Laboratory, U.S. Environmental Protection Agency, Cincinnati, OH. Retrieved May 3, 2013 from http://www.epa.gov/nrmrl/std/lca/lca.html.

Scofield, J. H. (2009). "Do LEED-certified buildings save energy? Not really…." *Energy and Buildings*, 41(12), 1386-1390.

Sempier, T., Swann, D., Emmer, R., Sempier, S., & Schneider, M. (2010). Coastal Community Resilience Index: A Community Self-Assessment. Retrieved from http://www.southernclimate.org/documents/resources/Coastal_Resilience_Index_Sea_Grant.pdf

Shah, V. P., Debella, D. C., & Ries, R. J. (2008). "Life cycle assessment of residential heating and cooling systems in four regions in the United States." *Energy and buildings*, 40(4), 503-513.

Sharifi, A., & Murayama, A. (2013). "A critical review of seven selected neighborhood sustainability assessment tools." *Environmental Impact Assessment Review*, 38, 73-87.

Sharifi, A., & Murayama, A. (2014a). "Neighborhood sustainability assessment in action: Cross-evaluation of three assessment systems and their cases from the US, the UK, and Japan." *Building and Environment*, 72, 243-258.

Sharifi, A., & Murayama, A. (2014b). Viability of using global standards for neighbourhood sustainability assessment: insights from a comparative case study. *Journal of Environmental Planning and Management*, 58(1), 1-23.

Sharrard, Aurora L, Matthews, H Scott, & Ries, Robert J. (2008). "Estimating construction project environmental effects using an input-output-based hybrid life-cycle assessment model." *Journal of Infrastructure Systems*, 14(4), 327-336.

Smith, J. M., Cialone, M. A., Wamsley, T. V., & McAlpin, T. O. (2010). "Potential impact of sea level rise on coastal surges in southeast Louisiana." *Ocean Engineering*, 37(1), 37-47.

Stevens, M., Berke, P., & Song, Y. (2010). "Creating disaster-resilient communities: Evaluating the promise and performance of new urbanism." *Landscape and Urban Planning*, 94(2), 105-115.

Sustainable Sites Initiative (SSI). (2009). The Sustainable Sites Initiative: Guidelines and Performance Benchmarks, 233 pp.

Thieler, E. & Hammar-Klose, E. (1999). National Assessment of Coastal Vulnerability to Future Sea-Level Rise: Preliminary Results for the U.S. Atlantic Coast. U.S. Geological Survey, Open-File Report 99-593, Available online at: http://pubs.usgs.gov/of/of99-593/.

Thieler, E. & Hammar-Klose, E. (2000a). National Assessment of Coastal Vulnerability to Future Sea-Level Rise: Preliminary Results for the U.S. Pacific Coast. U.S. Geological Survey, Open-File Report 00-178, Available online at: http://pubs.usgs.gov/of/of00-178/.

Thieler, E. & Hammar-Klose, E. (2000b). National Assessment of Coastal Vulnerability to Future Sea-Level Rise: Preliminary Results for the U.S. Gulf of Mexico Coast. U.S. Geological Survey, Open-File Report 00-179, Available online at: http://pubs.usgs.gov/of/of00-179/.

Todd, J. A., Crawley, D., Geissler, S., & Lindsey, G. (2001). "Comparative assessment of environmental performance tools and the role of the Green Building Challenge." *Building Research & Information*, 29(5), 324-335.

Tol, R. S. (2005). "Adaptation and mitigation: trade-offs in substance and methods." *Environmental Science & Policy*, 8(6), 572-578.

Treloar, G. (1998). *A comprehensive embodied energy analysis framework*. PhD Thesis, Deakin University.

Trusty, W. (2000). “Introducing and Assessment Tool Classification System.” Advanced Building Newsletter, 25, 18, Jul.

Trusty, W. (2009, December). “Incorporating LCA in Green Building Rating Systems.” Environmental Managers Magazine, 19-22.

Trusty, W. (2010). “An Overview of Life Cycle Assessments: Part One of Three.” *Building Safety Journal*. Retrieved from http://www.icces.org/Education/BSJ_overview_life_cycle_assessment_oct2010.pdf

United States Army Corps of Engineers (USACE). (2000). Generic depth-damage relationships, Economic Guidance Memorandum 01-03. Washington, D.C.: U.S. Army Corps of Engineers.

United States Army Corps of Engineers (USACE). (2003). Generic depth-damage relationships for residential structures with basements, Economic Guidance Memorandum 04-01. Washington, D.C.: U.S. Army Corps of Engineers.

United States Energy Information Administration (US EIA). (2013). Annual Energy Review- Energy Information Administration. Retrieved Aug. 22, 2013 from http://www.eia.gov/totalenergy/data/annual/index.cfm

United States Environmental Protection Agency (US EPA). (2012). Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI). Retrieved Aug. 31, 2012 from www.epa.gov/nrmrl/std/traci/traci.html.

United States Environmental Protection Agency (US EPA). (2013). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2011. EPA 430-R-13-001. US EPA, Washington, D.C.

United States Government Accountability Office (US GAO). (2005). National Flood Insurance Program: Oversight of Policy Issuance and Claims, GAO-05-532T, U.S. Congress, Washington D.C.

United States Green Building Council (USGBC). (2008). LEED® for Homes Rating System, 140 pp.

United States Green Building Council (USGBC). (2009a). LEED® 2009 for New Construction and Major Renovations: With Alternative Compliance Paths for Projects Outside the U.S., 117 pp.

United States Green Building Council (USGBC). (2009b). LEED® 2009 for Neighborhood Development, 145 pp.

United States Green Building Council (USGBC). (2012). Certified Project Directory. Retrieved Aug. 31, 2012 from www.usgbc.org/LEED/Project/CertifiedProjectList.aspx

Vazquez, E., Miguez, M., Alves, L., Valente, J., & Rossi, G. (2011). Certifications in construction: a case study comparing LEED and HQE. Proceedings of the Ecosystems and Sustainable Development VIII, Alicante, Spain.

Vijayan, A., & Kumar, A. (2005). “A review of tools to assess the sustainability in building construction.” *Environmental Progress*, 24(2), 125-132.

Wilks, D. S. (1993). “Comparison of three-parameter probability distributions for representing annual extreme and partial duration precipitation series.” *Water Resources Research*, 29(10), 3543-3549.

World Commission on Environment and Development (WCED). (1987). Our common future. Retrieved Mar. 30, 2015 from http://www.un-documents.net/our-common-future.pdf

Zabalza Bribián, I., et al. (2009). "Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification." *Building and Environment*, 44(12), 2510-2520.

Zhang, L. (2003). *Public hurricane loss projection model: exposure and vulnerability components.* MS Thesis, Florida Institute of Technology, Department of Civil Engineering.

APPENDIX A: CRITICAL RESILIENCE ANALYSIS OF SUSTAINABILITY ASSESSMENT FRAMEWORKS DATA

ELSEVIER LICENSE
TERMS AND CONDITIONS
Mar 29, 2015

This is a License Agreement between Elizabeth C Matthews ("You") and Elsevier ("Elsevier") provided by Copyright Clearance Center ("CCC"). The license consists of your order details, the terms and conditions provided by Elsevier, and the payment terms and conditions.

All payments must be made in full to CCC. For payment instructions, please see information listed at the bottom of this form.
Supplier
Elsevier Limited
The Boulevard,Langford Lane
Kidlington,Oxford,OX5 1GB,UK
Registered Company Number
1982084
Customer name
Elizabeth C Matthews

Customer address
Department of Construction Management
BATON ROUGE, LA 70803

License number
3580920881345

License date
Mar 02, 2015

Licensed content publisher
Elsevier

Licensed content publication
Environmental Impact Assessment Review

Licensed content title
A critical analysis of hazard resilience measures within sustainability assessment frameworks

Licensed content author
Elizabeth C. Matthews,Meredith Sattler,Carol J. Friedland

Licensed content date
November 2014

Licensed content volume number
49

Licensed content issue number
n/a

Number of pages
11

Start Page
59

End Page
69

Type of Use
reuse in a thesis/dissertation

Portion
full article

Format
both print and electronic

Are you the author of this Elsevier article?
Yes

Will you be translating?
No

Title of your thesis/dissertation
Flood and wind resilience and environmental impact optimization models for coastal, single-family, residential (SF) building designs

Expected completion date
May 2015

Estimated size (number of pages)
144

Elsevier VAT number
GB 494 6272 12

Permissions price
0.00 USD

VAT/Local Sales Tax
0.00 USD / 0.00 GBP

Total
0.00 USD

Terms and Conditions

INTRODUCTION

1. The publisher for this copyrighted material is Elsevier. By clicking "accept" in connection with completing this licensing transaction, you agree that the following terms and conditions apply to this transaction (along with the Billing and Payment terms and conditions established by Copyright Clearance Center, Inc. ("CCC"), at the time that you opened your Rightslink account and that are available at any time athttp://myaccount.copyright.com).

GENERAL TERMS

2. Elsevier hereby grants you permission to reproduce the aforementioned material subject to the terms and conditions indicated.

3. Acknowledgement: If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source, permission must also be sought from that source. If such permission is not obtained then that material may not be included in your publication/copies. Suitable acknowledgement to the source must be made, either as a footnote or in a reference list at the end of your publication, as follows:
"Reprinted from Publication title, Vol /edition number, Author(s), Title of article / title of chapter, Pages No., Copyright (Year), with permission from Elsevier [OR APPLICABLE SOCIETY COPYRIGHT OWNER]." Also Lancet special credit - "Reprinted from The Lancet, Vol. number, Author(s), Title of article, Pages No., Copyright (Year), with permission from Elsevier."

4. Reproduction of this material is confined to the purpose and/or media for which permission is hereby given.

5. Altering/Modifying Material: Not Permitted. However figures and illustrations may be altered/adapted minimally to serve your work. Any other abbreviations, additions, deletions and/or any other alterations shall be made only with prior written authorization of Elsevier Ltd. (Please contact Elsevier at permissions@elsevier.com)

6. If the permission fee for the requested use of our material is waived in this instance, please be advised that your future requests for Elsevier materials may attract a fee.

7. Reservation of Rights: Publisher reserves all rights not specifically granted in the combination of (i) the license details provided by you and accepted in the course of this licensing transaction, (ii) these terms and conditions and (iii) CCC's Billing and Payment terms and conditions.

8. License Contingent Upon Payment: While you may exercise the rights licensed immediately upon issuance of the license at the end of the licensing process for the transaction, provided that you have disclosed complete and accurate details of your proposed use, no license is finally effective unless and until full payment is received from you (either by publisher or by CCC) as provided in CCC's Billing and Payment terms and conditions. If full payment is not received on a timely basis, then any license preliminarily granted shall be deemed automatically revoked and shall be void as if never granted. Further, in the event that you breach any of these terms and conditions or any of CCC's Billing and Payment terms and conditions, the license is automatically revoked and shall be void as if never granted. Use of materials as described in a revoked license, as well as any use of the materials beyond the scope of an unrevoked license, may constitute copyright infringement and publisher reserves the right to take any and all action to protect its copyright in the materials.

9. Warranties: Publisher makes no representations or warranties with respect to the licensed material.

10. Indemnity: You hereby indemnify and agree to hold harmless publisher and CCC, and their respective officers, directors, employees and agents, from and against any and all claims arising out of your use of the licensed material other than as specifically authorized pursuant to this license.

11. No Transfer of License: This license is personal to you and may not be sublicensed, assigned, or transferred by you to any other person without publisher's written permission.

12. No Amendment Except in Writing: This license may not be amended except in a writing signed by both parties (or, in the case of publisher, by CCC on publisher's behalf).

13. Objection to Contrary Terms: Publisher hereby objects to any terms contained in any purchase order, acknowledgment, check endorsement or other writing prepared by you, which terms are inconsistent with these terms and conditions or CCC's Billing and Payment terms and conditions. These terms and conditions, together with CCC's Billing and Payment terms and conditions (which are incorporated herein), comprise the entire agreement between you and publisher (and CCC) concerning this licensing transaction. In the event of any conflict between your obligations established by these terms and conditions and those established by CCC's Billing and Payment terms and conditions, these terms and conditions shall control.

14. Revocation: Elsevier or Copyright Clearance Center may deny the permissions described in this License at their sole discretion, for any reason or no reason, with a full refund payable to you. Notice of such denial will be made

using the contact information provided by you. Failure to receive such notice will not alter or invalidate the denial. In no event will Elsevier or Copyright Clearance Center be responsible or liable for any costs, expenses or damage incurred by you as a result of a denial of your permission request, other than a refund of the amount(s) paid by you to Elsevier and/or Copyright Clearance Center for denied permissions.

LIMITED LICENSE

The following terms and conditions apply only to specific license types:

15. **Translation**: This permission is granted for non-exclusive world **English** rights only unless your license was granted for translation rights. If you licensed translation rights you may only translate this content into the languages you requested. A professional translator must perform all translations and reproduce the content word for word preserving the integrity of the article. If this license is to re-use 1 or 2 figures then permission is granted for non-exclusive world rights in all languages.

16. **Posting licensed content on any Website**: The following terms and conditions apply as follows: Licensing material from an Elsevier journal: All content posted to the web site must maintain the copyright information line on the bottom of each image; A hyper-text must be included to the Homepage of the journal from which you are licensing athttp://www.sciencedirect.com/science/journal/xxxxx or the Elsevier homepage for books athttp://www.elsevier.com; Central Storage: This license does not include permission for a scanned version of the material to be stored in a central repository such as that provided by Heron/XanEdu.
Licensing material from an Elsevier book: A hyper-text link must be included to the Elsevier homepage at http://www.elsevier.com . All content posted to the web site must maintain the copyright information line on the bottom of each image.

Posting licensed content on Electronic reserve: In addition to the above the following clauses are applicable: The web site must be password-protected and made available only to bona fide students registered on a relevant course. This permission is granted for 1 year only. You may obtain a new license for future website posting.

17. **For journal authors:** the following clauses are applicable in addition to the above:
Preprints:
A preprint is an author's own write-up of research results and analysis, it has not been peer-reviewed, nor has it had any other value added to it by a publisher (such as formatting, copyright, technical enhancement etc.).
Authors can share their preprints anywhere at any time. Preprints should not be added to or enhanced in any way in order to appear more like, or to substitute for, the final versions of articles however authors can update their preprints on arXiv or RePEc with their Accepted Author Manuscript (see below).
If accepted for publication, we encourage authors to link from the preprint to their formal publication via its DOI. Millions of researchers have access to the formal publications on ScienceDirect, and so links will help users to find, access, cite and use the best available version. Please note that Cell Press, The Lancet and some society-owned have different preprint policies. Information on these policies is available on the journal homepage.

Accepted Author Manuscripts: An accepted author manuscript is the manuscript of an article that has been accepted for publication and which typically includes author-incorporated changes suggested during submission, peer review and editor-author communications.
Authors can share their accepted author manuscript:

- - immediately
    - via their non-commercial person homepage or blog
    - by updating a preprint in arXiv or RePEc with the accepted manuscript
    - via their research institute or institutional repository for internal institutional uses or as part of an invitation-only research collaboration work-group
    - directly by providing copies to their students or to research collaborators for their personal use
    - for private scholarly sharing as part of an invitation-only work group on commercial sites with which Elsevier has an agreement
- - after the embargo period

    - via non-commercial hosting platforms such as their institutional repository
    - via commercial sites with which Elsevier has an agreement

In all cases accepted manuscripts should:

- \- link to the formal publication via its DOI
- \- bear a CC-BY-NC-ND license - this is easy to do
- \- if aggregated with other manuscripts, for example in a repository or other site, be shared in alignment with our hosting policy not be added to or enhanced in any way to appear more like, or to substitute for, the published journal article.

Published journal article (JPA): A published journal article (PJA) is the definitive final record of published research that appears or will appear in the journal and embodies all value-adding publishing activities including peer review co-ordination, copy-editing, formatting, (if relevant) pagination and online enrichment.

Policies for sharing publishing journal articles differ for subscription and gold open access articles:

Subscription Articles: If you are an author, please share a link to your article rather than the full-text. Millions of researchers have access to the formal publications on ScienceDirect, and so links will help your users to find, access, cite, and use the best available version.

Theses and dissertations which contain embedded PJAs as part of the formal submission can be posted publicly by the awarding institution with DOI links back to the formal publications on ScienceDirect.

If you are affiliated with a library that subscribes to ScienceDirect you have additional private sharing rights for others' research accessed under that agreement. This includes use for classroom teaching and internal training at the institution (including use in course packs and courseware programs), and inclusion of the article for grant funding purposes.

Gold Open Access Articles: May be shared according to the author-selected end-user license and should contain a CrossMark logo, the end user license, and a DOI link to the formal publication on ScienceDirect.

Please refer to Elsevier's posting policy for further information.

18. **For book authors** the following clauses are applicable in addition to the above: Authors are permitted to place a brief summary of their work online only. You are not allowed to download and post the published electronic version of your chapter, nor may you scan the printed edition to create an electronic version. **Posting to a repository:** Authors are permitted to post a summary of their chapter only in their institution's repository.

19. **Thesis/Dissertation**: If your license is for use in a thesis/dissertation your thesis may be submitted to your institution in either print or electronic form. Should your thesis be published commercially, please reapply for permission. These requirements include permission for the Library and Archives of Canada to supply single copies, on demand, of the complete thesis and include permission for Proquest/UMI to supply single copies, on demand, of the complete thesis. Should your thesis be published commercially, please reapply for permission. Theses and dissertations which contain embedded PJAs as part of the formal submission can be posted publicly by the awarding institution with DOI links back to the formal publications on ScienceDirect.

Elsevier Open Access Terms and Conditions

You can publish open access with Elsevier in hundreds of open access journals or in nearly 2000 established subscription journals that support open access publishing. Permitted third party re-use of these open access articles is defined by the author's choice of Creative Commons user license. See our open access license policy for more information.

Terms & Conditions applicable to all Open Access articles published with Elsevier:

Any reuse of the article must not represent the author as endorsing the adaptation of the article nor should the article be modified in such a way as to damage the author's honour or reputation. If any changes have been made, such changes must be clearly indicated.

The author(s) must be appropriately credited and we ask that you include the end user license and a DOI link to the formal publication on ScienceDirect.

If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source it is the responsibility of the user to ensure their reuse complies with the terms and conditions determined by the rights holder.

Additional Terms & Conditions applicable to each Creative Commons user license:

CC BY: The CC-BY license allows users to copy, to create extracts, abstracts and new works from the Article, to alter and revise the Article and to make commercial use of the Article (including reuse and/or resale of the Article by commercial entities), provided the user gives appropriate credit (with a link to the formal publication through the relevant DOI), provides a link to the license, indicates if changes were made and the licensor is not represented as endorsing the use made of the work. The full details of the license are available at http://creativecommons.org/licenses/by/4.0.

CC BY NC SA: The CC BY-NC-SA license allows users to copy, to create extracts, abstracts and new works from the Article, to alter and revise the Article, provided this is not done for commercial purposes, and that the user gives appropriate credit (with a link to the formal publication through the relevant DOI), provides a link to the license, indicates if changes were made and the licensor is not represented as endorsing the use made of the work. Further, any new works must be made available on the same conditions. The full details of the license are available at http://creativecommons.org/licenses/by-nc-sa/4.0.

CC BY NC ND: The CC BY-NC-ND license allows users to copy and distribute the Article, provided this is not done for commercial purposes and further does not permit distribution of the Article if it is changed or edited in any way, and provided the user gives appropriate credit (with a link to the formal publication through the relevant DOI), provides a link to the license, and that the licensor is not represented as endorsing the use made of the work. The full details of the license are available at http://creativecommons.org/licenses/by-nc-nd/4.0. Any commercial reuse of Open Access articles published with a CC BY NC SA or CC BY NC ND license requires permission from Elsevier and will be subject to a fee.

Commercial reuse includes:

- \- Associating advertising with the full text of the Article
- \- Charging fees for document delivery or access
- \- Article aggregation
- \- Systematic distribution via e-mail lists or share buttons

Posting or linking by commercial companies for use by customers of those companies.

20. **Other Conditions**:

Questions? customercare@copyright.com or +1-855-239-3415 (toll free in the US) or +1-978-646-2777. Gratis licenses (referencing $0 in the Total field) are free. Please retain this printable license for your reference. No payment is required.

Table A-1: Taxonomy for Critical Resilience Analysis of Sustainability Assessment Frameworks

Measure	Mean (RAFs)	Mean (SAFs)	Min	Max
Hazards Addressed	6.7	2.8	1	11
1. Hurricane	8. Hazardous Material Spill			
2. Flood	9. Explosion			
3. Fire	10. Biological, Chemical or Radiological Attack			
4. Extreme Wind	11. Resource Scarcity			
5. Tornado	12. Cyber Attack			
6. Mudslides	13. Subsidence			
7. Earthquake	14. Sea Level Rise/Climate Change Hazards			
Community Resilience	8.3	1.6	0	14
1. Social Support Networks, Structures & Capital	13. Communication Systems			
2. Economic Development & Future Planning	14. Transportation			
3. Diversity in Employment Sources	15. Population & Demographics			
4. Economic Response and Recovery Plan	16. Environmental/Ecosystem Resilience			
5. Emergency & Governmental Response Planning	17. Residential Structures			
6. Evacuation Plans and Routes	18. Commercial Structures			
7. Climate Impact and Adaptation Planning	19. Community Reaction & Collective Behavior			
8. Hazards Vulnerability Assessment	20. Impact to Resiliency of Communities			
9. Resiliency Planning (Long-Term Impacts)	21. Impact to Resiliency of Neighboring Communities			
10. Short-Term Hazard (Natural/Manmade) Preparation	22. Structure Shows No Increase to Flood Elevation			
11. Critical Facilities	23. Critical Facilities Designed for 500 Year Event			
12. Lifelines and Utilities	24. Floodplain Management			
Structural Resilience	23	3	0	63
1. Occupancy (Number of Occupants/Building Type)	38. Window Connections to Structure			
2. Building Height and Configuration	39. Window & Opening Protection (e.g., Storm Shutters)			
3. Building Overhangs	40. Critical Elements Exposed to Wind (e.g., Rooftops)			
4. Surrounding Area Density (Population/Structures)	41. Eave Width/Long Roof Spans/Wind Uplift Failure			
5. Nearby Structures (Collateral Damage)	42. Cladding Condition			
6. Replacement Value	43. Connection of Cladding/Enclosure to Structure			
7. Historic/Symbolic Building	44. Regular/Irregular Enclosure Geometries			
8. Structure Construction Type	45. Potential for Windborne Debris Damage (e.g., Trees)			
9. Number of Bays in Short Direction	46. Fire Resistance/Reduced Risk of Fire			
10. Column Spacing & Unbraced Column Height	47. Emergency Exits and/or Evacuation Routes			
11. Transfer Girder Condition	48. Earthquake Resistance			
12. Exterior Wall Construction Type	49. Unsecure Building Appendages (e.g., Chimneys)			
13. Roof Construction Type & Pitch	50. Location in Seismic Zone and/or Near Fault			
14. Redundancy of Lateral Systems (e.g., Shear Walls)	51. Seismic: Soil Type			

This table previously appeared Matthews, E., Sattler, M., & Friedland, C., "A critical analysis of hazard resilience measures within sustainability assessment frameworks," *Environmental Impact Assessment Review*, Vol 49, pp 59-69, 2014. It is reprinted from "A critical analysis of hazard resilience measures within sustainability assessment frameworks, Vol 49, Matthews, E., Sattler, M., & Friedland, C., *Environmental Impact Assessment Review*, pp 59-69, 2014 with permission from Elsevier by permission of Elsevier.

Table A-1: Taxonomy for Critical Resilience Analysis of Sustainability Assessment Frameworks (Continued)

Measure	Mean (RAFs)	Mean (SAFs)	Min	Max
15. Terrorist Target Potential	52. Seismic: Soil Liquidation Potential/Soil Spread Potential			
16. Terrorism: Site Accessibility (e.g., Barricades)	53. Seismic: Retaining Wall Present & Condition			
17. Terrorism: Access to Critical Elements (e.g., Columns)	54. Seismic: Short Columns/Walls Present			
18. Terrorism: Access to Air Intakes/Distribution Systems	55. Seismic: Topping Slab Present			
19. Security: Obstructed Views (e.g., Trees)	56. Seismic: Unbraced Partition Walls			
20. Security: Building & Cyber Systems	57. Seismic: Non-Structural Element Anchoring			
21. Hazardous Materials Storage	58. Seismic: Irregular Horizontal & Vertical Planes			
22. Flood Proofing Below BFE (e.g., Non-Residential)	59. Seismic: Soft Stories			
23. Adoption of Codes/Upgrades to Meet Current Codes	60. Seismic: Elevated Tanks/Vessels			
24. Building in Floodplain/Design Above BFE/Meet NFIP	61. Design for Durability			
25. Flood Parameters (i.e., Depth, Duration & Velocity)	62. Overall Maintenance to Extend Life			
26. Critical Elements Exposed to Flood	63. Service Life/Maintenance Cycle Interior Finishes			
27. Distance From Flood Source	64. Service Life/Maintenance Cycle Exterior Finishes			
28. Flood Control or Protective Structures Nearby	65. Service Life of Structure Frame Materials			
29. Construct Outside 100 Year Floodplain	66. Service Life/Maintenance Cycle Plumbing/Ductwork			
30. Construct on Developed Land >5 ft + 100 Year Flood	67. Operation of Utilities During/After Disaster			
31. Government Acquisition/Relocation Programs	68. Hardening of Structure/Retrofit for Hazards			
32. High Speed Wind Zone	69. Hardening of Critical Utilities and/or MEP Systems			
33. Hurricane Frequency	70. Avoid High Risk Geologies (e.g., Steep Hill Sides)			
34. Tornado Frequency	71. Tenant Safety Organizations, EOCs, & Evacuation Plans			
35. Foundation Condition	72. Mutual Aid Agreements (e.g., First Responders)			
36. Window Glass Type (e.g., Laminated Glass)	73. Disaster Recovery Plans & Impact Assessments			
37. Window Surface Area				
Energy	-	7.3	1	11
1. Energy Consumption & Efficiency (e.g., Net Zero Energy)	10. Efficient Water Heating (e.g., Solar Heating)			
2. Energy Saving Measure During Construction	11. Efficient Lighting			
3. Thermal Envelope & Design (e.g., Insulation)	12. Efficient Appliances/Equipment (e.g., Elevators)			
4. HVAC Design/Efficiency	13. Renewable Energy Use			
5. District Heating & Cooling	14. Design Structure for Future Renewable Energy Use			
6. Improve Community Electrical Infrastructure	15. Vegetation Shading Around Building/Windbreak			
7. Commissioning/Monitoring/Managing of Energy Systems	16. Passive Solar Design			

Table A-1: Taxonomy for Critical Resilience Analysis of Sustainability Assessment Frameworks (Continued)

Measure	Mean (RAFs)	Mean (SAFs)	Min	Max
8. Load Leveling of Network Electrical/Heating Grids	17. Solar Reflectivity/Penetration			
9. Verification of Energy Consumption Post Construction				
Water	-	6.3	4	9
1. Potable Water Consumption & Efficiency (e.g., Net Zero)	7. Use of Leak Detection Technology			
2. Grey Water Recycling and/or Rainwater Collection	8. Water Efficient Equipment (e.g., Water Saving Features)			
3. Wastewater Recycling/Reuse and/or On-Site Treatment	9. Monitor Impact to Water Sources (e.g., Contaminants)			
4. Water Feature Amenities with Minimal Potable Water	10. Project Stormwater Management Plan/Erosion Control			
5. Wastewater Loads and/or Quality Limits Reducing Loads	11. Permanent Surface Water Management & Measures			
6. Monitor Water Usage During & After Construction	12. Future Water Availability			
Land/Site	-	12.3	6	19
1. Limit Impacts to Natural Areas/Habitat Alteration	16. Impact on Water Bodies (e.g., Conservation)			
2. Habitat Exchange for Development	17. Impact on State Soils/Conservation of Soils			
3. Environmental Site Assessment/Ecological Survey	18. Impact to Dunes used as Buffers			
4. Damage to Ecologically Sensitive Areas Considered	19. Impacts to Virgin Prairie as Buffers			
5. Preserve Vegetation of Significance (e.g., Mature Trees)	20. Address or Prevent Contaminated Soil			
6. Vegetation/Biomass Density	21. Reduce Ground Subsidence (e.g., From Pumping)			
7. Improve/Preserve Biodiversity (e.g., Provide green spaces)	22. Conservation of Public Parkland			
8. Control Invasive Species/Native Plant Utilization	23. Erosion of Site Sediment/Restore Disturbed Soils			
9. Network Green Spaces/Provide Continuity	24. Minimize Disturbance of Site			
10. Improve or Restore Riparian & Aquatic Habitats	25. Brownfield/Contaminated/Greyfield Redevelopment			
11. Monitor Habitat Measures Taken	26. Development Near Established Infrastructure			
12. Conservation of Prime Farmland	27. Develop on Previously Developed Land			
13. Impact to Scenic Views/Town Landscape	28. Develop Near Previously Developed Land			
14. Promote Local Production (e.g., Community Garden)	29. Land Conservation			
15. Protection of Wetlands/Wetland Conservation				
Materials	-	7.6	0	11
1. Materials Consumption/Optimization	9. Design for Disposal/Recycling			
2. Material from Non-Threatened Species	10. Local Reclaimed/Recycled Material Use (e.g., Roads)			

Table A-1: Taxonomy for Critical Resilience Analysis of Sustainability Assessment Frameworks (Continued)

Measure	Mean (RAFs)	Mean (SAFs)	Min	Max
3. Environmentally Friendly/Rapidly Renewable Materials	11. Building Reuse (e.g., Existing Structures)			
4. Low/No VOC Materials	12. Promote Recycling in Facility/Community			
5. Local Materials Use	13. Promote & Manage Waste Reduction at Facility			
6. Life-Cycle Embodied Energy & Sustainable Materials	14. Reuse or Recycle Construction Waste/Waste Diversion			
7. Sustainable Procurement Sources	15. Reduce Construction Waste (e.g., Over Buying)			
8. Recycled Material Use/Material Reuse				
Environmental Loadings	-	7.3	3	13
1. Greenhouse Gas Emissions/Carbon Analysis	12. Address Liquid Waste Pollutants/Wastewater			
2. Minimize Greenhouse Gas During Construction	13. Toxins & Carcinogens/Heavy Metals			
3. Minimize Greenhouse Gas During Maintenance	14. Wind Obstruction			
4. Design for Greenhouse Gas Reduction	15. Monitor Wind Hazards in Area for Measures Taken			
5. Ozone Depleting Compound Emissions (e.g., CFCs)	16. Sunlight Obstruction			
6. Ozone Depletion Potential	17. Solar and/or Artificial Glare/Light Pollution			
7. Employ Measure to Capture Green House Gases	18. Waste Heat (Release of Heat into Environment)			
8. Monitor Measures to Reduce Green House Gases	19. Encourage/Implement Fuel Efficient Transportation			
9. Refrigerant Management (e.g., Reduction in Use)	20. Flexible Parking Use (e.g., Farmer's Market)			
10. Air Pollution Reduction (e.g., Summer Smog)	21. Reduce/Minimize Parking Capacity			
11. Address Solid Waste Pollutants				
Quality of Life	-	13.2	1	22
1. Indoor Air Quality/Respiratory Health (e.g., Venting)	23. Safety/Health Improvements/Provide Access to All			
2. Air Quality Monitoring (e.g., CO_2)	24. Promote Walking/Cycling/Safety in Pedestrian Areas			
3. Indoor Water Quality (e.g., Legionella)	25. Break/Rest Areas Provided (e.g., Indoor Break Rooms)			
4. Moisture Control	26. Nearness to Open Space/Recreation Facilities			
5. Temperature/Thermal Comfort (e.g., Controllability)	27. Nearness to Community Facilities (e.g., Supermarkets)			
6. Thermal Comfort Verification/Monitoring/Modeling	28. Internet & Communication Usability			
7. Radon Protection	29. Development Density			
8. Electrical Indoor Lighting	30. Community Inclusivity/Diversification of Income			
9. Natural Indoor Lighting & Views	31. Transportation Options Available & Safe			
10. Outdoor Air Pollution (e.g., Combustion Exhausts)	32. Cultural/Historical Preservation			
11. Limit Use of Fertilizers & Other Outdoor Chemicals	33. Consider Crime Prevention & Security (e.g., Lighting)			
12. Light Pollution	34. Impacts to Green Space/Recreation Areas			
13. Noise/Vibration	35. Quality of Life of Community/Impact to Infrastructure			

Table A-1: Taxonomy for Critical Resilience Analysis of Sustainability Assessment Frameworks (Continued)

Measure	Mean (RAFs)	Mean (SAFs)	Min	Max
14. Monitoring of Noise, Vibration, & Odors	36. Improve Social Networks in & Between Communities			
15. Dust Control	37. Maintain Site/Structures for Continued Sustainability			
16. Odors	38. Low Maintenance Interiors/Surface Materials			
17. Minimize Heat Island Effect (e.g., Shading)	39. Provide Space, Equipment, & Access for Maintenance			
18. Provide Circulation of Wind Flow in Outside Environment	40. Outdoor Site Design & Low Maintenance/Landscaping			
19. Reduce Potential for Toxic Pest Control Use	41. Design for Maintenance/Minimize Social Impacts			
20. Traffic Flow and Capacity of Transportation Considered	42. Post Occupancy Survey (e.g., Performance Results)			
21. Community Access/Connectivity (e.g., Mixed-Use)	43. Functionality/Ease of Use			
22. Visual Attractiveness, Appeal, and Comfort				
Economy	-	1.4	0	5
1. Contribution to Overall Economy of Community	6. Residential Project Development Near Job Opportunities			
2. Life Cycle Cost Analysis	7. Contribution to Stimulation of Sustainable Development			
3. Contribution to Workforce Knowledge/Improve Skill Sets	8. Inward Investment Considered			
4. Utilize Local Labor/Diversify Labor Group	9. Impact to Economy of Neighboring Communities			
5. Permanent Local Job Creation				
Other	-	3.6	0	7
1. Design Innovation	9. Best Practice & Responsible Construction Practice			
2. Design for Region	10. Involvement of Certified Official (e.g., LEED®)			
3. Design According to Culture (e.g., Local Character)	11. Effective Sustainability Leadership & Management			
4. Design for Topography	12. Collaboration on Achieving Sustainability Goals			
5. Design Space Considering IT	13. Stakeholder Involvement			
6. Design for Flexibility in Building (e.g., Flexible Space Use)	14. Identify & Address Un-Sustainable Policies			
7. Monitor Performance Sustainability Design Measures	15. Awareness/Education (e.g., Public/Building User)			
8. Building SAFs Incorporated in Community Development	16. Community Involvement in Design & Planning			

APPENDIX B: SUSTAINABILITY, RESILIENCE AND LIFE-CYCLE METHODOLOGIES BACKGROUND

B.1 The Art of Sustainability Tool Development

The most widely accepted philosophical definition of sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987, pg 41). Quantifying and applying this concept in real world situations has been interpreted, measured and employed in varying approaches around the world. One such approach is through the development of sustainability tools and guidelines. Currently, hundreds of tools and guidelines have been developed worldwide for sustainable development. These tools range in their complexity, level of application and geographical range of application. Some are designed to be used internationally, while others are specific to particular countries or locations.

Sustainability tools are often categorized according to the level or type of application. One proposed tool typology or classification of sustainability tools identifies four types of tools, including: 1) Level 1 – product comparison tools, 2) Level 2 – decision support tools for whole buildings 3) Level 3 – assessment framework tools for whole buildings, and 4) supporting tools (Trusty, 2000). Using this typology as a basis, this paper adapts and expands this classification in order to capture tools outside or beyond these four classifications (e.g. site and community), and discusses the current state of the art in sustainability and resilience tools. The expanded classification includes 1) product comparison tools, 2) whole building decision support tools, 3) whole building or building sub-assembly assessment framework tools, 4) site or supporting infrastructure assessment framework tools, and 5) neighborhood or community assessment framework tools.

B.1.1 Product Comparison Tools

These tools are used to weigh one product against one or more alternate products in order to make decisions early in the design or procurement process about which product to use on a project. Some of these tools may incorporate life cycle analysis (LCA) (Trusty, 2000) to identify the environmental impacts of products (e.g. CO2 emissions, embodied energy). BEES (NIST, 2015) is one such example of an LCA-based product comparison tool. Other product level tools provide guidance on products through guides, databases and other formats, or award green labels to products based on certain standards or criteria. While these tools are beneficial in comparing the environmental-friendliness of products, the extent to which comparisons are made are limited to the content of the product database within each tool. Most tools do not include all products on the market and even if there was a tool that did, the amount of time that would have to be invested in making comparisons for every product application within the scope of a project may be unfeasible.

B.1.2 Whole building decision support tools

These are tools used to make building design decisions based on one or only a few metrics (e.g. measures of environmental impacts such as global warming potential). They are also typically supported by objective data and official standards or guidelines (Trusty, 2000). ATHENA is one example of a whole building support tool, which calculates environmental impacts primarily based on the Environmental Protection Agency's TRACI method (ASMI, 2015; US EPA, 2012). Impacts are calculated for building assemblies for different designs and material combinations so that decisions can be made for the most advantageous design (Athena Sustainable Materials Institute, 2010). These tools are beneficial in comparing different design alternatives and are more feasible in their application to projects when compared with product level tools.

B.1.3 Sustainability Assessment Frameworks (SAFS)

These are tools typically used to assess building, site or community level projects based on multiple metrics, measures or criteria normally associated with sustainable development (i.e. economic, environment, and social). Many tools address environmental impacts (e.g. air pollution, water pollution, global warming), resource consumption (e.g. water, fossil fuels, raw materials), quality of life (e.g. air quality, safety, security), and economy. Most of these tools are initially employed early in the design process in order to ensure sustainable development goals are met after project completion. While these tools are more complex and attempt to address multiple issues, many SAFs rely on a combination of subjective and objective data (Trusty, 2000). Some incorporate LCA in order to support some of the measures or procedures within the assessment frameworks (e.g. sustainable material selection). The BREEAM Green Guide is on such example of a LCA supporting document used for BREEAM SAFs (BRE, 2015).

The first SAF developed and released for commercial use was the Building Research Establishment Environmental Assessment Method (BREEAM) in 1990 in the United Kingdom (Reeder, 2010). With the creation of BREEAM in the UK, many other countries followed suit and developed similar SAFs that were adapted for use within their own countries (Reeder, 2010). Green Globes in Canada and LEED in the United States are two such early examples of SAF tools developed in the 1990s (Reeder, 2010). Today, several SAFs exist but only a few are being implemented on a significant number of projects worldwide. Some of the most widely used and firmly established whole building assessment frameworks are part of the BREEAM and LEED assessment suites. BREEAM is the most widely used SAF globally, with around 200,000 buildings certified (BRE, 2012). LEED is also being implemented in several countries, with over 11,000 certified projects, excluding homes (USGBC, 2012). LEED, first launched in 1998, is similar to BREEAM in that it has multiple versions available for different types of projects, including both new construction and renovations.

Many of these tools also employ rating or weighting systems in order to provide an overall score or ranking for the level of sustainability for individual projects and to apply more emphasis to measures that have the greatest potential impact on mitigating environmental degradation. Weightings incorporate a certain level of subjectivity and in order to substantiate weightings, some weighting schemes are developed using scientifically based methods and/or consensus based processes. LEED New Construction 2009, for example, supported weighting decisions with the life cycle impact assessment tool TRACI (US EPA, 2012) and weightings developed by NIST for the BEES tool (USGBC, 2009a). BREEAM employed both a consensus based process and expert panels in the development of the weighting scheme for BREEAM New Construction (BRE, 2011b). While many tools weight measures relative to environmental impact, some tools weight all measures equally (e.g. Haute Qualité Environnementale) (Vazquez et al., 2011).

B.1.4 Whole Building Assessment Frameworks

These are tools used to assess and guide the development of buildings, which can include the new construction or renovation of various types of buildings. Whole building assessment tools exist for commercial, residential and public buildings (e.g. schools and hospitals), and the vast majority of SAFs focus on the sustainable development of whole buildings. Several whole building assessment frameworks award certifications or labels to buildings, which are sometimes validated through an external or third-party auditing process (Trusty, 2000). For example, for USGBC’s LEED building assessment systems projects are audited by the Green Building Certification Institute (GBCI) (USGBC, 2009a). Awards are often based on graded scales (e.g. LEED Certified, Silver, Gold or Platinum), but certification can also be awarded with a single label (e.g. Living Building). Audits often require sufficient documentation in order to validate certifications. Some frameworks also include required measures or prerequisites which must be accomplished in order to be certified.

B.1.5 Site or Supporting Infrastructure Assessment Framework

Recently, a few SAFs have been developed to address single sites or projects that fall outside of building footprints. These have been adapted from existing tools for use in projects such as green spaces and infrastructure (e.g. utility projects, roads, outdoor recreational facilities). While these sites may be connected to buildings, many whole-building SAFs do little to address sites outside of each individual construction project footprint. Envision (ISI, 2012) and Sustainable Sites Initiative™ (SSI, 2009) are two examples of SAFs that address sites or supporting infrastructure.

B.1.6 Neighborhood and Community Assessment Framework Tools

Beyond individual sites or buildings, there are also a few SAF tools that primarily focus on neighborhood or community level development projects. These SAFs focus on multiple buildings, supporting infrastructure and the space around structures. In addition to reducing negative impacts on the environment, community tools also try to shape infrastructure and space to encourage or discourage certain types of behavior through employing architectural design principals or theory. Behaviors related to health, safety, building community economy or social connectedness are usually foci in community SAFs. LEED Neighborhood Development (LEED ND), BREEAM for Communities and CASBEE for Urban Development are three examples of community level SAFs. LEED ND incorporates several design principals and theories associated with "smart growth, New Urbanism, and green infrastructure and building" (USGBC 2009b, pg xii). Examples of some of the principles on which LEED ND is based include mixed land use, compact development, walkable neighborhoods and land conservation (USGBC 2009b). BREEAM for Communities (BRE, 2011a) and CASBEE for Urban Development (IBEC, 2007b) are two more examples of community level SAFs.

B.2 The Art of Resilience Tool Development

Similar to sustainability, the concept of resilience has been defined and evaluated in multiple ways. The Department of Homeland Security defines resilience as the "ability to resist, absorb, recover from or successfully adapt to adversity or a change in conditions" (DHS, 2009). Components or concepts associated with resilience within literature include robustness, redundancy, rapidity, resourcefulness and recovery (Bruneau et al. 2003; Ettouney et al., 2011). Risk is also often key concept associated with resilience, which incorporates elements such as vulnerability, threat and consequences (Ettouney et al., 2011). Other concepts of resilience incorporate system capacity, mitigation, adaptation and hazard-resistance.

Adaptation and adaptation strategies focus on taking actions to react to environmental changes, often at a local scale (McEvoy et al., 2006). In the climate change arena, adaptation is often compared with and contrasted against mitigation, which concentrates on actions taken to prevent damaging environmental changes on the global scale (McEvoy et al., 2006; Tol, 2005). Within resilience, however, there is another definition for mitigation, which is much more local in its application. Local mitigation efforts include actions taken to prevent future damage and loss of life in natural and manmade hazard events (e.g. evacuation planning; disaster preparedness, response and recovery planning; and vulnerability and risk assessments).

Hazard-resistant design is also sometimes discussed within the parameters of resilience. Hazard-resistant design can involve hardening structures and infrastructure so that they are better able to resist the forces of hazard events, or it can be designing or siting structures and infrastructure so they are not exposed to hazard forces. Hazard-resistant designs and policies often incorporate both prescriptive and performance related codes, regulations and requirements; however, there have been recommendations for adopting more performance-based codes (Gilbert, 2010).

Resilience is often discussed or applied at either the structure or community level. There is, however, a connection between structure resilience and community resilience, since structures are subsystems of the entire community. Individual structural resilience can rely on varying assemblies and parts of the structure, while community resilience relies the performance of whole groups of structures (Gilbert, 2010). Structures also interact with each other and the resilience of one structure may impact neighboring structures (e.g. wind-borne, flood-borne or falling debris damage) (Ettouney et al., 2011).

Recent disaster experiences, both natural and manmade, have demonstrated a great need for the improvement in the performance of the built environment and communities during disaster events. Resilience tools have been developed in order to define and assess resilience at different levels of development, mainly at the building and community levels. Resilience assessment frameworks (RAFs) are tools that have been developed to help communities, building owners and users to better identify structural, societal and economic vulnerabilities which can be addressed in order to prevent future damage and speed recovery after and event. These tools are well suited to building adaptation and resilience strategies. RAFs assess and measure the resilience of structures or communities and provide some insight through which improvements to resilience can be made.

RAFs differ from SAFs in that they are typically applied to assess existing buildings and communities, rather than being employed at the design or planning stages of a project. However, these tools have the potential to be incorporated into planning and design phases of new construction, renovation and urban planning type projects. By considering key planning and design vulnerabilities up front, expensive damage repairs, retrofits and upgrades can be avoided later. Some RAF tools may be geographically specific and focus only on hazards present within a certain area (e.g. Sempier et. al., 2010), while others are designed to cover a wider range hazards from multiple geographical areas (e.g. earthquakes, wind, flooding) (e.g. Ettouney et al., 2011).

B.2.1 Resilience Assessment Frameworks for Buildings

Building or structure level RAFs address building features, design and construction that have the potential to impact the vulnerability of a structure or group of buildings given exposure to specific hazards. Assessment metrics can range from general measures (e.g. low, medium or high) to very specific in nature (e.g. walls braced or not braced). The Department of Homeland Security's Integrated Rapid Visual Screen Series (IRVS) is an example of a set of multi-hazard RAFs designed for three types of structures (i.e. buildings, mass transit systems and tunnels). This tool addresses both natural (e.g. hurricanes, flooding, and earthquakes) and manmade (e.g. explosion, cyber-attack, and biological attack) hazards (Ettouney et al., 2011).

B.2.2 Resilience Assessment Frameworks for Communities

Community level RAFs can incorporate a wide range of issues, both structural and non-structural. While structural vulnerability of individual buildings is a key part of community resilience, community RAFs also tend to focus on the vulnerability of components that have a broader impact on the community as a whole (e.g. transportation and utility networks). Bruneau et al. (2003) identified four dimensions to community resilience, including technical, organizational, social and economic in the development of a RAF to assess community seismic resilience. The structural performance of critical infrastructure networks during hazards and how resilience and disaster related issues are managed relates to the technical and organizational dimensions, respectively, while the social and economic pieces are related to alleviating the impacts of hazards within the context of the society and economy (Bruneau et al., 2003).

NIST expanded the number of dimensions of community resilience to seven in the development of the PEOPLES framework (Renschler et al., 2010). The PEOPLES dimensions include population and demographics, environmental/ecosystem, organized governmental services, physical infrastructure, lifestyle and community competence, economic development, and social-cultural capital. PEOPLES uses functionality and interdependencies between a defined set of components within the seven dimensions in determining community resilience. For example, within the physical infrastructure dimension, components include facilities (e.g. residential and commercial) and lifelines (e.g. communication, utilities, and transportation). The PEOPLES framework proposes that the number of interdependencies between functioning components and systems affects the resilience of a community, and that interdependencies can be eliminated through using redundancy and other measures (Renschler et al., 2010).

B.3 Life-cycle Assessment Methodologies

B.3.1 Processed-based LCA

Process-based LCA is an assessment method where you quantify the impact of a product's lifecycle on the environment by determining the environmental flows (i.e., resources and emissions or wastes) within a defined system boundary of a product life-cycle. The product life-cycle is typically defined by four phases or stages; 1) acquisition of raw materials and material production, 2) manufacturing/construction, 3) use, reuse or/and maintenance, and 4) disposal/waste management, end-of-life, and/or recycling (Ashby, 2009; SAIC, 2006; Dixit et al., 2012). A methodology for LCA is outlined in the international standard ISO 14040. This methodology includes four main steps: 1) goal and scope definition, 2) inventory analysis, 3) impact assessment and 4) interpretation.

The complexity of the assessment is related to the extent to which the system boundary is defined (i.e. how much of the life-cycle is captured) within the goal and scope step, and the number of flows captured within the inventory analysis (Trusty, 2010; Ashby, 2009). To simplify LCA sometimes assessors limit the system boundary to exclude process elements that do not have significant environmental impacts or which lie outside the scope of the study (e.g. including only primary flows or only part of the life-cycle) (Ashby 2009; SAIC, 2006). There is little guidance in existing LCA standards on explicitly how to define system boundaries or scopes, which leads to some subjectivity on the part of the assessor (Ashby 2009). Also, when limiting boundaries significant truncation errors can be incurred (Dixit et al., 2010; Lenzen, 2000).

The goal of the inventory analysis is to map flows within defined boundaries and collect data which defines these flows (e.g. energy and emissions) (Trusty, 2010). When inventory data is not available or cannot be collected from a primary source (e.g. industry) studies rely on secondary data sources (e.g. literature or databases) (Trusty, 2010). The environmental impacts of buildings are estimated using material eco-data (e.g. carbon footprint), which is typically based on a per weight quantity or per unit area. The proportion of energy and other environmental impacts contributed by materials depends on the individual eco-properties of the materials and the quantity of materials used in construction (Asif et al., 2005).

B.3.2 Input/Output (IO) Based Analysis

IO-LCA method is a linear model based on economic input/output models. IO-LCA models estimate impact associated with direct and indirect sources of input by converting transactions of money among applicable sectors of the economy into environmental impact data. One example is the EIO-LCA model developed by Carnegie Mellon, which can be accessed through an online tool platform. The EIO-LCA tool outputs environmental impacts and resource requirements for a defined dollar amount (i.e. initial demand) of a particular economic sector of activity (e.g. asphalt paving). The model also outputs all the environmental impacts and resources requirements for economic sectors which supply the activity of interest (Carnegie Mellon University Green Design Institute, 2013a).

Since impacts are computed based on monetary values, errors can result from inaccurate estimates of dollar values. Also, IO-LCA assumes uniformity in individual material types, where in reality materials vary in there compositions, especially in the case of mixtures (e.g. concrete). These variations affect the resulting environmental impacts. Other factors which affect the validity of results include the assumption that impacts are proportional to economic inputs and the double counting of flows within the system (Teloar, 1998).

B.3.3 Hybrid LCA

Hybrid models, which combine process-based analysis with IO-LCA, have been developed (Treloar, 1998). There are varying approaches to combining the two, but the main types described in literature are process-based hybrid analysis and input-output-based hybrid analysis (Dixit et al., 2010; Treloar, 1998). Process-based hybrid analysis involves applying I-O impact data to measured material amounts in the end product. Input-output-based hybrid analysis adjusts an EIO-LCA model using data derived from process-based analysis (Treloar, 1998). The Carnegie-Mellon Hybrid model is an example of a hybrid model, which allows modification of demand input values for supplies based on customized process-based or EIO-LCA data for a particular product (Sharrad et al., 2008; Carnegie Mellon University Green Design Institute, 2013b).

B.4 LCA Metrics

Global warming potential (i.e. GHGs emitted in making a product) and embodied energy (i.e. energy consumed in making a product) data for building materials can be found extensively through literature sources (e.g. Hammond & Jones, 2008), software databases and national databases (e.g. NREL, 2013). While many data sources exist, the variability in data is significant. Hammond and Jones (2008) showed significant ranges in embodied energies from more than 250 sources for three material types: steel (6 - 81.1 MJ/kg), timber (0.3 – 61.3 MJ/kg) and concrete (0.07 – 23.9 MJ/kg). Dixit et al. (2010) and Dixit et al (2012) discuss the variation in embodied energy data for buildings and make a case for the need for standardizing embodied energy measurement. Dixit et al. (2010) identifies ten parameters which impact the variability of embodied energy values (e.g., system boundary definition, location of study area, age of data sources).

Beyond individual material units, embodied energies and GWP of structural sub-systems and whole residential structures vary significantly. Design configurations and material combinations from one house to the next are different, especially when looking across a variety of climates and countries (Dixit et al., 2010). The same variance can be seen in energy consumption and carbon footprint during the use phase, since these impacts depend on many variables (e.g. source of electricity, design of the home, occupant behavior, maintenance and upkeep required). For example, one U.S, study compared two home designs, a standard design and energy efficient design, and estimated the energy efficient design consumed 60% less energy over its life time than the standard home. The largest reductions were associated with the use-phases of the homes (Keoleian et al., 2000).

APPENDIX C: DEPTH-DAMAGE CURVE FUNCTIONS AND CASE STUDY CALCULATIONS

Table C-1: First Floor Only Depth Damage Functions (-1 to 15 feet)

Component	Floor Depth Relative to First Floor (Feet)																			
	-1	-0.5	0	0.5	1	1.5	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Sheetrock																				
Wall, Paper-faced	0	0	25	25	25	25	50	50	100	100	100	100	100	100	100	100	100	100	100	100
Wall, Non-paper-faced	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ceiling, Paper-faced	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100
Ceiling, Non-paper-faced	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bottom Cabinets	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Upper Cabinets	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100
Countertops	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Water Heater	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Floor Insulation Closed-cell Foam	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Floor Insulation All Other types	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Wall Insulation Closed-cell Foam	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wall Insulation All Other types	0	0	25	25	25	25	50	50	100	100	100	100	100	100	100	100	100	100	100	100
Ceiling Insulation Closed-cell Foam	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ceiling Insulation All Other types	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100
Subflooring	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Base Molding	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Paint/ Wallpaper	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Wainscoting	0	0	0	12.5	25	37.5	50	75	100	100	100	100	100	100	100	100	100	100	100	100
Electrical - Floor Receptacles	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Electrical - Wall Receptacles	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Electrical - Switches	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100
Electrical - Fixtures	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100
Dishwasher	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Clothes Dryer	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Clothes Washer	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100
Kitchen Hood	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100
Windows - Floor Level	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Windows - Sill Height	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Windows - High Windows	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100
Doors - Interior	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Doors - Exterior	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Finish Flooring - All (W. S.)	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Vinyl, Carpet, Wood (C.S.)	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Ceramic (C. S.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AC Condenser Unit	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Heating Unit (1st Floor)	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Ductwork (Below 1st)	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Table C-2: Second Floor Only Depth Damage Functions (-1 to 15 feet)

Component	Floor Depth Relative to First Floor (Feet)																			
	-1	-0.5	0	0.5	1	1.5	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Sheetrock																				
Wall, Paper-faced	0	0	0	0	0	0	0	0	0	0	0	0	0	25	25	50	50	100	100	100
Wall, Non-paper-faced	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ceiling, Paper-faced	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ceiling, Non-paper-faced	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bottom Cabinets	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100
Top Cabinets	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100
Countertops	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100
Plumbing Fixtures (WH)	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100
Wall Insulation Closed-cell Foam	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Wall Insulation All Other types	0	0	0	0	0	0	0	0	0	0	0	0	0	25	25	50	50	100	100	100
Ceiling Insulation Closed-cell Foam	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ceiling Insulation All Other types	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Subflooring	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100
Base Molding	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100
Paint/ Wallpaper	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100
Wainscoting	0	0	0	0	0	0	0	0	0	0	0	0	0	0	25	50	75	100	100	100
Electrical																				
Floor Receptacles	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100
Wall Receptacles	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100
Switches	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100
Fixtures	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100
Built-in Appliances																				
Dishwasher	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100
Clothes Dryer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100
Clothes Washer	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100
Hood	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100
Windows																				
Floor Level	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100
Sill Height	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100
High Windows	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100
Doors																				
Interior	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100
Exterior	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100
Finish Flooring																				
All (W. S.)	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100
Vinyl, Carpet, Wood (C. S.)	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100
Ceramic (C. S.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Roof Covering	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100
Roof Sheathing	0	0	0	0	0	0	0	0	0	0	0	0	0	**	**	**	**	**	**	**
Heating Unit (2^{nd} Floor)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100
Ductwork (2^{nd} Floor)	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100

Table C-3: Third Floor Only Depth Damage Functions (-1 to 15 feet)

Component	Floor Depth Relative to First Floor (Feet)																			
	-1	-0.5	0	0.5	1	1.5	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Plumbing Fixtures (WH)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ceiling Insulation																				
Closed-cell Foam	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
All Other types	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Electrical																				
Fixtures	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Roof																				
Covering	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sheathing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
HVAC																				
Heating Unit (3rd Floor Level)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ductwork (3rd Floor Level)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table C-4: First and Second Floor Combined Depth Damage Functions (-1 to 15 feet)

Component	Floor Depth Relative to First Floor (Feet)																			
	-1	-0.5	0	0.5	1	1.5	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Exterior Wall/Siding (All Except Stone and Brick)																				
One-story, Short Duration	0.0	0.0	0.0	2.0	12.5	13.2	16.1	16.6	19.9	21.8	24.1	24.5	26.8	27.2	28.3	28.7	29.2	29.7	30.1	30.6
One-story, Long Duration	0.0	0.0	0.0	15.4	27.6	35.9	41.1	42.2	45.5	54.7	58.1	58.6	60.8	61.3	62.4	62.8	63.3	63.7	64.2	64.6
Two-story, Short Duration	0.0	0.0	0.0	1.3	7.8t	7.8	11.0	11.0	16.1	16.5	18.3	18.3	19.8	19.8	20.1	22.6	22.6	27.1	27.1	27.1
Two-story, Long Duration	0.0	0.0	0.0	1.9	13.7	15.5	21.8	22.1	29.6	30.8	33.2	34.0	38.3	46.3	46.3	48.8	50.1	55.1	56.8	59.4
Brick/Stone Siding Materials	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Foundation - Pier	0.72	1.08	3.19	6.38	6.63	6.63	6.63	6.63	6.63	6.63	6.63	6.63	6.63	6.63	6.63	6.63	6.63	6.63	6.63	6.63
Foundation - Slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Structural Frame	0.00	0.00	0.00	2.33	3.20	3.20	3.69	4.09	4.71	5.23	5.35	5.42	5.42	6.04	6.33	6.33	6.33	6.33	6.33	6.33
Roof - Soffits/Fascia, One-story	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.9	56.7	64.4	64.4	64.4	64.4	64.4	64.4
Roof - Soffits/Fascia, Two-story	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.4	10.4	10.4	10.4	10.4	10.4	20.4	20.4
Stairs - Pier Foundation	0.0	0.0	7.7	31.6	44.9	63.4	67.6	69.1	77.6	79.0	80.4	82.0	82.6	82.6	82.6	82.6	82.6	82.6	82.6	82.6
Stairs - Slab Foundation	0.0	0.0	5.5	16.6	24.5	25.9	44.3	46.4	56.2	58.8	60.2	61.6	62.9	62.9	62.9	62.9	62.9	62.9	62.9	62.9
Fireplace - Two-story, Short Duration	0.0	0.0	0.0	18.4	38.5	45.3	47.3	47.3	47.3	47.3	47.3	47.3	47.3	52.3	52.3	52.3	52.3	52.3	52.3	52.3
Fireplace - Two-story, Long Duration	0.0	0.0	0.0	21.9	51.7	61.9	65.9	65.9	65.9	65.9	65.9	65.9	65.9	70.9	70.9	70.9	70.9	70.9	70.9	70.9

Table C-5: Depth-damage Curve Case Study Calculation Table (-1 to 7 feet)

	Component	TNC	TRC				Floor Depth Relative to First Floor (Feet)								
				-1	-0.5	0	0.5	1	1.5	2	3	4	5	6	7
First Floor	Wall, Paper-faced	3602.90	4386.14	0	0	25	25	25	25	50	50	100	100	100	100
	Ceiling, Paper-faced	2097.54	2508.82	0	0	0	0	0	0	0	0	0	0	0	0
	Bottom Cabinets	1575.21	1689.42	0	0	0	100	100	100	100	100	100	100	100	100
	Upper Cabinets	2412.96	2529.60	0	0	0	0	0	0	0	0	100	100	100	100
	Countertops	4900.00	5059.74	0	0	0	100	100	100	100	100	100	100	100	100
	Water Heater	549.79	599.79	0	0	100	100	100	100	100	100	100	100	100	100
	Wall Insulation	900.25	979.22	0	0	25	25	25	25	50	50	100	100	100	100
	Ceiling Insulation	280.19	429.62	0	0	0	0	0	0	0	0	0	0	0	0
	Base Molding	223.60	365.50	0	0	100	100	100	100	100	100	100	100	100	100
	Paint/ Wallpaper	2169.16	2169.16	0	0	100	100	100	100	100	100	100	100	100	100
	Wall Receptacles	1050.96	1163.04	0	0	0	100	100	100	100	100	100	100	100	100
	Switches	788.12	876.85	0	0	0	0	0	0	0	0	0	100	100	100
	Fixtures	2360.25	2799.25	0	0	0	0	0	0	0	0	0	100	100	100
	Dishwasher	360.88	410.88	0	0	100	100	100	100	100	100	100	100	100	100
	Clothes Dryer	655.54	685.54	0	0	0	100	100	100	100	100	100	100	100	100
	Clothes Washer	636.58	666.58	0	0	0	0	0	0	0	0	100	100	100	100
	Hood	148.37	198.37	0	0	0	0	0	0	0	0	100	100	100	100
	Sill Height	1069.24	1099.08	0	0	0	0	0	100	100	100	100	100	100	100
	High Windows	2739.20	2829.36	0	0	0	0	0	0	0	0	0	100	100	100
	Interior Doors	2121.86	2275.91	0	0	0	0	100	100	100	100	100	100	100	100
	Exterior Doors	575.89	590.81	0	0	0	0	0	100	100	100	100	100	100	100
	Carpet (Slab)	2286.32	2394.54	0	0	100	100	100	100	100	100	100	100	100	100
	Wood (Slab)	3688.73	4102.12	0	0	100	100	100	100	100	100	100	100	100	100
	Ceramic (Slab)	2937.51	3164.96	0	0	0	0	0	0	0	0	0	0	0	0
	AC Condenser Unit	1400.00	1706.60	0	0	0	0	100	100	100	100	100	100	100	100
Second Floor	Fixtures	97.39	114.95	0	0	0	0	0	0	0	0	0	0	0	0
	Roof Covering	14987.82	17030.18	0	0	0	0	0	0	0	0	0	0	0	0
	Roof Sheathing	5498.68	6441.31	0	0	0	0	0	0	0	0	0	0	0	0
	Heating Unit (Attic)	5489.70	5746.66	0	0	0	0	0	0	0	0	0	0	0	0
	Ductwork (Attic)	2654.17	2723.17	0	0	0	0	0	0	0	0	0	0	0	0
Combined	Siding	10976.69	11861.14	0	0	0	2.0	12.5	13.2	16.1	16.6	19.9	21.8	24.1	24.5
	Wall Sheathing	2763.92	3332.49	0	0	0	2.0	12.5	13.2	16.1	16.6	19.9	21.8	24.1	24.5
	Foundation - Slab	5450.19	6526.34	0	0	0	0	0	0	0	0	0	0	0	0
	Structural Frame	37535..43	40212.17	0	0	0	2.33	3.20	3.20	3.69	4.09	4.71	5.23	5.35	5.42
	Roof – Soffits/Fascia	258.35	348.31	0	0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sum		127243.37	140117.61	0	0	7281.2	17290.3	24113.5	25969.5	28195.8	28475.3	35584.6	42749.9	43343.8	43466.8
Permitting			656	0	0	72.8	172.9	241.1	259.7	282	284.8	355.8	427.5	433.4	434.7
Mold Remediation/Cleaning			6646	0	0	0	2494.2	2492.2	2492.2	2492.2	4984.5	4984.5	4984.5	4984.5	4984.5
Total Repair Cost				0	0	7354.0	19955.5	26846.9	28721.4	30970.0	33744.5	40925.0	48161.9	48761.7	48886.0
Total % Damage				0	0	5.8	15.7	21.1	22.6	24.3	26.5	32.2	37.9	38.3	38.4

Table C-6: Depth-damage Curve Case Study Calculation Table (8 to 20 feet)

	Component	TNC	TRC	Floor Depth Relative to First Floor (Feet)												
				8	9	10	11	12	13	14	15	16	17	18	19	20
First Floor	Wall, Paper-faced	3602.90	4386.14	100	100	100	100	100	100	100	100	100	100	100	100	100
	Ceiling, Paper-faced	2097.54	2508.82	100	100	100	100	100	100	100	100	100	100	100	100	100
	Bottom Cabinets	1575.21	1689.42	100	100	100	100	100	100	100	100	100	100	100	100	100
	Upper Cabinets	2412.96	2529.60	100	100	100	100	100	100	100	100	100	100	100	100	100
	Countertops	4900.00	5059.74	100	100	100	100	100	100	100	100	100	100	100	100	100
	Water Heater	549.79	599.79	100	100	100	100	100	100	100	100	100	100	100	100	100
	Wall Insulation	900.25	979.22	100	100	100	100	100	100	100	100	100	100	100	100	100
	Ceiling Insulation	280.19	429.62	100	100	100	100	100	100	100	100	100	100	100	100	100
	Base Molding	223.60	365.50	100	100	100	100	100	100	100	100	100	100	100	100	100
	Paint/ Wallpaper	2169.16	2169.16	100	100	100	100	100	100	100	100	100	100	100	100	100
	Wall Receptacles	1050.96	1163.04	100	100	100	100	100	100	100	100	100	100	100	100	100
	Switches	788.12	876.85	100	100	100	100	100	100	100	100	100	100	100	100	100
	Fixtures	2360.25	2799.25	100	100	100	100	100	100	100	100	100	100	100	100	100
	Dishwasher	360.88	410.88	100	100	100	100	100	100	100	100	100	100	100	100	100
	Clothes Dryer	655.54	685.54	100	100	100	100	100	100	100	100	100	100	100	100	100
	Clothes Washer	636.58	666.58	100	100	100	100	100	100	100	100	100	100	100	100	100
	Hood	148.37	198.37	100	100	100	100	100	100	100	100	100	100	100	100	100
	Sill Height	1069.24	1099.08	100	100	100	100	100	100	100	100	100	100	100	100	100
	High Windows	2739.20	2829.36	100	100	100	100	100	100	100	100	100	100	100	100	100
	Interior Doors	2121.86	2275.91	100	100	100	100	100	100	100	100	100	100	100	100	100
	Exterior Doors	575.89	590.81	100	100	100	100	100	100	100	100	100	100	100	100	100
	Carpet (Slab)	2286.32	2394.54	100	100	100	100	100	100	100	100	100	100	100	100	100
	Wood (Slab)	3688.73	4102.12	100	100	100	100	100	100	100	100	100	100	100	100	100
	Ceramic (Slab)	2937.51	3164.96	0	0	0	0	0	0	0	0	0	0	0	0	0
	AC Condenser Unit	1400.00	1706.60	100	100	100	100	100	100	100	100	100	100	100	100	100
Second Floor	Fixtures	97.39	114.95	0	0	0	0	0	0	0	100	100	100	100	100	100
	Roof Covering	14987.82	17030.18	100	100	100	100	100	100	100	100	100	100	100	100	100
	Roof Sheathing	5498.68	6441.31	0	12.9	25.1	36.6	47.4	57.5	67	75.7	83.5	89.1	94.0	98.2	100
	Heating Unit (Attic)	5489.70	5746.66	0	0	100	100	100	100	100	100	100	100	100	100	100
	Ductwork (Attic)	2654.17	2723.17	0	100	100	100	100	100	100	100	100	100	100	100	100
Combined	Siding	10976.69	11861.14	26.8	27.2	28.3	28.7	29.2	29.7	30.1	30.6	30.6	30.6	30.6	30.6	30.6
	Wall Sheathing	2763.92	3332.49	26.8	27.2	28.3	28.7	29.2	29.7	30.1	30.6	30.6	30.6	30.6	30.6	30.6
	Foundation – Slab	5450.19	6526.34	0	0	0	0	0	0	0	0	0	0	0	0	0
	Structural Frame	37535..43	40212.17	5.42	6.04	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33	6.33
	Roof – Soffits/Fascia	258.35	348.31	20.9	56.7	64.4	64.4	64.4	64.4	64.4	64.4	64.4	64.4	64.4	64.4	64.4
Sum		127243.37	140117.61	63601.4	67624.4	74561.3	75397.0	76211.2	76980.4	77687.2	78481.2	78981.7	79342.4	79659.3	79931.8	80046.4
Permitting			656	656	656	656	656	656	656	656	656	656	656	656	656	656
Mold Remediation/Cleaning			6646	4984.5	6646	6646	6646	6646	6646	6646	6646	6646	6646	6646	6646	6646
Total Repair Cost				69241.9	74926.4	81863.3	82699.0	83513.2	84282.4	84989.2	85783.2	86283.7	86644.4	86961.3	87233.8	87348.4
Total % Damage				54.4	58.9	64.3	65.0	65.6	66.2	66.8	67.4	67.8	68.1	68.3	68.6	68.6

APPENDIX D: ISRA-F DATA

Table D-1: Life-cycle Inventory Data (ISRA-F Model)

	Component	Unit	Embodied Energy MJ/unit	CO^2 Footprint kg CO^2 eq./unit	Water m^3/unit	Component Manufacturing Location[1]	Waste (%)	Source
Site	HVAC: AC	each	10134.10	687.73	16.00	Witchita, KS	0	Ashby (2009); Shah et al. (2008)[2]
Structure	Foundation Slab	S.F.	55.70	4.01	0.01	Local[3]	0	NIST (2015)
	Framing	LBS.	4.53	0.74	0.31	Agusta, GA	10	Ashby (2009)
Roof Covering	Asphalt Roof Cover	S.F.	73.42	1.44	0.01	Hampton, GA	10	NIST (2015)
	Fascia-Soft Wood	S.F.	8.00	0.48	0.63	Agusta, GA	10	Ashby (2009)
	Eaves- Soft Wood	S.F.	2.67	0.16	0.21	Agusta, GA	10	Ashby (2009)
	Sheathing Plywood	S.F.	18.20	0.41	0.00	Hosford, FL	10	NIST (2015)
Exterior Walls	Sheathing Plywood	S.F.	18.20	0.41	0.00	Hosford, FL	10	NIST (2015)
	Wood Siding	S.F.	43.94	0.21	0.01	Agusta, GA	10	NIST (2015)
	Sill Height Windows	S.F.	72.49	3.63	0.03	Lithia Springs, GA	0	Ashby (2009)
	High Windows	S.F.	72.49	3.63	0.03	Lithia Springs, GA	0	Ashby (2009)
	Exterior Door (Fiberglass)	S.F.	7.94	0.56	0.01	Lithia Springs, GA	0	Ashby (2009)
	Exterior Door (Glass)	S.F.	19.06	1.22	0.01	Lithia Springs, GA	0	Ashby (2009)
	Insulation Closed Cell Foam (Wall)	S.F.	2.31	0.10	0.00	Lakeland, FL	10	Ashby (2009)
	Insulation Fiberglass (Wall)	S.F.	2.31	0.10	0.00	Lakeland, FL	10	NIST (2015)
	Insulation Closed Cell Foam (Ceiling)	S.F.	2.58	0.19	0.00	Lakeland, FL	10	Ashby (2009)
	Insulation Fiberglass(Ceiling)	S.F.	2.58	0.19	0.00	Lakeland, FL	10	NIST (2015)
Interiors	Cabinets Upper	L.F	240.93	326.60	482.14	Gibsonton, FL	0	Ashby (2009)[4]
	Cabinets Lower	L.F.	383.90	654.80	969.22	Gibsonton, FL	0	Ashby (2009)[4]
	Countertops Stone (3/4in)	S.F.	37.85	1.21	0.02	Brazil	10	Ashby (2009)
	Solid Wood Flooring	S.F.	12.92	0.77	1.54	Agusta, GA	10	Ashby (2009)
	Broadloom Carpet	S.F.	141.43	5.93	0.44	Dalton, GA	10	NIST (2015)
	Ceramic Tile	S.F.	39.64	2.82	0.01	Dallas, TX	10	NIST (2015)
	Gypsum Board (paper-faced)	S.F.	36.42	2.11	0.00	Gibsonton, FL	10	NIST (2015)
	Gypsum Board (non-paper-faced)	S.F.	44.91	1.97	0.00	Gibsonton, FL	10	NIST (2015), Ashby (2009)[5]
	Latex Paint	S.F.	4.98	0.22	0.00	Orlando, FL	10	NIST (2015)
	Molding Hardwood	S.F.	12.06	0.72	1.45	Agusta, GA	10	Ashby (2009)
	Interior Door	S.F.	21.04	0.62	0.00	Kissimmee, FL	10	Ashby (2009)
	Hot Water Heater	each	1601.43	125.48	4.23	Ashland City, TN	0	Ashby (2009)[6]
	Dishwasher	each	5599.02	264.49	291.79	Findley, OH	0	Ashby (2009)[6]
	Clothes Washer	each	6039.96	360.36	293.36	Marion, OH	0	Ashby (2009); Bole (2006)[6]
	Clothes Dryer	each	5279.41	317.81	291.88	Clyde, OH	0	Ashby (2009); Bole (2006)[6]
	Electrical Wall Receptacles	each	2.29	0.12	0.00	Morganton, NC	0	Ashby (2009)[6]

Table D-1: Life-cycle Inventory Data (ISRA-F Model) (Continued)

	Component	Unit	Embodied Energy MJ/unit	CO^2 Footprint kg CO^2 eq./unit	Water m^3/unit	Component Manufacturing Location[1]	Waste (%)	Source
	Electrical Switches	each	6.54	0.35	0.01	Morganton, NC	0	Ashby (2009)[6]
	HVAC: Furnace	each	4049.55	295.59	7.03	Witchita, KS	0	Ashby (2009); Shah, et al. (2008)[7]
	HVAC: Fan Coil Unit	each	3131.10	243.37	4.40	Witchita, KS	0	Ashby (2009); Shah, et al. (2008)[7]
	HVAC: Ductwork	per story	6073.94	441.16	6.71	Witchita, KS	0	Ashby (2009); (Shah, et al. (2008))[7]

1. Environmental impact of transportation from manufacturing facility to building site base on transportation environmental impact factors provided in Ashby (2009).
2. Assumed locally manufactured and transportation was negligible from manufacturing plant to construction site.
3. Material weights for the air conditioner listed in Shah, et al. (2008) were utilized and environmental impacts for the materials were taken from Ashby (2009).
4. Assumed lower and upper cabinets were made from solid wood and the material weight per linear foot of cabinet was assumed to be 28lbs/lf for lower cabinets and 19lbs/lf for the upper cabinets.
5. Utilized material data for paper-faced Gypsum Board in NIST (2015) and data for fiberglass materials provided in Ashby (2009) to derive environmental impact data for non-paper-faced gypsum board, where fiberglass mesh is used in place of paper.
6. For these components, which consist of a mixture of material types, the materials types considered to contribute to a large percent of weight and material impact were assumed and the percent by weight of each material type were estimated. The hot water heater was assumed to be composed primarily of steel (92 pounds). The dishwasher was assumed to be 75 pounds and composed of 75% polypropylene and 15% steel, with the remaining materials (10%) assumed to be a mixture of other materials which were not included. For the washer, materials weights for the top five materials by percent composition listed in Bole (2006) for an average 2005 washer were utilized for the washer LCA. The dryer was assumed to weigh 104 pounds and composed of 73% steel, 15% polypropylene and 5% Aluminum, which were similar percentages for same materials which composed the washer. The electrical switches and wall receptacles were assumed to be 0.07 pounds a pieces and composed of 33% steel, 33% copper and 33% polypropylene. All environmental impacts for the materials used in the LCA were taken from Ashby (2009).
7. Material weights for the furnace, fan coil unit, and ductwork listed in Shah, et al. (2008) were utilized and environmental impacts for the materials were taken from Ashby (2009). The ductwork materials weights were divided in two, to represent a weight per building story.

Table D-2: Design 1 - First Floor Only Depth Damage Functions (-1 to 15 feet)

Component	Floor Depth Relative to First Floor (Feet)																			
	-1	-0.5	0	0.5	1	1.5	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Sheetrock																				
Wall, Paper-faced	0	0	25	25	25	25	50	50	100	100	100	100	100	100	100	100	100	100	100	100
Ceiling, Paper-faced	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100
Bottom Cabinets	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Upper Cabinets	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100
Countertops	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Water Heater	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Wall Insulation																				
All Other types	0	0	25	25	25	25	50	50	100	100	100	100	100	100	100	100	100	100	100	100
Ceiling Insulation																				
All Other types	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100
Base Molding	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Paint	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Electrical - Wall Receptacles	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Electrical - Switches	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100
Electrical – Fixtures	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100
Dishwasher	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Clothes Dryer	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Clothes Washer	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100
Kitchen Hood	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100
Windows - Sill Height	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Windows - High Windows	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100
Doors – Interior	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Doors – Exterior	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Wood, Carpet (C.S.)	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Ceramic (C. S.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AC Condenser Unit	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Table D-3: Design 1 - Second Floor Only Depth Damage Functions (-1 to 15 feet)

Component	Floor Depth Relative to First Floor (Feet)																			
	-1	-0.5	0	0.5	1	1.5	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Electrical																				
Fixtures	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100
Roof Covering	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100
Roof Sheathing	0	0	0	0	0	0	0	0	0	0	0	0	0	12.88	25.07	36.58	47.4	57.53	66.98	75.73
Heating Unit (2nd Floor)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100
Ductwork (2nd Floor)	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100

Table D-4: Design 1 - Second Floor Only Depth Damage Functions (16 to 28 feet)

Component	Floor Depth Relative to First Floor (Feet)												
	16	17	18	19	20	21	22	23	24	25	26	27	28
Electrical													
Fixtures	100	100	100	100	100	100	100	100	100	100	100	100	100
Roof Covering	100	100	100	100	100	100	100	100	100	100	100	100	100
Roof Sheathing	83.47	89.07	93.99	98.22	100	100	100	100	100	100	100	100	100
Heating Unit (2nd Floor Level)	100	100	100	100	100	100	100	100	100	100	100	100	100
Ductwork (2nd Floor Level)	100	100	100	100	100	100	100	100	100	100	100	100	100

Table D-5: Design 1 - First and Second Floor Combined Depth Damage Functions (-1 to 15 feet)

Component	Floor Depth Relative to First Floor (Feet)																			
	-1	-0.5	0	0.5	1	1.5	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Exterior Wall/Siding (All Except Stone and Brick)																				
One-story, Short Duration	0.0	0.0	0.0	2.0	12.5	13.2	16.1	16.6	19.9	21.8	24.1	24.5	26.8	27.2	28.3	28.7	29.2	29.7	30.1	30.6
Foundation - Slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Structural Frame	0.00	0.00	0.00	2.33	3.20	3.20	3.69	4.09	4.71	5.23	5.35	5.42	5.42	6.04	6.33	6.33	6.33	6.33	6.33	6.33
Roof - Soffits/ Fascia, One-story	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.9	56.7	64.4	64.4	64.4	64.4	64.4	64.4

Table D-6: Design 2 - First Floor Only Depth Damage Functions (-1 to 15 feet)

Component	Floor Depth Relative to First Floor (Feet)																			
	-1	-0.5	0	0.5	1	1.5	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Sheetrock																				
Wall, Non-paper-faced	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ceiling, Non-paper-faced	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bottom Cabinets	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Upper Cabinets	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100
Countertops	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Wall Insulation																				
Closed-cell Foam	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ceiling Insulation																				
Closed-cell Foam	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Base Molding	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Paint	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Electrical - Wall Receptacles	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Electrical - Switches	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100
Electrical - Fixtures	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100
Dishwasher	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Clothes Dryer	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Clothes Washer	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100
Kitchen Hood	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100
Windows - Sill Height	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Windows - High Windows	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100
Doors - Interior	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Doors - Exterior	0	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
Ceramic (C. S.)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
AC Condenser Unit	0	0	0	0	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100

Table D-7: Design 2 - Second Floor Only Depth Damage Functions (-1 to 15 feet)

Component	Floor Depth Relative to First Floor (Feet)																			
	-1	-0.5	0	0.5	1	1.5	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Plumbing Fixtures (WH)	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100
Electrical - Fixtures	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100
Roof Covering	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100
Roof Sheathing	0	0	0	0	0	0	0	0	0	0	0	0	0	12.88	25.07	36.58	47.4	57.53	66.98	75.73
Heating Unit (2nd Floor)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100
Ductwork (2nd Floor)	0	0	0	0	0	0	0	0	0	0	0	0	0	100	100	100	100	100	100	100

Table D-8: Design 2 - Second Floor Only Depth Damage Functions (16 to 28 feet)

Component	Floor Depth Relative to First Floor (Feet)												
	16	17	18	19	20	21	22	23	24	25	26	27	28
Plumbing Fixtures (WH)	100	100	100	100	100	100	100	100	100	100	100	100	100
Electrical - Fixtures	100	100	100	100	100	100	100	100	100	100	100	100	100
Roof Covering	100	100	100	100	100	100	100	100	100	100	100	100	100
Roof Sheathing	83.47	89.07	93.99	98.22	100	100	100	100	100	100	100	100	100
Heating Unit (2nd Floor Level)	100	100	100	100	100	100	100	100	100	100	100	100	100
Ductwork (2nd Floor Level)	100	100	100	100	100	100	100	100	100	100	100	100	100

Table D-9: Design 2 - First and Second Floor Combined Depth Damage Functions (-1 to 15 feet)

Component	Floor Depth Relative to First Floor (Feet)																			
	-1	-0.5	0	0.5	1	1.5	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Exterior Wall/Siding (All Except Stone and Brick)																				
One-story, Short Duration	0.0	0.0	0.0	2.0	12.5	13.2	16.1	16.6	19.9	21.8	24.1	24.5	26.8	27.2	28.3	28.7	29.2	29.7	30.1	30.6
Foundation - Slab	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Structural Frame	0.00	0.00	0.00	2.33	3.20	3.20	3.69	4.09	4.71	5.23	5.35	5.42	5.42	6.04	6.33	6.33	6.33	6.33	6.33	6.33
Roof - Soffits/ Fascia, One-story	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.9	56.7	64.4	64.4	64.4	64.4	64.4	64.4

APPENDIX E: ISRA-W DATA

Table E-1: Life-cycle Inventory Data (ISRA-W Model)

	Component	Unit	Embodied Energy MJ/unit	CO2 Footprint kg CO2 eq./unit	Water m^3/unit	Component Manufacturing Location1	Waste (%)	Source
Site	HVAC: AC	each	10134.10	687.73	16.00	Witchita, KS	0	Ashby (2009); Shah et al. (2008)[2]
Structure	Foundation Slab	S.F.	55.70	4.01	0.01	Local[3]	0	NIST (2015)
	Framing	LBS.	4.53	0.74	0.31	Agusta, GA	10	Ashby (2009)
Roof Covering	Asphalt Roof Cover	S.F.	73.42	1.44	0.01	Hampton, GA	10	NIST (2015)
	Fascia-Soft Wood	S.F.	8.00	0.48	0.63	Agusta, GA	10	Ashby (2009)
	Eaves- Soft Wood	S.F.	2.67	0.16	0.21	Agusta, GA	10	Ashby (2009)
	Sheathing Plywood	S.F.	18.20	0.41	0.00	Hosford, FL	10	NIST (2015)
Exterior Walls	Sheathing Plywood	S.F.	18.20	0.41	0.00	Hosford, FL	10	NIST (2015)
	Wood Siding	S.F.	43.94	0.21	0.01	Agusta, GA	10	NIST (2015)
	Roof-to-wall Straps	Each	1.6	0.12	0.002	Local[3]	0	Ashby (2009)
	Sill Height Windows	S.F.	72.49	3.63	0.03	Lithia Springs, GA	0	Ashby (2009)
	High Windows	S.F.	72.49	3.63	0.03	Lithia Springs, GA	0	Ashby (2009)
	Exterior Door (Fiberglass)	S.F.	7.94	0.56	0.01	Lithia Springs, GA	0	Ashby (2009)
	Exterior Door (Glass)	S.F.	19.06	1.22	0.01	Lithia Springs, GA	0	Ashby (2009)
	Insulation Closed Cell Foam (Wall)	S.F.	2.31	0.10	0.00	Lakeland, FL	10	Ashby (2009)
	Insulation Fiberglass (Wall)	S.F.	2.31	0.10	0.00	Lakeland, FL	10	NIST (2015)
	Insulation Closed Cell Foam (Ceiling)	S.F.	2.58	0.19	0.00	Lakeland, FL	10	Ashby (2009)
	Insulation Fiberglass(Ceiling)	S.F.	2.58	0.19	0.00	Lakeland, FL	10	NIST (2015)
Interiors	Cabinets Upper	L.F	240.93	326.60	482.14	Gibsonton, FL	0	Ashby (2009)[4]
	Cabinets Lower	L.F.	383.90	654.80	969.22	Gibsonton, FL	0	Ashby (2009)[4]
	Countertops Stone (3/4in)	S.F.	37.85	1.21	0.02	Brazil	10	Ashby (2009)
	Solid Wood Flooring	S.F.	12.92	0.77	1.54	Agusta, GA	10	Ashby (2009)
	Broadloom Carpet	S.F.	141.43	5.93	0.44	Dalton, GA	10	NIST (2015)
	Ceramic Tile	S.F.	39.64	2.82	0.01	Dallas, TX	10	NIST (2015)
	Gypsum Board (paper-faced)	S.F.	36.42	2.11	0.00	Gibsonton, FL	10	NIST (2015)
	Gypsum Board (non-paper-faced)	S.F.	44.91	1.97	0.00	Gibsonton, FL	10	NIST (2015), Ashby (2009)[5]
	Latex Paint	S.F.	4.98	0.22	0.00	Orlando, FL	10	NIST (2015)
	Molding Hardwood	S.F.	12.06	0.72	1.45	Agusta, GA	10	Ashby (2009)
	Interior Door	S.F.	21.04	0.62	0.00	Kissimmee, FL	10	Ashby (2009)
	Hot Water Heater	Each	1601.43	125.48	4.23	Ashland City, TN	0	Ashby (2009)[6]
	Dishwasher	Each	5599.02	264.49	291.79	Findley, OH	0	Ashby (2009)[6]
	Clothes Washer	Each	6039.96	360.36	293.36	Marion, OH	0	Ashby (2009); Bole (2006)[6]

Table E-1: Life-cycle Inventory Data (ISRA-W Model) (Continued)

	Component	Unit	Embodied Energy MJ/unit	CO2 Footprint kg CO2 eq./unit	Water m^3/unit	Component Manufacturing Location1	Waste (%)	Source
	Clothes Dryer	Each	5279.41	317.81	291.88	Clyde, OH	0	Ashby (2009); Bole (2006)[6]
	Electrical Wall Receptacles	Each	2.29	0.12	0.00	Morganton, NC	0	Ashby (2009)[6]
	Electrical Switches	Each	6.54	0.35	0.01	Morganton, NC	0	Ashby (2009)[6]
	HVAC: Furnace	Each	4049.55	295.59	7.03	Witchita, KS	0	Ashby (2009); Shah, et al. (2008)[7]
	HVAC: Fan Coil Unit	Each	3131.10	243.37	4.40	Witchita, KS	0	Ashby (2009); Shah, et al. (2008)[7]
	HVAC: Ductwork	Per story	6073.94	441.16	6.71	Witchita, KS	0	Ashby (2009); (Shah, et al. (2008))[7]

1. Environmental impact of transportation from manufacturing facility to building site base on transportation environmental impact factors provided in Ashby (2009).
2. Assumed locally manufactured and transportation was negligible from manufacturing plant to construction site.
3. Material weights for the air conditioner listed in Shah, et al. (2008) were utilized and environmental impacts for the materials were taken from Ashby (2009).
4. Assumed lower and upper cabinets were made from solid wood and the material weight per linear foot of cabinet was assumed to be 28lbs/lf for lower cabinets and 19lbs/lf for the upper cabinets.
5. Utilized material data for paper-faced Gypsum Board in NIST (2015) and data for fiberglass materials provided in Ashby (2009) to derive environmental impact data for non-paper-faced gypsum board, where fiberglass mesh is used in place of paper.
6. For these components, which consist of a mixture of material types, the materials types considered to contribute to a large percent of weight and material impact were assumed and the percent by weight of each material type were estimated. The hot water heater was assumed to be composed primarily of steel (92 pounds). The dishwasher was assumed to be 75 pounds and composed of 75% polypropylene and 15% steel, with the remaining materials (10%) assumed to be a mixture of other materials which were not included. For the washer, materials weights for the top five materials by percent composition listed in Bole (2006) for an average 2005 washer were utilized for the washer LCA. The dryer was assumed to weigh 104 pounds and composed of 73% steel, 15% polypropylene and 5% Aluminum, which were similar percentages for same materials which composed the washer. The electrical switches and wall receptacles were assumed to be 0.07 pounds a pieces and composed of 33% steel, 33% copper and 33% polypropylene. All environmental impacts for the materials used in the LCA were taken from Ashby (2009).
7. Material weights for the furnace, fan coil unit, and ductwork listed in Shah, et al. (2008) were utilized and environmental impacts for the materials were taken from Ashby (2009). The ductwork materials weights were divided in two, to represent a weight per building story.

VITA

Elizabeth Chisolm Matthews, a native of Louisiana, received her bachelor's degree in May 2005 and master's degree in November 2007 at Louisiana Tech University in Ruston, Louisiana. Here master's thesis investigated the impacts of hurricane and flood events on buried urban infrastructure networks, specifically water and wastewater utility systems. She then worked as a public works engineer for the Department of the Army. Here interest in resilience and sustainability grew from past experience with her work and growing up with first-hand knowledge of disasters and the devastating impact hurricanes had on her home state of Louisiana. After working for the army, she began her doctoral graduate education in 2011 as a Louisiana Board of Regents Graduate Fellow. She is currently working as a graduate teaching assistant instructor in Department of Construction Management at Louisiana State University. She will receive her doctoral degree in May 2015.