METHODOLOGY FOR THE INTEGRATION OF ENVIRONMENTAL AND ECONOMIC IMPACTS USED IN THE DYNAMIC DETERMINATION OF THE SUSTAINABILITY OF RESIDENTIAL BUILDING MATERIALS

A Dissertation
Presented to
The Academic Faculty

by

Elizabeth Minné

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy in the
School of Civil and Environmental Engineering

Georgia Institute of Technology
August 2015

METHODOLOGY FOR THE INTEGRATION OF ENVIRONMENTAL AND ECONOMIC IMPACTS USED IN THE DYNAMIC DETERMINATION OF THE SUSTAINABILITY OF RESIDENTIAL BUILDING MATERIALS

Approved by:

Dr. John C. Crittenden, Advisor
School of Civil and Environmental Engineering
Georgia Institute of Technology

Dr. Yongsheng Chen
School of Civil and Environmental Engineering
Georgia Institute of Technology

Dr. Kimberly Kurtis
School of Civil and Environmental Engineering
Georgia Institute of Technology

Dr. Steve French
School of City and Regional Planning
Georgia Institute of Technology

Dr. Javier Irizarry
School of Building Construction
Georgia Institute of Technology

Date Approved: July 16, 2015

ACKNOWLEDGEMENTS

I would like to first thank my advisor, Dr. John C. Crittenden, for being a visionary in the field of sustainability who has supported my work throughout this journey. He has showed me how to keep my eye on the big picture even while I refine and improve the details for my research. Thank you for your encouragement and guidance over the years and for helping me get to where I am today.

I would like to thank my committee members, Dr. Yongsheng Chen, Dr. Kimberly Kurtis, Dr. Steve French, and Dr. Javier Irizarry, for taking the time to be on my committee. You all have pushed me to think critically and pargmatically about how to improve our built infrastructure. I would like to say an extra thank you to Dr. Irizarry for teaching me about the finer points of building construction and his infectiously positive attitude when I needed advice throughout this process.

I would like to thank all members of the Urban Sustainability group at Brook Byers Institute for Sustainable Systems. Jean-Ann James, Arka Pandit, Hyunju Jeong, Zhongming Lu, and Xuewei Yu have all been an integral part of my support system as we adventured to get PhDs, and I could not have done this work without their help and advice along the way. I would like to especially thank Arka for being a mentor to us all, ready and willing to help whenever needed, and Jean-Ann for being my sounding board for ideas, my go-to person to converse with about the stressful situations which happen during graduate school.

I would not be a doctoral candidate without the best study group I have ever had the privilege to be a part of, Pribes and Promers. Rish Vaidyanathan, Stephanie Chinnapongse, Neel Kotra, Jared McGrath, and Jean-Ann James: you all brought the perfect mix of knowledge and fun to help me get through one of the most stressful times in my life, and I could not have passed the preliminary exam without those study hours.

I want to thank my wonderful, endlessly supportive family: my mom, Kimberly, my dad, Stefan, my sister, Valerie, and her husband, Matt. I learned at an early age that with knowledge, my life had no limits. My mom always told me to embrace what makes me different, and dare I say weird, and she has inspired me to use my brain for the good of humanity and for this environment in which we live. Thank you to both my parents for allowing me to push societal boundaries and for being forever encouraging and proud of me.

Special thanks to Chris and my pets: our dog, Puzzles, and our cat, Baggles. Coming home to the best pets who love you unconditionally after a stressful day of work is the best feeling and their smiling, excited faces helped get me through the toughest moments of graduate school. Finally, I want to thank my fiancé, Chris Coen. Chris supported me through every step of this process with words of encouragement, love, and understanding. You have helped me grow as a person and have helped give me the perspective I needed about what is truly important in life. I am so excited to have you by my side, now and forever.

TABLE OF CONTENTS

Page

CHAPTER

LIST OF TABLES

LIST OF FIGURES

Page

SUMMARY

Substantial environmental impacts come from the construction and operation of buildings. As of 2006, more than 75% of the raw materials (by weight) consumed in the United States were used for construction [1]. Additionally, home and commercial buildings consume 70% of electricity and emit 40% of the total greenhouse gas emissions in the United States [2, 3]. Improvements to buildings through more efficient materials could dramatically change the world's energy consumption.

The goal of this research is to conduct a Life Cycle Assessment (LCA) and a Life Cycle Costing (LCC) analysis on various components in homes to determine which materials selections are best in terms of the environment, cost, and overall sustainability performance for the lifetime of a home. All phases of the life of a product are considered; including resources, manufacturing, installation, end-of-life, and most notably, use. Housing components chosen for the study can be retrofitted in an existing home and can make a significant impact on the energy or material use of a home. The housing components studied include flooring, windows, roofing systems, and wall insulation. Energy use was modeled for the windows, roofing systems, and wall insulation studies for a standard single-family home in 17 different US cities, representing all of the climate zones in the US. The energy consumption information was used to determine how using different materials as well as efficiency increases for a material, such as increasing R-value, could affect the environmental impacts and economic impacts over the lifetime of a product and a home. Retrofitting windows, roofing systems, and wall insulation can greatly impact the energy demand of a home for heating, ventilation, and cooling, leading to lower environmental and economic impacts. While flooring does not directly impact

the home's energy demand for heating and cooling, flooring's environmental impacts over a lifetime can be attributed primarily to flooring maintenance, particularly when the maintenance involves vacuuming.

This study asserts the crucial link between the use phase of housing components on the environmental, economic, and sustainability performance of a home. It establishes a sustainability metric which can be utilized by developers, homeowners, or manufacturers to understand the performance of a product employed in a home over the time frame the home is in operation. The developed framework can be employed to look at any components within a home. Additionally, the study investigates the importance of location and climate zone on these results.

After introducing the subject in Chapter I, the subsequent four chapters address the case studies for each housing component; Chapter II on flooring, Chapter III on windows, Chapter IV on roofing systems, and Chapter V on wall insulation. Chapter VI draws overall conclusions on the work. Finally, Chapter VII discusses future research directions. My publications that originated from this research are listed below.

- **Minne, E**., Wingrove, K., Crittenden, J.C. (2015). Influence of climate on the environmental and economic life cycle assessments of window options in the United States. Manuscript accepted to *Energy & Buildings*. doi: 10.1016/j.enbuild.2015.05.039

- **Minne, E.**, Crittenden, J.C. (2015). Impact of maintenance on life cycle impact and cost assessment for residential flooring options. *International Journal of Life Cycle Assessment*, *20* (1), 36-45.

- **Minne, E.**, Crittenden, J.C. Interaction between energy and climate in choosing a sustainable roofing option. Manuscript in preparation.

Additionally, I have done work while pursing my doctoral degree that is outside of the scope of this dissertation. Those have included works on urban sustainability in general and collarborations with other researchers. Those publications are listed below.

- **Minne, E.**, Pandit, A., et al. (2012). Interdependence between electric energy, gas, transportation, and water infrastructures in large urban areas. In *Encyclopedia of Sustainability Science and Technology*; Meyers, R.A., Begovic, M. M., Eds.; Transport Electrical Transmission Systems and Smart Grids; Springer.
- **Minne, E.**; Crittenden, J.C., et al. (2011). Water, energy, land use, transportation, and socioeconomic nexus: A blue print for more sustainable urban systems. In IEEE *Proceedings,* 2011 International Symposium on Sustainable Systems and Technology, Chicago, IL, May 16–18, 2011.
- Jeong, H., **Minne, E.**, Crittenden, J.C. (2015). Life cycle assessment of the City of Atlanta, Georgia's centralized water system. *International Journal of Life Cycle Assessment*. *20* (6), 880-891.

CHAPTER I

INTRODUCTION

1.1 Motivation

There are many definitions for sustainability. Mathis Wackernagel, creator of the ecological footprint concept, defined sustainability as “securing people’s quality of life within the means of nature” [4]. The United Nations’ World Commission on Environment and Development, (the Brundtland Commission) defined sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [5]. We have defined sustainability as the development of the anthroposphere within the means of nature for this work. Here, the anthroposphere is the built environment or the environment that humans created for security, wealth generation, and comfort. For it to exist within the means of nature implies that the anthroposphere must use resources that nature provides, and generate only the kind and amount of waste that can be assimilated into the environment without overwhelming natural cycles. At the global scale, there are several examples that suggest that current development patterns are unsustainable. Presently worldwide, there are approximately 7 billion people using well over 14 Gigatons (Gt) of materials [6]; 14 Gt only includes the US, the European Union, and China, so we would expect this figure to be significantly larger. With less than 5% of the global material use being renewable [7], the extraction of natural resources is beyond what nature can reasonably supply. At the other end, an enormous amount of synthetic and potentially toxic materials are being introduced into the global material cycle.

To fully understand sustainability, one needs to take a whole system approach and incorporate life cycle thinking. In the traditional reductive engineering paradigm, each of the individual infrastructure components, such as water, energy and transportation are optimized separately. However, since the function of all of the components depend on each other, a more optimal solution can occur if all the urban pieces are considered together. These inter-dependencies form an ecosystem of infrastructure that if functioning properly, provides a lasting basis for human enterprise. An example of the interdependencies and the need for them to be considered together is the water-energy nexus. In most developed and developing countries, it takes water to create useful energy and energy to create useful water. This nexus requires a comprehensive understanding not just of power generation or of water resource management, but of both and how they connect and interact at temporal and spatial scales that are both large and small. Considering everything from products to infrastructure systems over their entire life is also crucial to making the most sustainable choices. If a system will perform well, but only for a few years, replacements will need to be considered in accounting for impacts. Built infrastructure tends to last many years, so we need to transition from thinking only about initial costs to costs over times and environmental and social implications. The three pillars of sustainability: people, planet, and profit, must be integrated to get the complete sustainability assessment. The three Ps of the triple bottom line, which is a sort of accounting framework for sustainability, and their interactions can be seen in Figure 1.1 [8].

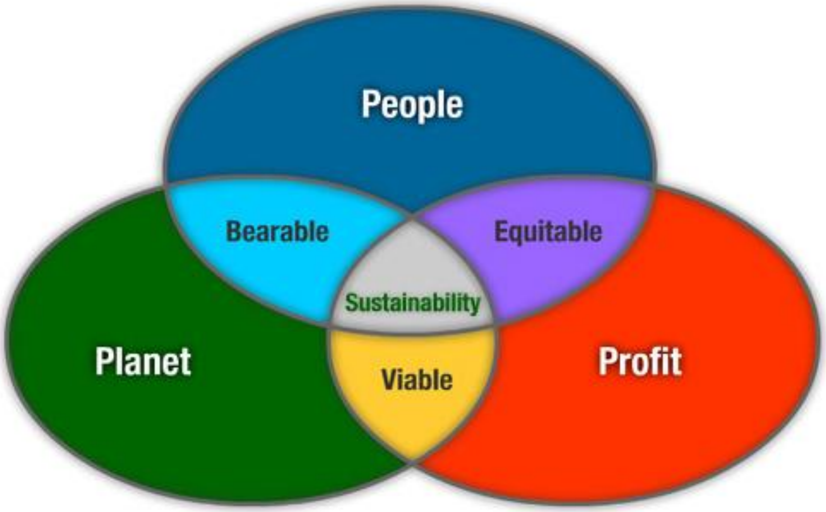

Figure 1.1: The three Ps needed to achieve sustainability: people, planet, and profit [8].

Why is sustainability, particularly urban sustainability, so important? The United Nations Environmental Program (UNEP) chief, Klaus Toepfer, stated in 2005 that “cities pull in huge amounts of resources including water, food, timber, metals and people. They export large amounts of wastes including household and industrial wastes, wastewater and the gases linked with global warming. Thus their impacts stretch beyond their physical borders, affecting countries, regions and the planet as a whole. So the battle for sustainable development, for delivering a more environmentally stable, just, and healthier world, is going to be largely won and lost in our cities” [9]. The UNEP expects 64% of the world’s population to live in urban areas by 2040, a dramatic increase from 50.5% in 2010 [10]. For the developed countries like the US and countries within the European Union, the share of urban population is projected to be 87% in the same time period [10]. With such an influx of people from rural areas to urban areas, cities must be prepared for this mass in-migration. With much of this movement expected in developing countries, those that adopt sustainability as a guiding framework for development could leapfrog other countries that are financially and systemically burdened with maintaining the status quo. New or old, each city has different demographics, cultural values, fiscal and physical constraints, climate, and topology, and any solution to the demand for urban infrastructure, sustainable or not, will have to be uniquely tailored to consider these differences. As we begin to see increasingly severe events which are likely related to climate change, global leaders must work and advocate for change, while being sure to adapt solutions to their countries and cities.

Pacala [11] wrote about the trajectory of the amount of CO_2 being emitted to the atmosphere and what steps would be needed to stabilize global carbon emissions. Emphasizing sustainability in one sector will not be enough to stabilize emissions, so Pacala and his colleagues employed a wedge system where each wedge represented energy efficiency or conservation measures that could greatly lower the global CO_2 emission if selected. To stabilize our emissions, we would need to reduce our trajectory by about 7 wedges, or about 7 Gigatons of carbon per year. Creating buildings with minimal operating energy and energy efficient materials leading a 25% reduction in greenhouse gases is wedge the research generated. Reducing the carbon intensity of building construction materials could be another way to create a wedge.

The earth has a limited amount of natural resources to create our materials. In order to sustain the planet and stay within the means of nature, these resources must not be depleted faster than they can be replenished. Currently, the world is almost entirely dependent on non-renewable materials (around 96% [7]), a percentage that cannot be sustained indefinitely. Figure 1.2 shows how this trend has changed over time, most significantly during the industrial revolution. Water and energy are required to extract and process resources, as well as to manufacture and distribute products created from these resources. The production of materials consumes a large portion of global energy, around 21% [7]. Of the materials created, 84% by weight are ceramics, which is mostly concrete, while other large contributors include wood and steel.

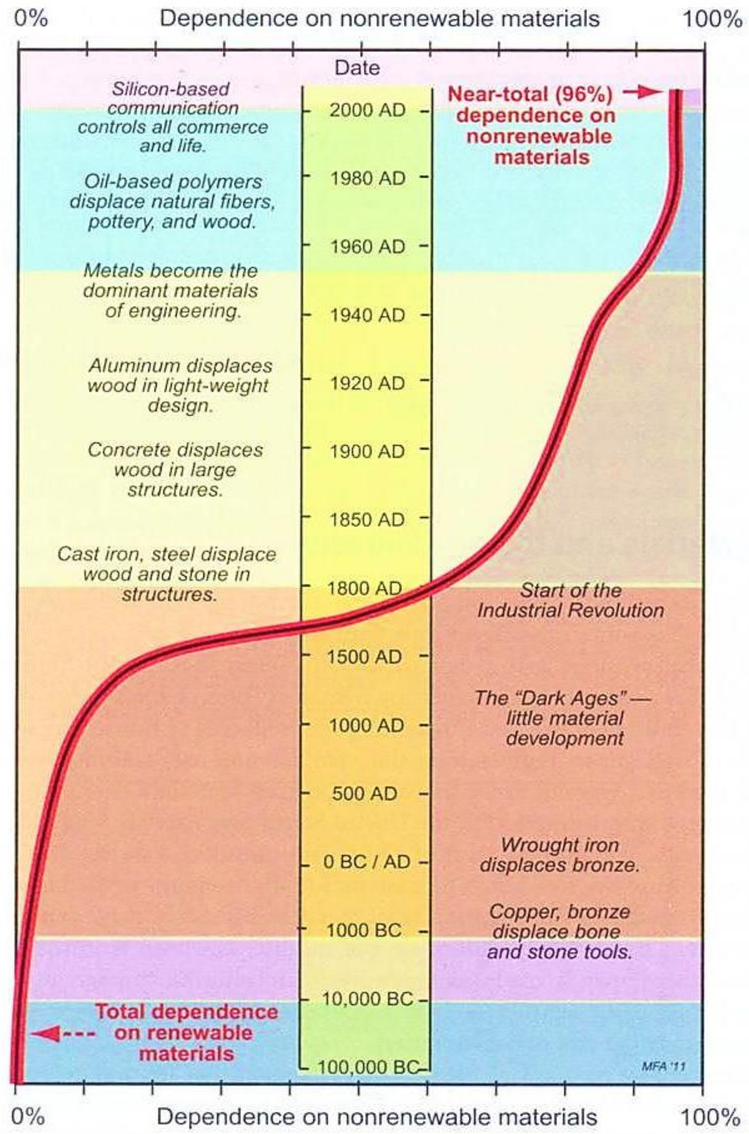

Figure 1.2: Trend in dependence on non-renewable materials over time [7].

Further investigation shows that as of 2006, more than 75% of the raw materials (by weight) consumed in the United States were used for construction [1]. Figure 1.3 shows us that the percent by weight of all materials and the absolute amount of construction materials being used is increasing significantly over time, with notable dips occurring during wars and economic crises which slow down construction. Home and commercial buildings make up about 40% of US energy use [12], as shown in Figure 1.4, consume over 70% of electricity [2], as shown in Figure 1.5, and emit 40% of the total greenhouse gas emissions in the United States [3]. The built infrastructure in the U.S. is estimated to increase by more than 40% from 2000 to 2030, with almost 80% of the growth being residential [13]. Additionally, many residents in currently existing homes are looking to retrofit their homes to be more energy efficient and "greener." Decisions regarding how we plan urban growth and which materials we use for construction will have an impact on resource availability and environmental quality provided to future generations.

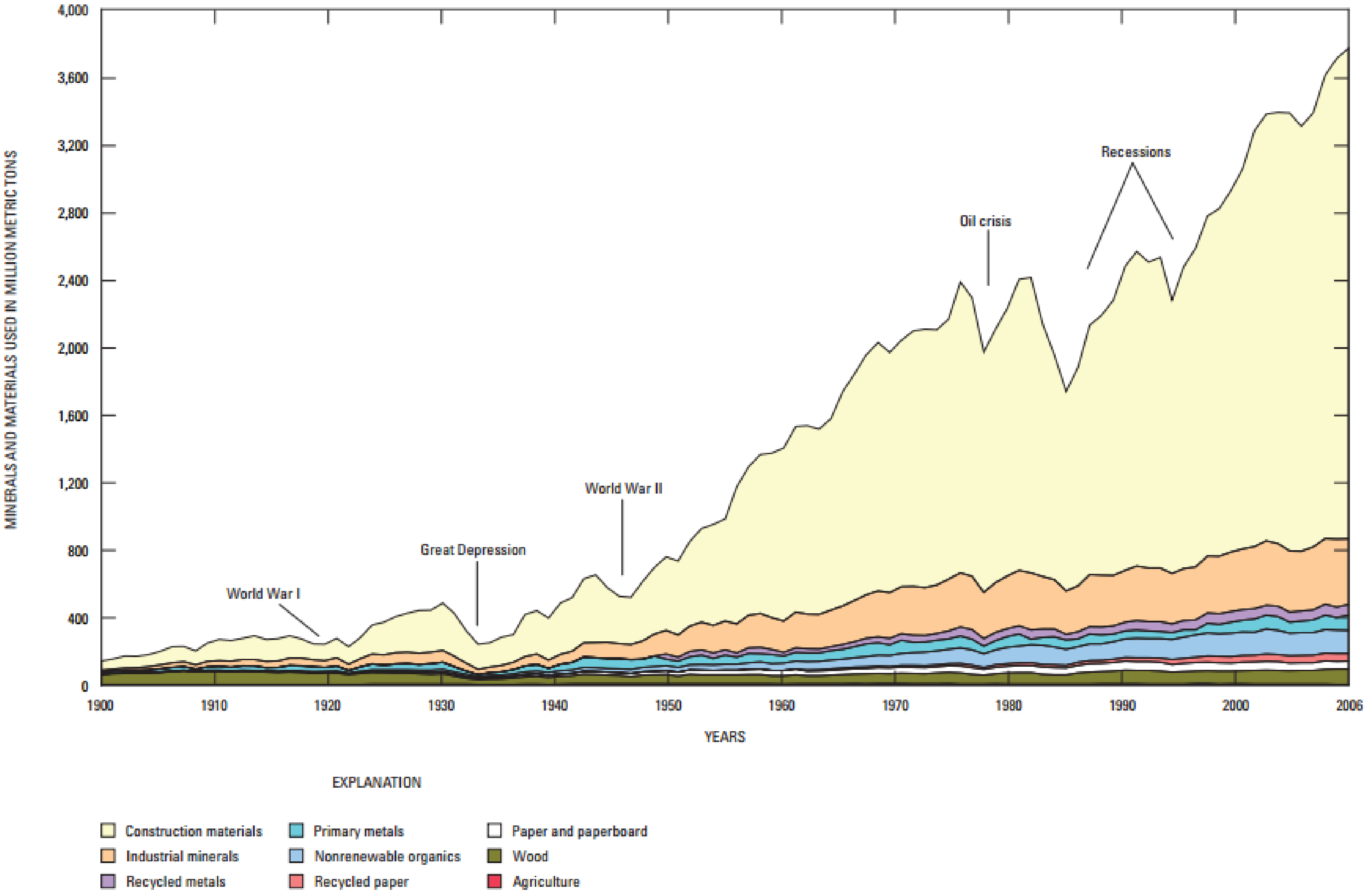

Figure 1.3: Use of minerals and materials in the US over time [1].

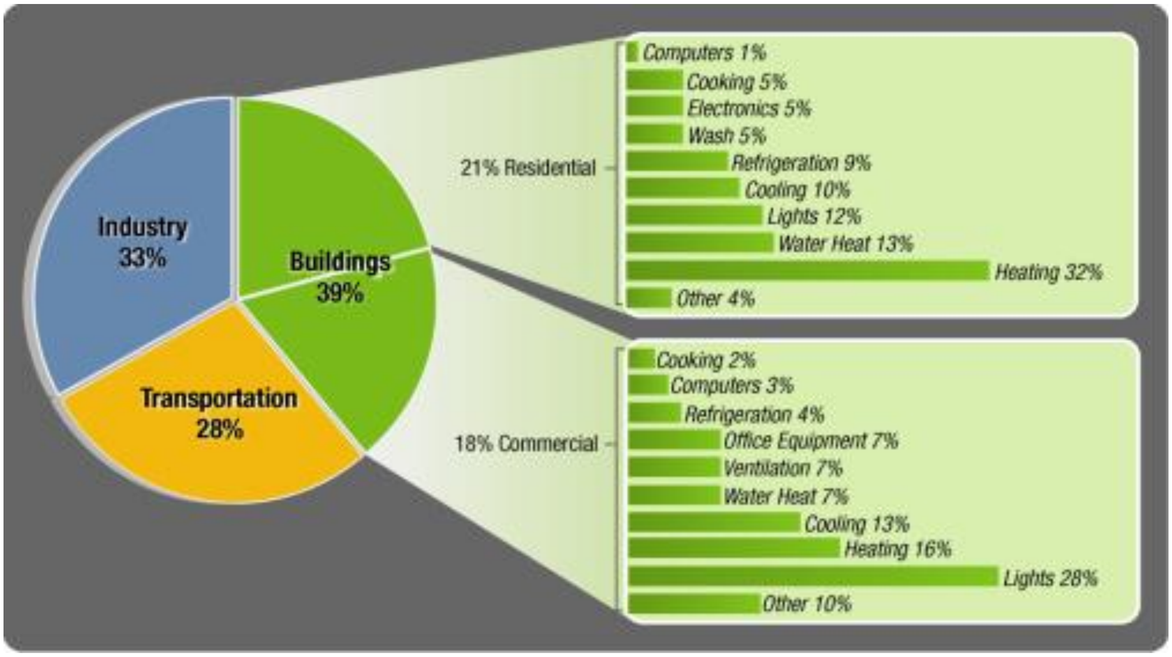

Figure 1.4: Distribution of US energy end uses, 2009 [12].

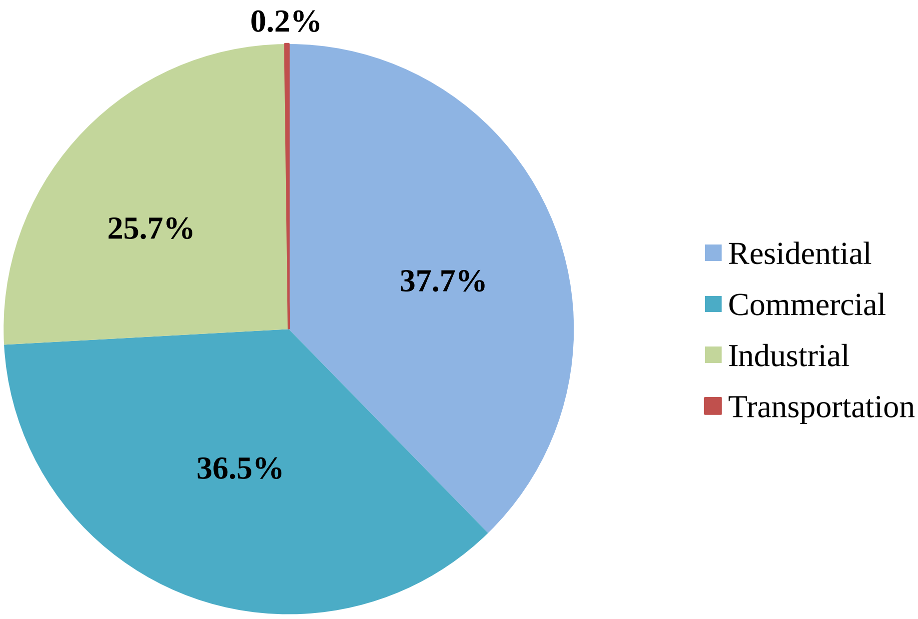

Figure 1.5: Distribution of US electricity end uses, 2014 [2].

1.2 Energy and Material Studies of Buildings

1.2.1 Building Construction

Research in construction has been looking into different ways to build. A life-cycle energy study by Keoleian [14], found that building an energy efficient home could reduce life cycle greenhouse gas emissions by almost two-thirds when compared to an equivalent standard home. The life cycle energy also shows similar improvements, and the materials became a more important life cycle phase as operational energy was reduced. Another study [15] looked into the difference in embedded energy for one-story and two-story homes of the same square footage. The two-story building showed energy savings due to the increased use of lower energy materials like wood instead of concrete. As anticipated, total life cycle energy scales linearly with dwelling size. In the case of low density versus high density developments, annual greenhouse gas emissions and annual energy use were lower for high density development in term of per person and per square meter [16].

Additional studies have compared prefabricated [17] and modular prefabricated [18] building methods to conventional build-on-site construction methods. Prefabricated buildings have lower global warming potential [18] from reduced wastes and lower worker transport needed to the site. Other advantages include being protected from weather, workers can be more specialized in certain stages of the building process leading to higher production, and making better executed buildings [17]. Recently, prefabrication has been scaled up in China to create a 57-story apartment building which was fabricated in four and a half months and erected in 19 days [19]. Three dimension printing is also being studied for its potential to shake up the building construction industry. A high tech firm in China printed 10 single-family homes in one day for an estimated $5,000 each, while architects in Amsterdam and an engineer in California are developing large scale 3D printers for the use of creating housing [20]. Printing houses could lead to greater ability to customize features as well as creating a quick and affordable option for housing in developing countries and refugee camps. Using sustainable, local materials could completely change the environmental impacts of the industry.

As global building stock increases, design for disassembly should be considered. Organizations like the Lifecycle Building Center in Atlanta [21] and the Deconstruction & ReUse Network in Los Angeles [22] take donated materials from deconstructed buildings and sell or donate these materials for new construction, extending the life of products and decreasing construction and demolition waste.

Density of developments, the process in which they are developed, and the size of the buildings are all important considerations in developing sustainable buildings and communities. A number of certification systems have worked to advance the topic of sustainable buildings including Leadership in Energy and Environmental Design (LEED), the Living Building Challenge, and Green Globes to name a few. The most well known, LEED, has sections from location and linkage to education and awareness, but two of the sections are particularly applicable to this research: energy and atmosphere and materials and resources [23]. The greatest numbers of possible points are in the energy and atmosphere section, which reflects the importance of energy use on climate change and the sustainability of a building as has been shown in many studies. New protocols in LEED version 4 are also pushing material transparency and materials improvements, giving points to buildings which use materials that have disclosed their components and impacts as well as points for materials which reduce the life cycle impact of the building.

1.2.2 Building Materials

We have seen progress in improving and creating materials for construction for both structural and non-structural components due to a changing marketplace with LEED and more informed consumers. Although structural materials in the modern era consist mostly of concrete and steel, two materials with large energy requirements and greenhouse gas emissions, these materials can be made more efficient, and in some cases, mostly replaced for low rise buildings. Concrete is composed of Portland cement and aggregates. One study [24] looks at replacing the aggregates (which make up about 13–20% of the CO_2 emissions of cement) with non-reactive "wastes." Although replacing Portland cement may be difficult, reducing its emissions would be an effective step, as it is the most used construction material in the world.

A number of waste materials are explored as possible aggregates, some of which not only lower emissions but also improve strength and durability of cement, such as rice husk ash and fluidized bed cracking catalyst. Beyond improving a material, some studies have compared materials used for exterior walls to see which were most effective over the entire life cycle [3, 25-27]. These studies are very dependent on the climate being evaluated, given that in a colder climate insulating materials are generally preferred because they greatly reduce operational energy, though they have higher embodied energy. The reverse may be true, however, in more temperate climates. Additionally the time of operation of the building is an important factor in making this decision, as some materials may be more durable than others but have increased embodied energy. For these life cycle assessments to be valid, location and time in operation need to be correct.

In the case of residential or other low-rise building, other structural materials may be considered to reduce environmental effects. Milutiene [28] investigates renewable materials for single-family homes. Load-bearing materials included pressed straw, sawn timber, light clay brick, concrete block, and lightweight concrete block; thermo insulating materials included pressed straw, cellulose fiber, glass wool, polystyrene, rock wool, and mineral wool. In both cases pressed straw was the material with the lowest environmental impact. The company Modcell® currently produces prefabricated panels and thermal insulation panels made of straw bale claim to be carbon-negative [29]. Other studies [30, 31] have looked into the effects of additional insulation and alternative insulation on the life cycle energy use of homes. Insulation should be optimized based on climate and material.

Beyond the structural components, a number of studies have investigated the environmental effects of non-structural components. These components have a lower impact, but can often make a significant difference in for homes that are already built, as well as newly constructed. These features are often easier and less expensive to change, while still having an impact on both cost and the environment. Features such as roofing and windows can greatly affect energy usage of a home, and making environmental choices can still be economical when energy savings are considered. Other features, such as flooring also have a significant impact on the environment when the maintenance phase is considered. Flooring features were studied in trying to create a green labeling system, where Rajagopalan [32] compared life cycle assessment (LCA) results for traditional and “green” carpets, paints, and linoleum flooring. Although it is noted that consistency in LCA data is needed to improve this process, the “green” products were favorable in most of the environmental categories.

1.2.3 Building Energy

When considering materials for a building, it is essential to assess how the materials affect the operational phase of the life cycle. The operations phase is often ignored in studies of individual components because it is difficult to determine what amount of energy or chemicals is attributed to a specific component, and there is variation in how an individual lives and uses a component. However, many studies have shown that the operational phase of a building is the most significant life cycle phase in terms of energy and greenhouse gas effects [14, 15, 17, 18, 33-35]. These figures are greatly affected by the length of the operational phase. Skelton [36] showed that office blocks were being used for less than half of their optimal life. The actual life of office blocks was, on average, 60 years, whereas the optimal life was 135 years. Considering the buildings were not being used for their optimal life, their life-cycle emissions per year of use were higher, so adding built-in redundancy may increase the buildings useable life and emissions. Understanding life-cycle optimization for the replacement of various products would help us improve their lifespan [37], including whole buildings and construction materials [36]. Figure 1.6 shows that heating and cooling the living space in a home accounts for about 48% of the energy demand for a US home, on average [38]. The percent of energy needed for heating and cooling needs has actually gone down over the past couple decades to more efficient equipment and materials and an increasing electrical demand with technological advances such as smart phones.

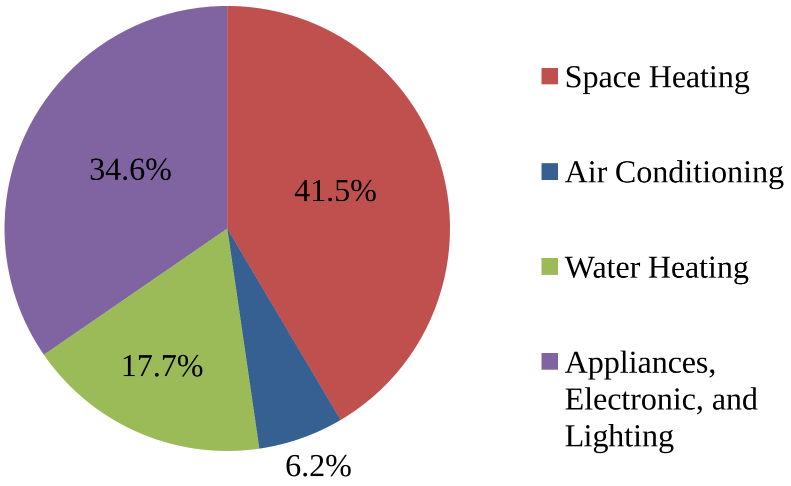

Figure 1.6: Distribution of end use energy consumption in an average US home [38].

1.2.4 Sustainable Building Product Claims

With developments in the field of energy efficiency, the life cycle of residential and commercial buildings can be greatly improved. As buildings get increasingly efficient, the material piece of the life cycle does become more important [14, 15, 18]. Considering the effects of building construction on our energy use and greenhouse gas effects, both the operational phase and the materials phase are meaningful for the future sustainability of our world. However, Rajagopalan's paper [32] mentions that there is currently a disconnect between consumer knowledge on "green products" and their want to buy products that would save them energy and be better for the environment. The life cycle assessment system could be the correct method to rank and label products, but Rajagopalan suggests that results depend on the database and must improve in consistency in order to be used in labeling products. Making the life cycle assessment available and understandable to consumers may help interested consumers better evaluate the green claims of a product.

1.2.5 Current Sustainable Building Tools

A number of building tools are available to aid architects and developers in creating more sustainable homes. Some of these tools are described below, along with their benefits and disadvantages.

- A tool named GreenWizard [39] allows architects and developers to design, build, and monitor projects to make sure they meet LEED (Leadership in Energy and Environmental Design) specifications. It may help in meeting standards set by the U.S. Green Building Council; however, these standards may not always give the optimal environmental solution, and once the minimum for a certain level of certification is achieved there is little motivation for a developer to do more. Additionally, this software is not free or accessible for public use.
- Athena [40] is a data intensive program that allows users to input material data to get an LCA output. It does not have any visual display, and without knowing specifically the material types and amount of those materials needed for a home, the user cannot run the program. The price of the program and lack of material housing data make this program inaccessible to the average consumer.
- Building for Environmental and Economic Sustainability (BEES) [41] is a free, open-access, web-based software developed by the National Institute of Standards and Technology (NIST) that allows the user to compare the environmental and

economic impacts of some components of buildings. It does not have any visual representations, nor can it create a complete building frame for an overall output. The data set offered is small, but provides an accessible interface for anyone to compare selected building products.

- Green Building Studio® [42] is a software which outputs weather conditions, energy use, water use, and alternatives to meet LEED certification for the given home in a specific location. Green Building Studio is an add-on to architecture design software, Autodesk Revit®[43], which is expensive.
- Green Up DC [44] is a web application where residents of DC can plan energy and water saving projects on their property, such as solar panel or rain barrels, and the costs and annual savings are calculated, as well as CO_2 saved or storm water retained. This is a great app for planning projects for DC and will hopefully be expanded or replicated for other cities.
- An energy audit app, iViro [45], lets the user input detailed characteristics about their home and outputs energy costs and emissions. It also suggests upgrades for the home to decrease energy costs. The app does not output environmental or water data, however, and reviews suggest it is often bugged and unusable.
- The website Opower [46], a partnership between Facebook and the National Resource Defense Council, allows the user to input their electricity bill and see how their bill stacks up against friends, standard homes, and homes in the top 20% of energy-efficiency. Opower has a platform for users to interact and share ideas on how to save energy and employs the powerful motivator of competition to improve users’ energy use with respect to their friends.

- GoodGuide [47] is an app that allow the user to scan a barcode of a product, and shows a score for the product’s sustainability performance based on three criteria: health, environment, and society. Users can also set preferences for which issues are most important to them, and the app will suggest products that best fit those criteria. This app currently does not cover building materials, but this could be a useful expansion of the app.
- An app that is being built at the Changing Places lab at MIT, called CityHome [48]. This app allows users to answer a questionnaire about their preferences and what functions they are looking for in their living space [49, 50]. An algorithm is used to output a modular, transitioning apartment home to best fit the consumer’s needs. The interactive app has not yet been released and it does not address environmental concerns for the apartment.

1.3 Research Focus

A great deal of life cycle assessments (LCA) and life cycle costing (LCC) analyses have been done on buildings and building components. However, based on the current research in the literature there are only a few studies on building materials that consider both the cost and environmental impacts of a product, and include all of the phases of its’ life over the lifetime of the building. Additionally, there is growing research on how to best combine LCA and LCC scores in order to make the results easier to communicate; however, there is still room for this research to add to the discussion in this area.

The majority of US buildings are residential [51]. Of those residential units, 74% were built before 1990 [52]. With a majority of housing units being 25 years or older, we have chosen to focus on the components of a home which can be retrofitted, while noting that these choices are often favorable for new construction as well. Figure 1.7 shows the types of housing that is currently operational based on the decade of construction. Around 96% of homes have not had an energy audit performed [52], so the proper retrofits for a home to reduce energy use may not have been considered. To standardize our studies, we assumed the home was a 1-story single-family detached home because 74% of homes were 1-story and 63% were single-family detached homes [52].

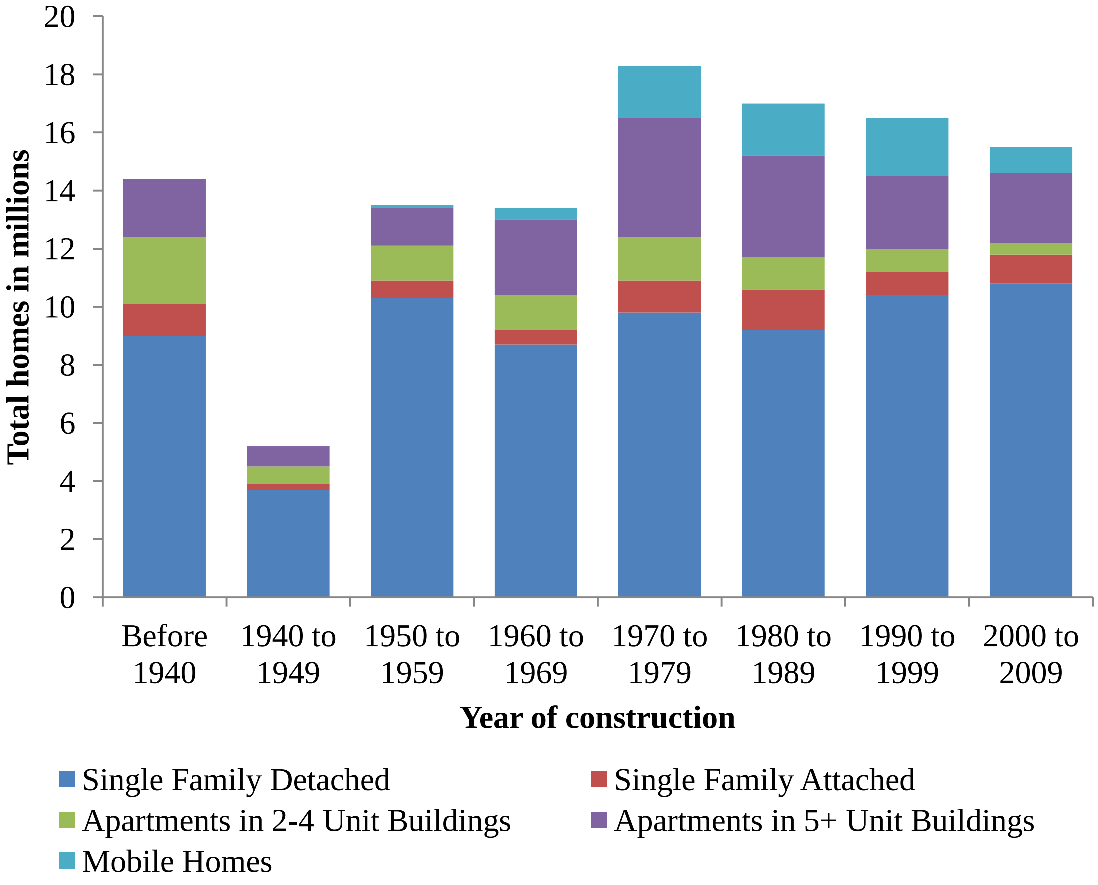

Figure 1.7: Total US residential building stock based on year of construction [52].

We focused on four housing components in the home which have a sizeable energy and environmental footprint: flooring, windows, roofing systems, and wall insulation. Housing components studied were chosen to be components for which the structure of the home would not need to be changed in order to do the retrofit. For each feature, we are accounting for the environmental and economic impacts over the life cycle of a home, which is defined as 60 years [53].

The case studies for the components are also used to develop a scoring system that combines economic and environmental impacts. In this way we can create a scoring system that is easier to communicate to the public, and can be balanced based on the weighted values of economic and environmental impacts.

1.4 Creating a Sustainability Metric

Klöpffer [54] proposed that in order to consider the sustainability of a product, the three pillars of sustainability must be considered: environment, economic, and social issues. The paper noted that in order to do a complete life cycle sustainability assessment (LSCA), three assessments should be completed with the same scope without overlapping (i.e., LCA, LCC, and social life cycle assessment - SLCA). After Klöpffer's paper was published, much of the discussion has been on how to properly integrate these scores [41, 55-57], as well as the relevance of each assessment to total sustainability [58, 59]. Currently, LCA is the only assessment of the three that has been standardized [60], and a code of practice has been developed for LCC [61, 62]. In the case of the SLCA, it is difficult to find quantitative data to compare social impacts and SLCA standards are undeveloped at the moment [56, 61]. For this dissertation, we have chosen to focus on the two more developed pillars (LCA and LCC) to demonstrate which windows are both more environmentally and economically sound over the lifetime of a home.

LCAs, LCCs, and LCSAs were conducted for each case study in this thesis; however, the way the assessments were carried out varies slightly by case due to availability of data and differences in analysis. The general process though remains the same, and is represented in the Figure 1.8.

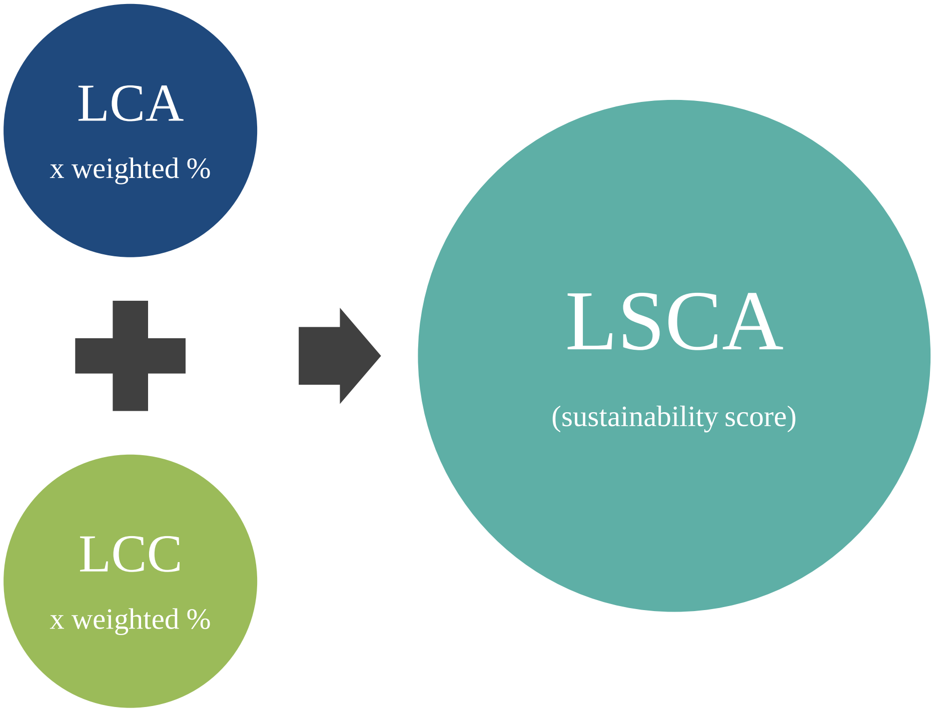

Figure 1.8: Graphic of general process for creating a sustainability score.

1.5 Organization of Dissertation

This dissertation is grouped by case studies. Chapters II – V each present a new case study which explores a housing component, which are, in order, flooring, windows, roofing systems, and wall insulation. Methodology is discussed within each section because although the methods of LCA, LCC, and LCSA are similar throughout, each materials and component system is complex and often varies from the exact methodology of other studies. Each case study also presents results and conclusions specific to that component in the home.

Chapter VI presents overall conclusions which use the studies to gain perspective on the home and investigate where the most significant improvements may be possible. It also highlights the significance of the work presented in this thesis. The final chapter, Chapter VII, presents ideas on the future work that could from the results and methods presented in the case studies.

CHAPTER II

IMPACT OF MAINTENANCE ON LIFE CYCLE IMPACT AND COST ASSESSMENT FOR RESIDENTIAL FLOORING OPTIONS

2.1 Introduction

Most life cycle assessment (LCA) studies for flooring exclude the environmental and economic impacts incurred from the maintenance required due to uncertainty in average cleaning procedures, although some studies indicate it may be the most significant component of the life cycle. This study investigates the impacts of maintenance on types of flooring and develops a single scoring system to compare floors based on both environmental and economic impacts.

Consumers who are choosing flooring for their home may consider a number of factors before deciding, such as texture, aesthetics, noise reduction, and price. Such features can be easily and fairly judged in a store setting, and although exact trends on residential flooring choices are unavailable, carpet is still the most frequently used flooring, with hardwood making gains in popularity [63]. However, it is difficult for a consumer to assess the life cycle effects of flooring on the environment and on cost in such a setting. The Building for Environmental and Economic Sustainability (BEES) tool [41] provides a life cycle impact assessment of building products, including floor coverings, but focuses primarily on the raw materials and manufacturing process, as well as having a set lifetime for the floors and homes. The lifetime of various floor coverings directly affects the total price and environmental impacts of flooring, because with each reinstallation the lifetime effects increase. Additionally, research by Potting [64] and

Jönsson [65], which are the basis for many later studies on flooring, ignore the use phase of flooring due to large uncertainties in how people maintain their floors. However, others [66, 67] have suggested that the use phase may be the most important phase of the life cycle of flooring. Jönsson completed a later study on the use phase of flooring, but this included the off-gassing emissions from the floorings and not the effects from maintaining the floors [68]. Günther's study [66] of resilient floor coverings suggested that cleaning could account for more energy and water demand over a floor's lifetime than the production of the flooring, but did not include cleaning data in the final flooring comparisons due to uncertainty in cleaning habits. Paulsen also studied the significance of frequent and periodic maintenance on vinyl and linoleum flooring in commercial buildings and estimated it to be highly significant in global warming potential and acidification [67, 69]. The primary objective of this study is to determine the significance of floor maintenance on the total cost and environmental impact of floor products. Unlike previous studies, this study conducts a sensitivity analysis on the effect of multiple maintenance routines and frequencies to create a range of effects, and includes this maintenance impacts in the final scoring after determining best maintenance practices.

2.2 Scope of Study

2.2.1 Functional Unit

This study examines five common types of floor coverings, which include nylon 6,6 broadloom carpet, solid hardwood, linoleum, vinyl composition tile, and ceramic tile with recycled glass. In order to compare the different flooring options, data is normalized for 1m^2 of flooring and the total lifetime of a home is considered. The lifetime of a home is assumed to be 61 years based on Atkas's study of the microdata is the 2009 American Housing Survey [53]. Additionally, this study calculates the mean values for the lifetime of each type of flooring based on the distributions of data points from previous LCA studies. Atkas's lifetimes of flooring products are used for this study with the number of installs needed for a home with a service life of 61 years, rounded up to the next integer value as shown below in Table 2.1.

Table 2.1: Number of installs of flooring products for an average US home [53].

	Carpet	**Hardwood**	**Linoleum**	**Vinyl**	**Ceramic**
Lifetime (years)	10	42	22	22	48
Number of installs	7	2	3	3	2

2.2.2 System Boundaries

To create a systematic assessment of all of the flooring, the boundary of the LCA is determined. This study separates the life cycle into five phases which are raw materials, manufacturing, installation, use phase (which is composed of the maintenance and off-gassing of flooring), and end-of-life management of the flooring products. The environmental impacts and costs are multiplied by the number of installs needed for the lifetime of the home. However, some aspects are outside the scope of this study such as human labor, production of the machines and infrastructure used in the creation of the floorings, the effect of the heat capacity of flooring on energy use of the home, and occasional spot treatments due to spills or other reasons. The effect of cleaning on indoor air quality also is outside the bounds of this study. In addition, the transportation of products for distribution to the home is excluded to keep data consistent across the US.

For the LCC analysis, the three phases studied are material and installation, maintenance, and disposal. Material and installation includes the cost of the product as well as the labor and installation costs. Disposal cost includes labor and debris removal. Maintenance costs are more varied by flooring but may include needed chemical cleaners and polish, energy (for vacuuming), water (for mopping), and labor and job material for periodic maintenance when appropriate. Maintenance does not, however, include the cost of personal cleaning equipment such as vacuums, mops, and brooms, as this is out of the bounds of this study.

2.3 Methods

2.3.1 Data Sources

The data for raw materials, manufacturing, installation, and end-of-life phases was obtained from the BEES database of products for “Generic Nylon Carpet Broadloom,” “Generic Linoleum Flooring,” “Generic Vinyl Composition Tile,” and “Generic Ceramic Tile w/ Recycled Glass” [41]. Hardwood flooring is not including in the BEES tool, but is a popular flooring choice in homes. Life cycle inventory data for solid hardwood floor boards was used from an LCA study which compared wood floor coverings [70]. Flooring maintenance data for each kind of floor covering in an average US home does not exist, which is why most flooring LCAs ignore maintenance. In order to study maintenance of flooring, health and industry standards were used and the sensitivity of the estimations was tested. Appropriate selections were made to input the inventory data into SimaPro software (v7.3.3).

The data for costs of material and installation and for disposal were calculated from average national values found on a well-reviewed, vendor neutral home costing website [71]. Maintenance costs came from a number of different sources because maintenance products and procedures are different for each kind of flooring. In the case of carpet, the energy cost for vacuuming comes from the Energy Information Administrations's US average residential electricity cost [72] and the deep cleaning cost is from the ChemDry [73] because it offers dry steam cleaning which was the method discussed in the LCA. Other professional carpet cleaning companies offered comparable prices on their services. For the other floors the cost of recommended cleaners and polishes were used, but also compared to similar products to ensure prices were reasonable for its purpose. The cost of water was based on the national average Environmental Protection Agency reported [74], and is used along with cleaners in the cost of mopping. All costs increase over time due to inflation, which is explained in the methods for LCC.

2.3.2 Treatment of Transportation Information

When choosing materials to compare in the BEES database, the user is supposed to specify the distance the product needs to travel to get to the users home. For certain products this may make a significant difference in the overall results, particularly pertaining to heavier products. In order to consider this, calculations were run for each product using a distance of 0 miles to 3000 miles (the maximum allowed in BEES) with data points every 500 miles. In the case of carpet and linoleum, the difference between 0 miles and 3000 miles makes a difference of less than 10% in the environmental score.

Essentially this means whether carpet is traveling 100 miles from Dalton, Georgia, where 95% of US carpet is manufactured [75], to Atlanta, Georgia or 3,000 miles to Seattle, Washington, the difference in the environmental score is negligible. Vinyl and ceramic, however, are heavier materials and therefore transportation makes a more significant impact on environmental score. Both these materials have manufacturing plants distributed around the country, with ceramic plants in at least 12 states [76] and the EPA estimates the average mileage from retail to customer for vinyl composition tiles is 430 miles [77]. When the transportation for vinyl or ceramic is 500 miles instead of 0 miles, the difference in environmental score is around 10%. The BEES Scores with varied transportation distances are shown in Figure 2.1. Given the limited effect of transportation from retailer to customer, this factor has been omitted for all products.

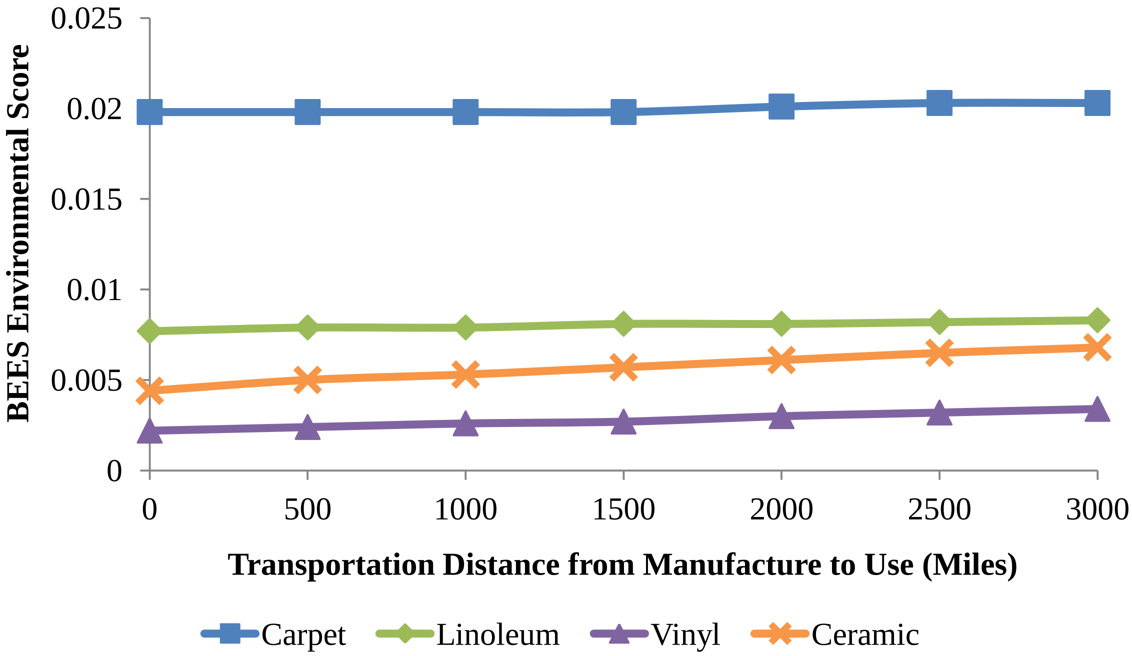

Figure 2.1: Effect of transportation on environmental scores for 4 flooring options.

2.3.3 Maintenance Considerations

For each flooring type, frequent and periodic maintenance procedures were considered. A summary of the recommended cleaning regimens are provided in Table 2.2, with ✓s indicating the maintenance methods that were examined for each kind of flooring, and ×s indicating the method was not examined. The energy and water uses as well as chemicals in cleaners were considered for different cleaning methods. The life cycle of the cleaning apparatus that is used to clean the floor, such as a mop or vacuum, is not included. Because the average frequency and method a US consumer uses to clean their homes is unknown, a number of methods and frequencies are analyzed and compared. The Carpet and Rug Institute, the trade association for US carpet manufacturers, recommends vacuuming carpet at least once per week [78]. To understand the effect of frequency of vacuuming on the total life cycle, we also examined frequent vacuuming and less frequent vacuuming as twice per week and once every other week respectively. The National Wood Flooring Association recommends dust mopping, sweeping, or vacuuming on a regular basis, although what is regular is not defined [79]. The home improvement store, Lowes, recommends dust-mopping daily and using a cleaner on hardwood floor weekly [80]. Little information is available for the frequency to clean vinyl, linoleum, or ceramic tile flooring, but rather sweeping away grit and mopping any stains or spills is recommended.

Based on these resources we tested the frequency of sweeping or dust mopping as once daily, three times per week, and once weekly, and mopping with a cleaner as twice weekly, once weekly, and every other week for all hard floorings, meaning all floorings studied except carpet. All hard floorings also can be vacuumed, so this option also was tested. The energy for vacuuming hard flooring and carpet was different, however, with hard floorings taking just 12 seconds to vacuum per m^2 [70] and carpet taking a minimum recommended 1.2 minutes per m^2 [81].

Table 2.2: Options compared for maintenance phase in flooring study.

	Frequent			Periodic		
	Vacuum	Sweep or Dust Mop	Mop with Cleaner	Dry Steam Clean	Polish	Refinish
Carpet	✓	×	×	✓	×	×
Hard Floors	✓	✓	✓	×	✓	hardwood
Frequency	2x/week	1x/day	2x/week	1x/year	4x/year	2x/install
	1x/week	3x/week	1x/week	0.8x/year	2x/year	1x/install
	0.5x/week	1x/week	0.5x/week	0.667x/year	1x/year	

In addition to the frequent maintenance needed for flooring, each type of flooring has to undergo periodic maintenance. For carpets this entails a deep cleaning every 12 to 18 months depending on the condition of the carpet [82], and the environmental effects are tested for getting a professional deep cleaning at 12 month, 15 month, and 18 month intervals. Polishing hardwood is recommended every two to four months [80], and maintenance tips for the other hard flooring from various manufacturers suggest polishing when surfaces go dull, anywhere from three months to a year. When polishing a floor covering is not enough due to wear, scuffs, or other damage, floors of a certain thickness can be refinished. Nebel notes that wood flooring is sanded down and refinished about every 15 years [70]. Forbo, a manufacturer that accounts for about 90% of the US market share of linoleum [83], notes that for residential use of its flooring refinishing is probably not necessary unless there is a great deal of wear and tear [84]. A floor stripper and floor finish is included in regular maintenance of vinyl flooring to create a polish surface when needed, but the process of sanding and refinishing is not recommended for residential usage [85]. Ceramic tile is finished in the manufacturing process to have an easy to clean sheen, making refinishing unnecessary for most ceramic tiles with proper maintenance.

2.3.4 Sensitivity Analysis

As noted, most life cycle studies of flooring ignore the use phase in the total life cycle. To evaluate how sensitive the total life cycle is to the use phase, we calculate the percentage each maintenance activity accounts for of the total. These assumptions are not verified, so it is important that we test how varying the cleaning regimens affect the LCC and LCA. Although each frequency of maintenance is evaluated and compared, three levels of maintenance are defined for use in this paper; high, regular, and no maintenance. Maintenance conditions are listed in Table 2.3, where high is the highest frequency of each maintenance technique evaluated, no maintenance shows results when all maintenance is neglected, and regular maintenance shows an evaluation based on recommendations and best practices from manufacturers and flooring studies.

Table 2.3: Maintenance parameters compared in flooring study.

		Frequent			Periodic		
		Vacuum	Sweep or Dust Mop	Mop with Cleaner	Dry Steam Clean	Polish	Refinishing[a]
High Maintenance	Carpet	2x/week	-	-	1x/yr	-	-
	Hard Floors	2x/week	1x/day	2x/wk	-	4x/yr	2x/install[a]
Regular Maintenance	Carpet	1x/week	-	-	0.8x/yr	-	-
	Hard Floors	-	3x/wk	1x/wk	-	2x/yr, 4x/yr[a]	1.5x/install[a,b]
No Maintenance	All Floors	-	-	-	-	-	-

[a] Hardwood only

[b] Regular hardwood maintenance defined as 1.5x/ install because hardwood is refinished every 15 years [70] and has a service life of 42 years [53], meaning 3 refinishing procedures over the lifetime of the home, and 1.5 per install.

2.3.5 LCA Method

The LCA process is carried out in four steps, as defined by the ISO 14040:2006 and ISO 14044:2006 standards: goal and scope, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation [86]. After the inventory is completed, the window's environmental life cycle impacts are assessed from cradle-to-grave, and separated into five life cycle stages: resources, manufacturing, installation, use, and disposal (or end-of-life), displayed in Figure 2.2. SimaPro the world's most widely used LCA software [87], was used as the primary software for all stages of the Life Cycle Assessment process. Conducting an LCA in SimaPro requires both foreground data (for a specific product system) and background data (for generic energy, materials, and waste management systems). The former must be collected from specific companies, often through questionnaires.

Figure 2.2: Visual representation of input phases in LCA.

The background data inputs were drawn from the full v3.0 version of the ecoinvent database, which SimaPro has available [87]. The ecoinvent database was launched in the year 2003 to produce an updated, uniform, and high quality set of data for Life Cycle Inventory, thus increasing credibility of methods and results [88]. It is the most comprehensive database on the SimaPro platform, and processes are available as unit or system processes. Whenever presented with a choice in SimaPro between unit or system process, unit was consistently chosen so as to get a more complete representation of impacts.

For this study, ReCiPe Endpoint H (Hierarchist) and ReCiPe Midpoint H were chosen for impact assessment. Compared to other methods, ReCiPe facilitates superior harmony between the midpoint and endpoint category indicators [89]. The individualistic perspective considers a short time of around 20 years, and the egalitarian perspective looks at long timeframe of 500 years. The hierarchist perspective, however, is the ReCiPe's scientific consensus model because unlike the other options (egalitarian and individualistic) it considers common policies over an average timeframe, most frequently 100 years. The method is designed to transform Life Cycle Inventory results from a long list into a smaller set of indicator scores that express the relative severity of the inventory result on an environmental impact category. The two levels are midpoint, which included eighteen measurable indicators such as ozone depletion and water consumption, and endpoint, which is comprised of three highly uncertain indicators: damage to human health, damage to ecosystem diversity, and damage to resource availability. Endpoint indicators have greater uncertainty but are often easier to conceptualize and interpret, while those near the midpoint are more accurate. For example, a midpoint indicator might be freshwater eutrophication (measured in kilograms of phosphorous equivalent) which contributes to an endpoint of damage to the ecosystem (measured in species lost per year). The single score, however, simplifies comparison of materials and so the single score endpoint indicator is used as the metric of environmental impacts (*NI*) for the final comparison.

2.3.6 Uncertainty Analysis

As with any environmental analysis, this comparative LCA involves a certain amount of uncertainty. This uncertainty can come from a number of factors, such as the data being from different locations, uncertainty in input data, or old and outdated data. To account for these uncertainties, SimaPro has a built-in Monte Carlo simulation.

Environmental mechanisms provided the basis for modeling; however, there are three main types of model uncertainty: data uncertainty, correctness uncertainty, and incompleteness [87]. For the ecoinvent database, all data points have an uncertainty specification that assumes a lognormal distribution due to experimental observations following lognormal behavior [90]. This is due to field report that showed that in impact pathway analysis a lognormal distribution was more representative than a normal distribution. The database uses a pedigree matrix developed to estimate standard deviation based off a basic uncertainty factor: for example, the air emissions of CO_2 has a basic uncertainty factor of 1.05 and air emissions combustion of CO has a basic uncertainty of 5.00, meaning the data for air emissions of CO combustion is less certain than the air emissions of CO_2 [91]. The uncertainty factor in a lognormal distribution is the square geometric standard deviation; in the case of a factor of 5.00, 95% of all calculated values are between the input value multiplied by five and the input value divided by five, whereas a factor of 1.00 would indicate no variation and therefore absolute certainty of the input data [87]. There are six additional user defined criteria which can increase the uncertainty factor: sample size, further technological correlation, geographical correlation, temporal correlation, completeness, and reliability.

US data was used, when available; however, ecoinvent largely collects data from European sources. When European data was necessary in order to perform the analysis, the geographical correlation data quality indicator was changed to indicate the data was from a distinctly different area to account for variation in the data. European data was only necessary for man-made materials involved in manufacturing the flooring, such as the polypropylene fibers needed for carpet backing. In the case of electricity, which was the largest environmental contributor, US data was used. Electricity for vacuuming and for manufacturing was entered as the US electricity production mix from the ecoinvent database (when a specific energy mix was not indicated), which was current in 2004 and corrected with temporal uncertainty factors.

With all the data inputs completed, SimaPro can conduct the Monte Carlo simulation which randomizes values from the given input parameters and run for a given number of iterations [92, 93], in our case 1,000 iterations. This data is presented as a distribution, with the median score and a 95% confidence interval.

2.3.7 LCC Method

There has been some debate as to whether LCC is a necessary element to assess and understand the sustainability of a product [58]. However, LCC can help consumers understand the cost of a product over an entire life cycle, meaning that environmentally favorable products that are initially more expensive may be more economical when considering energy-efficiency or replacements over a lifetime [59]. Cost often plays an important role in which flooring a home owner chooses for their home, and looking at the cost of flooring over the entire life cycle of a home might lead consumer selection in a different direction.

In this study, we considered the material and installation costs, the cost of maintenance, and the cost of removing and disposing of flooring. As is specified in the code of practice, only real monetary flows are accounted for so as not to double count environmental impacts, and the scope of the LCC is the same as for the LCA [61]. The National Institute of Standards and Technology (NIST) developed a LCC manual to be used for federal projects [94]. This methodology calculates the price in terms of the present value of money, and assumes current costs and technologies will remain relatively steady. We calculated the total cost of each floor type based on the costs accrued over the 61 year service life of the home. These costs are broken up into three costs (installation, maintenance, and disposal), and are calculated using the Equations shown below. The sum of all costs per install gives the total cost.

$$PV_I = \frac{I}{(1+d)^n} \tag{2.1}$$

$$PV_M = M \times \left[\frac{1-(1+d)^{-n}}{d}\right] \tag{2.2}$$

$$PV_D = \frac{D}{(1+d)^n} \tag{2.3}$$

$$NPV = \sum PV_I + PV_M + \sum PV_D = CI \tag{2.4}$$

PV represents the present value for each phase, and *I, M,* and *D* are the present cost of installation, maintenance, and disposal respectively. The nominal discount rate, *d*, is based on the US Office of Management and Budget's 30-year discount rate of 3.9%, which accounts for the real discount rate and inflation [95]. The discount rate is based on the 30-year interest rates of US Treasuring Notes and Bonds, which NIST uses for in the Handbook on LCC for long-term approximation purposes [96]. Install and disposal costs are calculated for each installation and disposal interval at year *n*, dependent on the lifetime of each flooring, whereas total maintenance costs can be calculated at any year *n*.

The total cost is the Net Present Value (*NPV*) at an *n* of 61 years, which gives us the flooring's economic performance (*CI*).

2.3.8 Single Scoring

To do a complete life cycle sustainability assessment (LCSA), it has been suggested that the three pillars of sustainability be considered by doing three assessments; LCA, LCC, and a social LCA (SLCA) [54]. However, SLCA is far from standardization and quantitative data is largely unavailable, so a number of articles are working to connect results from LCA and LCC [55, 56, 61, 62]. In order to compare the overall performance of each floor type, we had to normalize the environmental and economic scores in a systematic way. The method used is similar to the method used by Centiner [57], which compares the economic and environmental performance of various retrofits to the building without retrofits; however, we do not assume a certain flooring is being retrofitted, and instead normalize performance based on average values in both categories. The performance score should not be seen as a definite score, but rather as a way to compare its performance to other floorings assessed with the same methodology. With the normalized performances, we calculate a single score that indicates the percentage better or worse for each flooring type as compared to the average. The importance of environmental and economic performance is weighted, and can be adjusted. These calculations are made using Equations 2.5-2.7, listed below.

$$NP_i = \frac{(\overline{NI} - NI_i)}{\overline{NI}} \times 100 \tag{2.5}$$

$$CP_i = \frac{(\overline{CI} - CI_i)}{\overline{CI}} \times 100 \tag{2.6}$$

$$P_i = \frac{NP_i \times m_n + CP_i \times m_c}{100} \tag{2.7}$$

NI represents the environmental impact score in Pts from the SimaPro analysis (with $\overline{NI}$ being the average environmental impact score of the five floorings), the CI represents the economic impact is US dollars determined in the LCC analysis (with $\overline{CI}$ being the average economic impact of the five floorings), and m is the weighted importance for both impacts.

2.4 Results and Discussion

2.4.1 LCA Results and Sensitivity to Maintenance

To determine the environmental impacts of the floorings, we input each inventory cradle-to-grave inventory into SimaPro. World ReCiPe Midpoint H (Hierarchist) and Endpoint H were the chosen methodologies for this analysis because they give the most extensive set of midpoint impact categories and have endpoints that lead to a single score which is useful for this comparative analysis [89]. The hierarchist perspective was chosen because it is the consensus model based on common policies and over a common timeframe, compared to individualistic which considers a short timeframe and egalitarian which considers a long timeframe.

A selection of some of the frequently compared midpoint results for the five floorings are shown below in Table 2.4. We can see that in 6 of the 8 categories listed below (and 14 of the 18 total categories), carpet has the highest environmental effects of the floorings. The floorings with the least midpoint environmental effects are relatively equally split in number of categories between linoleum and ceramic tiles, 5 and 3 categories respectively of those listed below. These numbers are somewhat indicative of how floorings will rate when compared with a single score, but because each category is weighted differently based on significance in the single scoring stage, these numbers are not directly used to get the endpoint single score.

Table 2.4: Results for midpoint indicators for total life cycle of flooring types (per m^2).

Impact indicators	**Carpet**	**Hardwood**	**Linoleum**	**Vinyl**	**Ceramic**
Climate change (kg CO_2 eq)	183.11	77.13	15.04	60.43	57.20
Ozone depletion (kg CFC-11 eq)	2.51×10^{-6}	3.70×10^{-7}	1.18×10^{-6}	1.16×10^{-6}	2.83×10^{-7}
Human toxicity (kg 1,4-DB eq)	41.72	22.15	1.51	18.88	11.41
Photochemical oxidant formation (kg NMVOC)	1.29	1.70	0.05	0.10	0.50
Particulate matter formation (kg PM_{10} eq)	0.31	0.13	0.02	0.05	0.14
Ionising radiation (kg U_{235} eq)	22.44	0.69	0.79	9.96	0.29
Terrestrial acidification (kg SO_2 eq)	1.20	0.55	0.10	0.16	0.64
Freshwater eutrophication (kg P eq)	0.043	0.025	0.006	0.014	0.004
Marine eutrophication (kg N eq)	0.101	0.012	0.0072	0.0068	0.0050
Terrestrial ecotoxicity (kg 1,4-DB eq)	0.0133	0.0056	0.0417	0.0036	0.0061
Freshwater ecotoxicity (kg 1,4-DB eq)	1.06	0.74	0.06	0.51	0.49
Marine ecotoxicity (kg 1,4-DB eq)	0.69	0.48	0.03	0.44	0.20
Agricultural land occupation (m^2a)	0.95	0.66	5.36	0.46	0.13
Urban land occupation (m^2a)	0.56	0.46	0.05	0.14	0.15
Natural land transformation (m^2)	0.005	0.003	0.013	0.002	-0.002
Water depletion (m^3)	1.42	0.12	1.16	0.20	0.03
Metal depletion (kg Fe eq)	0.56	0.94	0.13	1.06	0.10
Fossil depletion (kg oil eq)	63.52	23.40	7.50	10.74	25.46

In comparing the total environmental effects of floorings, the endpoint indicators from the World ReCiPe simulations are used. The most comprehensive methods in SimaPro use European averages and world averages not North American, so the world averages were used in this method. Single scores are given in units of points (Pts), where one point is equal to one thousandth of the yearly environmental load of one average person.

To demonstrate the possible effect of maintenance on each flooring type, the life cycle with no maintenance is compared to the life cycle with high maintenance. Figure 2.3 demonstrates that maintenance can be a significant piece of the life cycle and in the case of carpet actually more than doubles the environmental impact (an increase of 114%). To further quantify the significance of each cleaning procedure, we computed its percent contribution to the total life cycle. The results concluded all sweeping, mopping, and polishing procedures for hard floorings were negligible in terms of the total life cycle, all being well under 0.05% of the total score. Refinishing hardwood accounted for under 1% of hardwood’s life cycle, and maximizing steam cleaning to once per year for carpet only increased the score by less than 3%.

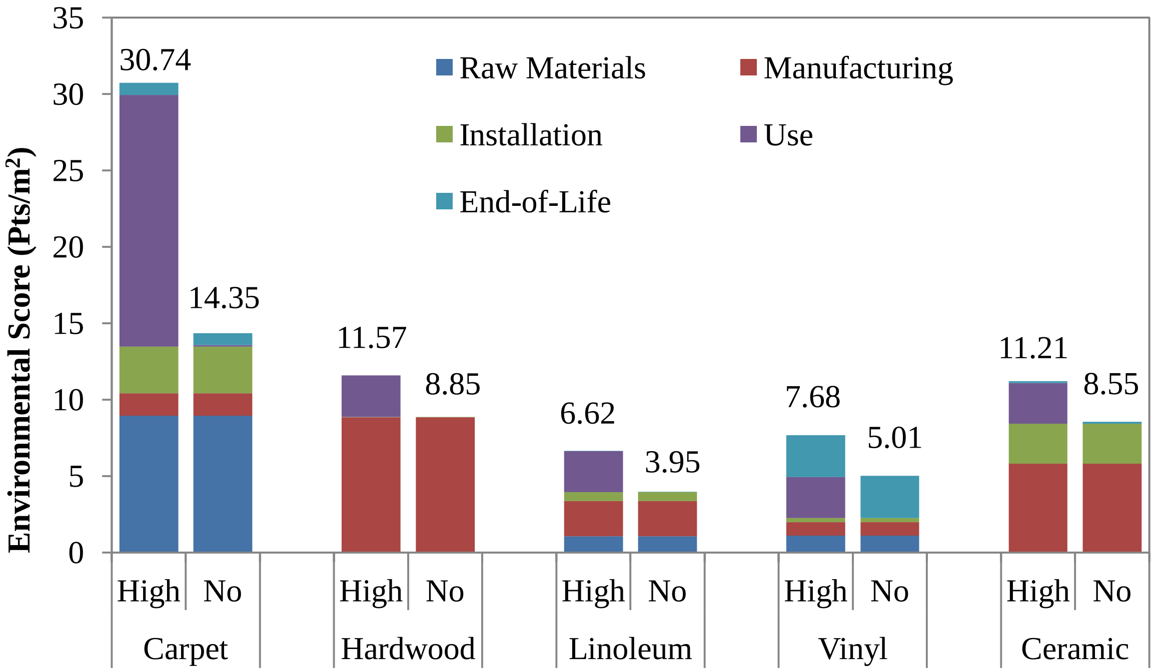

Figure 2.3: Maintenance analysis of floorings broken into phases of the life cycle.

However, the energy consumed for vacuuming each type of flooring was significant. When vacuuming is included in the life cycle two times per week, it constitutes over 50% of the life cycle impacts of carpet and 40% of the life cycle impact of linoleum. Figure 2.4 shows the percentage each flooring type is affected by various levels of vacuuming. Although it is uncertain how often the average citizen vacuums or cleans their floor, we can see how the life cycle is effected over a range. For all four hard floorings, sweeping and mopping was chosen as a viable alternative to vacuuming for analysis of regular maintenance.

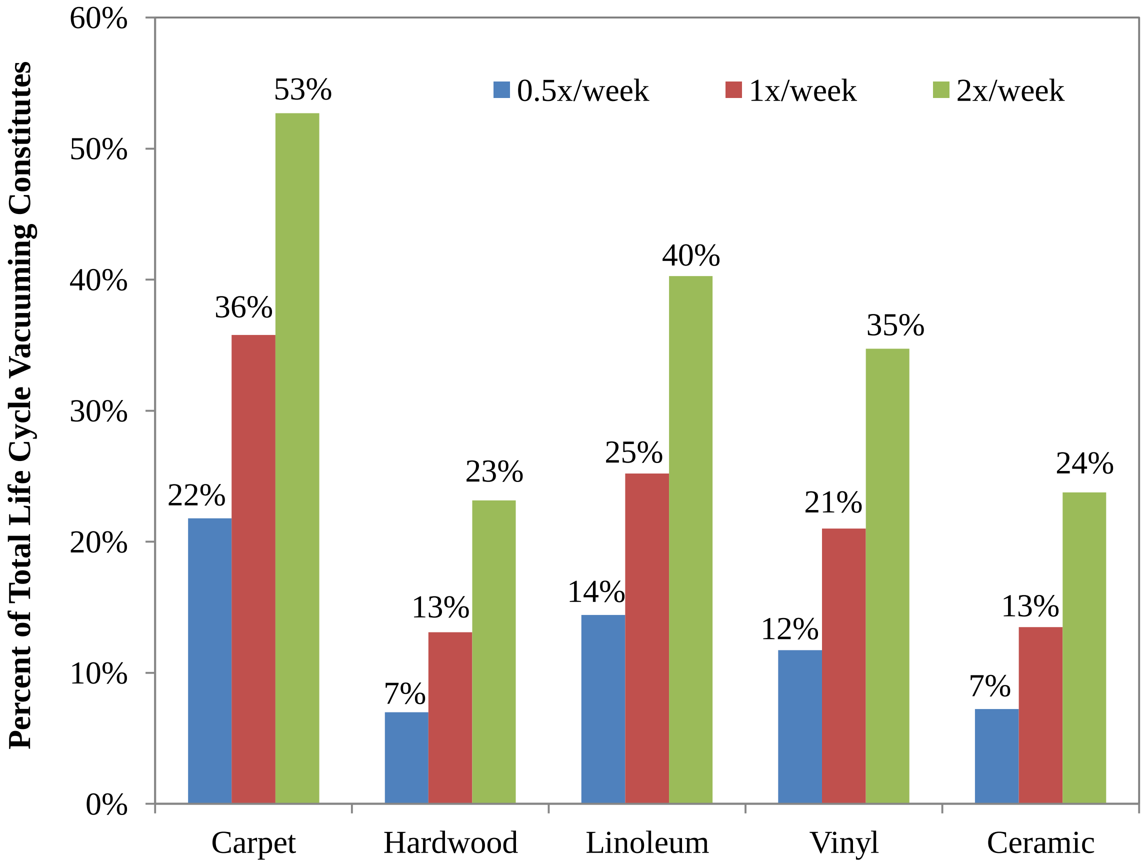

Figure 2.4: Significance of three frequencies of vacuuming on total life cycle.

Beyond the effects of maintenance, we also can note that different phases of the life cycle are more significant for some floorings that others. The raw materials needed for carpet are heavily dependent on petroleum products which lead to high environmental effects, making up 62% of the total score for no maintenance. In the case of hardwood and ceramic tiles, the majority of environmental effects comes from manufacturing (99% and 68% respectively), which is due to the extensive energy needed to kiln-dry both of these products. Linoleum is made from mostly natural materials (mostly linseed), so the energy to manufacture linoleum also is the most significant phase for linoleum without maintenance, comprising 59% of the total score. The end-of-life disposal of vinyl has a significant effect of 55% on its life cycle because polyvinyl chloride products release a number of toxic byproducts into the environment, such as phthalates and contributors to toxic compounds like dioxins [97].

2.4.2 Uncertainty Analysis Results

A Monte Carlo simulation was run for each of the floorings under regular maintenance conditions. Figure 2.5 shows the spread of environmental scores within a 95% confidence interval for each flooring type based on the uncertainty analysis. Based on the 1,000 sample uncertainty analysis, we calculated p-values to prove that there was not a relationship between any of the flooring options, which is a rejection of the null hypothesis. The p-value always showed very strong presumption against null hypothesis, except in case of hardwood vs. ceramic (p-value =0.0305) shows strong presumption against null hypothesis. Furthermore, all floorings were compared in the Monte Carlo simulation which presented the percentage of trials in which one floor type had a greater environmental score than a different floor type.

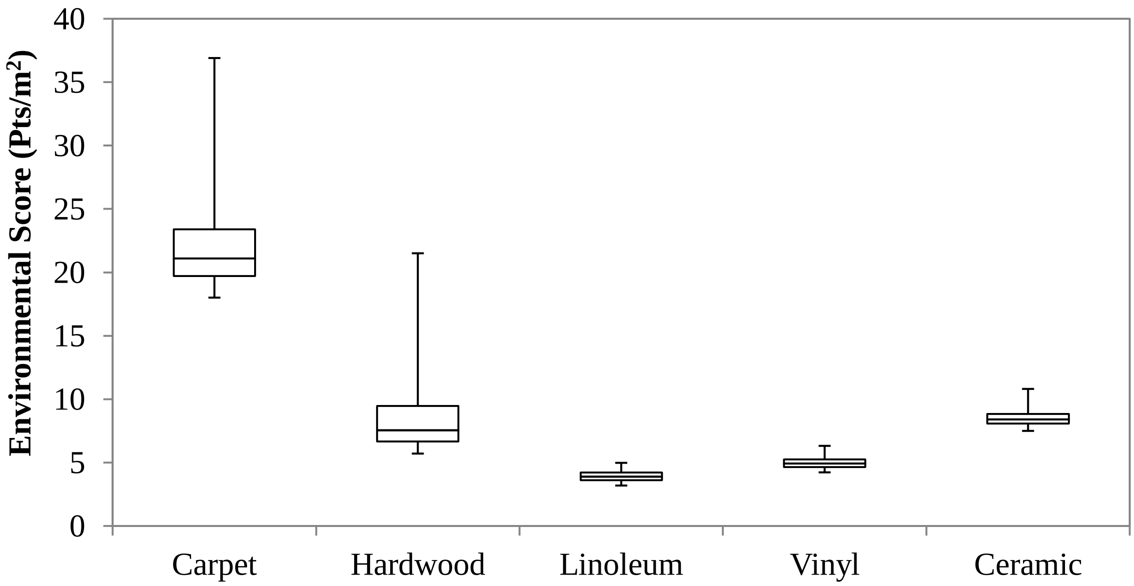

Figure 2.5: Distribution of flooring scores in uncertainty analysis.

Carpet was greater than all other floor types in 100% of trials, giving it the largest environmental impact. Linoleum was lowest in 100% of trials when compared with carpet, hardwood, and ceramic, and rarely higher than vinyl (4.2% of trials), making it likely the flooring with the smallest environmental impact. Vinyl is lower than all flooring except for linoleum, for which it is larger in 95.6% of trials. Hardwood looks to have the second highest environmental impact, but the mean is largely influenced by outlier score, and it is actually has a lower environmental impact than ceramic in 66.9% of trials, but the percentage is not significant enough to say with certainty that hardwood has a smaller environmental impact than ceramic.

2.4.3 LCC Results

The cost of all five flooring types with a regular maintenance schedule over their lifetime is shown in Figure 2.6. Despite carpet being the cheapest to install initially, over the lifetime the 6 replacements needed make it one of the more costly options. Hardwood has a higher first install cost than carpet, but is replaced only once, with the majority of cost coming from cleaning, polishing, and refinishing. Linoleum and vinyl are more balanced in terms of cost over the three phases. Ceramic has a comparatively high material and install cost, but has low maintenance and in the total life of a home is the second least expensive option, and the least expensive at a lower discount rate (below 2.5%). Linoleum is the least expensive option overall, and this holds true for discount rates above 2.5%. Including maintenance in the LCC proves significant for most floor types, making up 49% of hardwood cost, 30% of carpet and linoleum cost, and 29% of vinyl cost.

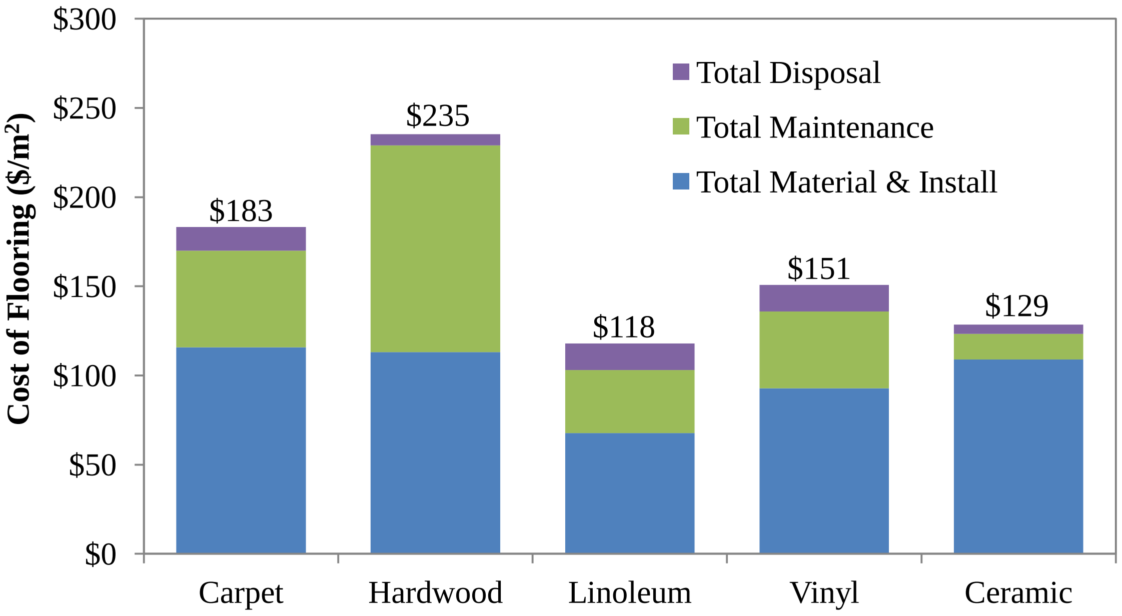

Figure 2.6: Life cycle costing of flooring options.

2.4.4 Single Score Results

The single scoring methodology was used to determine an overall performance score. After the economic and environmental scores were normalized, they were weighted in five ways to show differences in single scores based on the weighted importance of economic and environmental impacts. Five ratios were tested for the weighting where environmental scores are the only factor (100%), and are heavily weighted (75%), where economics are the only factor, and are heavily weighted, and where environmental and economic scores were equally weighted. Shown in Table 2.5 are the percentage better (+) or worse (-) each flooring is compared to the average of all floorings given the weighted ratios of economic to environmental scores. The best scoring flooring option (linoleum) and the worst scoring (carpet) do not change rank for these weighted ratios (with the exception of 100% economic, for which hardwood is the worst performing floor), however, we can see a heavily weighted economic score gives values that are more clustered and heavily weighted environmental scores have a greater spread.

Table 2.5: Performance of floorings over the lifetime of home.

	Performance for different weighted economic/environmental ratios (%)				
Floor types	0/100	25 / 75	50 / 50	75 / 25	100/0
Carpet	-131.0%	-101.3%	-71.6%	-42.0%	-12.3%
Hardwood	+9.5%	-3.9%	-17.3%	-30.8%	-44.2%
Linoleum	+59.7%	+51.7%	+43.7%	+35.7%	+27.7%
Vinyl	+48.9%	+38.6%	+28.2%	+17.9%	+7.6%
Ceramic	+12.9%	+15.0%	+17.0%	+19.1%	+21.2%

This evaluation looks at the scores only at the end of the service life of the home, however, homeowners may renovate at any point within this service life. The cost and environmental scores change over time, so the best performing floor for 61 years may not be the best performing floor for 40 years. Figure 2.7 illustrates the cumulative cost and environmental scores over the service life of a home. Steps in these scores occur from installations and disposal, and in the case of hardwood 15 year increments of refinishing the floor. Maintenance costs happen yearly, giving these costs a slope, but only in the case of carpet does maintenance affect the yearly environmental score. This is because vacuuming and steam cleaning create substaintial environmental effects, but mopping and polish the hard floors does not. For a weighted single score of 50/50, in the first 10 years carpet is an above average flooring, wheras ceramic is well below average. However, with the installs needed for carpet, after a period of 18 years carpet always has the worst performance and ceramic has the best performance for a service life between 44 and 47 years. For renovations, the remaining service life of the home is an important factor in choosing flooring.

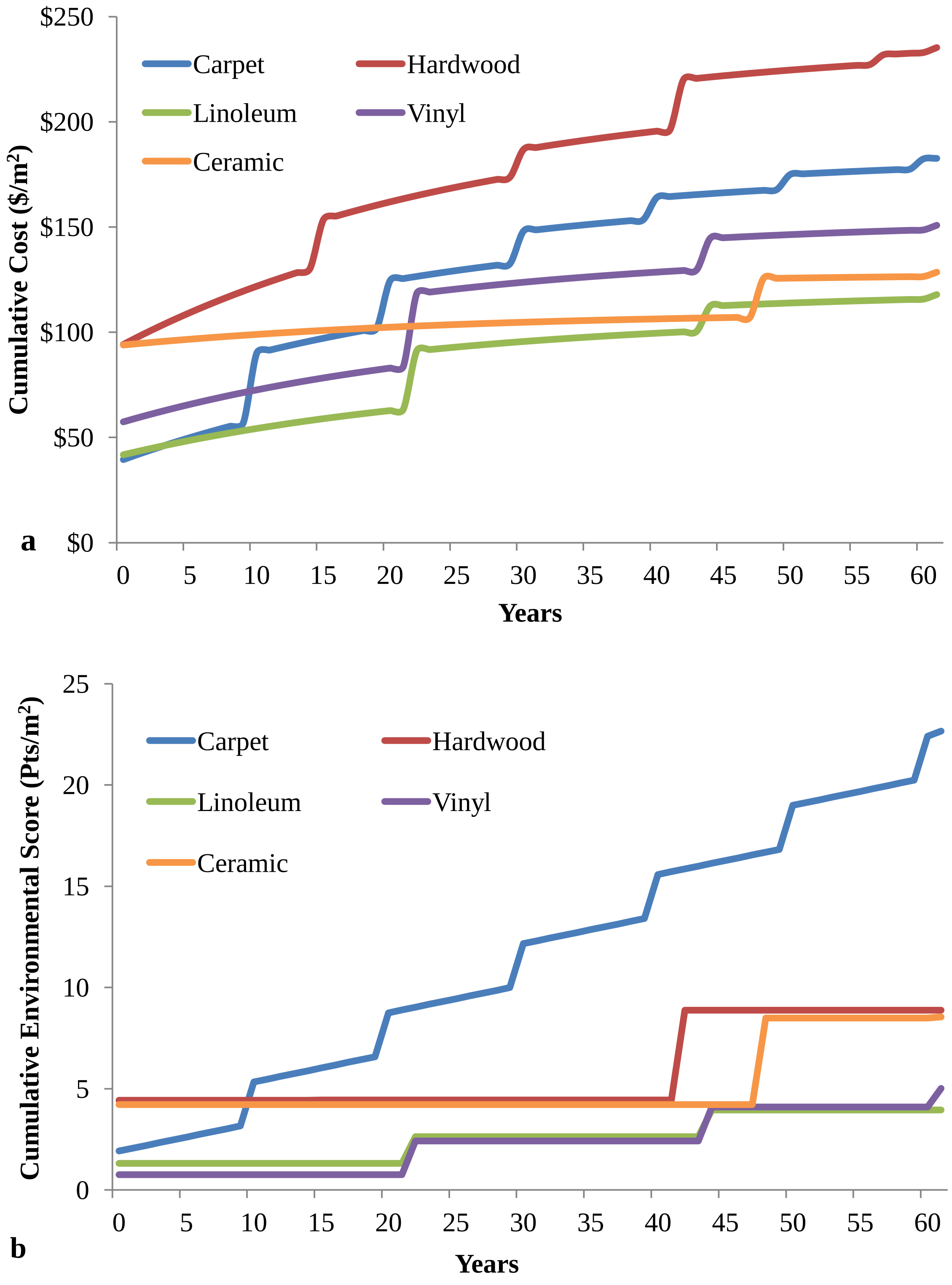

Figure 2.7: Cost (a) and environmental score (b) for flooring over service life of a home.

2.5 Conclusions

The results of this study of flooring choices suggests that cleaning procedures involved in the maintenance of floors may contribute significantly to environmental and economic impacts. Energy for vacuuming is the most significant environmental contributor to the use phase of the maintenance techniques tested, whereas mopping and sweeping are negligible in terms of the life cycle. Although frequent vacuuming only constituted a small percent of the maintenance cost, mopping represented 29%–33% of the cost for hard floorings. In terms of periodic maintenance; polishing, refinishing, and deep steam cleaning have limited environmental effects, but make up about 40% of maintenance costs for vinyl and linoleum, 53% for ceramic, 63% for hardwood, and 92% for carpet.

Despite the fact that vacuuming and cleaning products may add to the life cycle of flooring, the data in this article is not meant to discourage cleaning floors regularly. Although it is outside the scope of this study, indoor air quality is affected by how often and how well floors are cleaned [98], and not cleaning effectively can cause adverse health effects.

Based on this evidence it is likely that maintenance plays an important part in the life cycle of floorings, however, to more accurately understand to what extent better data on average cleaning procedures and more detailed information on contents of cleaners would be needed. It should be noted the life cycle inventories are for generic versions of each floor type, and different variations of flooring, say carpet tiles or bamboo, may score differently than their generic counterpart. Although generic linoleum may perform better than generic carpet in this study that does not all linoleum floor is better than all carpet.

Additionally, the preferred flooring for a new construction project or a renovation is dependent on how many years are left in the expected service life of the home.

It is also interesting to note that the two most popular residential flooring options also performed worst in the separate categories: carpet had the worst environmental impact and hardwood cost the most over the total life cycle. Given these results, perhaps builders and consumer may want to consider other options for their homes which are often forgotten, such as linoleum and vinyl.

CHAPTER III

INFLUENCE OF CLIMATE ON THE ENVIRONMENTAL AND ECONOMIC LIFE CYCLE ASSESSMENTS OF WINDOW OPTIONS IN THE UNITED STATES

3.1 Introduction

Residential buildings contribute significantly to the United States (US) economy and environment impacts. The National Association of Home Builders cites that housing constituted 16% of the total US Gross Domestic Product in 2013 and averages around 18%, through residential investment and housing services [99]. Construction materials account for 75% of the total minerals and materials used for physical goods in the US [1], and 60% of the total square footage of infrastructure is residential [13]. Additionally, residential electricity contributes 20% of US' greenhouse gases to the atmosphere [100].

To better understand the environmental and economic effects of a building, a LCA and LCC should be conducted. A LCA for an entire building would include raw material extraction and manufacturing, transportation, on-site construction, use, and disposal at the end of life. However, knowing that analyses of buildings are quite difficult because of the interactive nature of the large and complex number of systems, it is useful to isolate particular components, as was done in this case study for windows. The Office of Energy Efficiency estimates that windows account for 10–25% of heat loss in a residential building [101], thus highlighting the importance of technological improvements in window design, and the importance of windows to the overall building

LCA and LCC. Comparing energy savings as part of the LCA and LCC will allow renovating homeowners to weigh the cost as well as resource and manufacturing impacts of more energy-efficient windows against the energy savings provided over the window's life cycle. According to Energy Information Administration (EIA), 42% of homes have single-pane windows, and even for newer homes 20% of the homes constructed between 2000 and 2009 installed single-pane windows [52, 102]. We can see these trends displayed in Figure 3.1. Figure 3.2 shows us that for a majority of the US residential building stock, the windows have not been replaced. Single pane windows offer the least amount of insulation from outside temperature swings, though the total effect of window glazing is expected to be significantly different based on the climate. The objective of this study is to analyze the economic and environmental impacts associated with renovating windows in existing homes for 17 climate zones in the US.

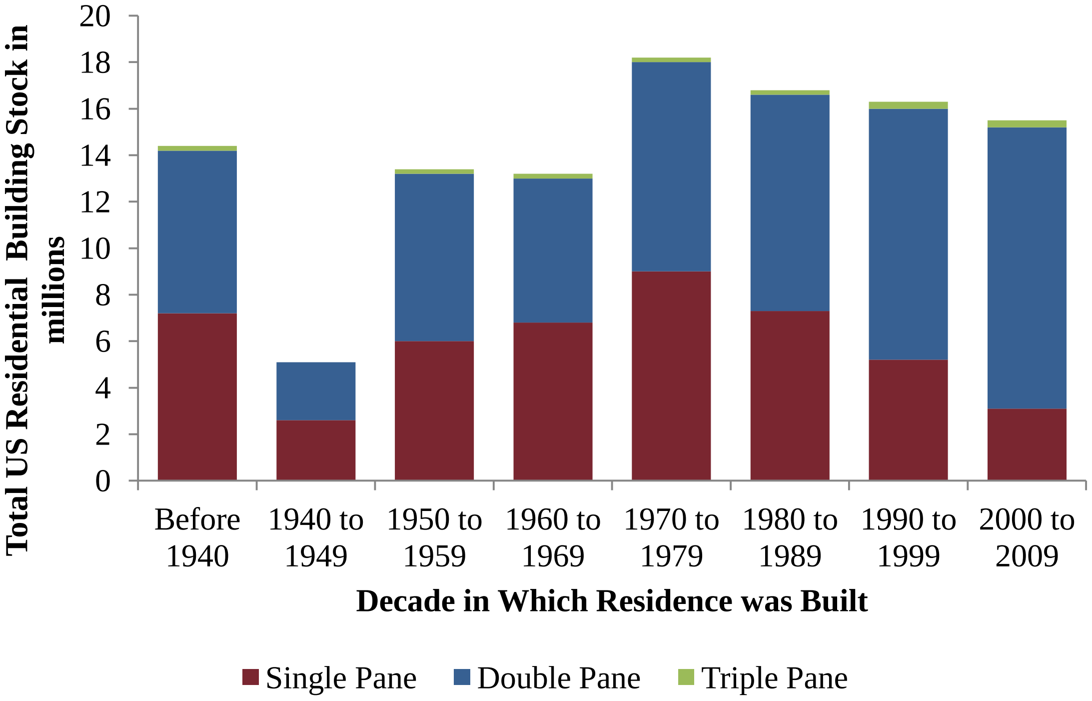

Figure 3.1: Trends for window glazing based on age of home.

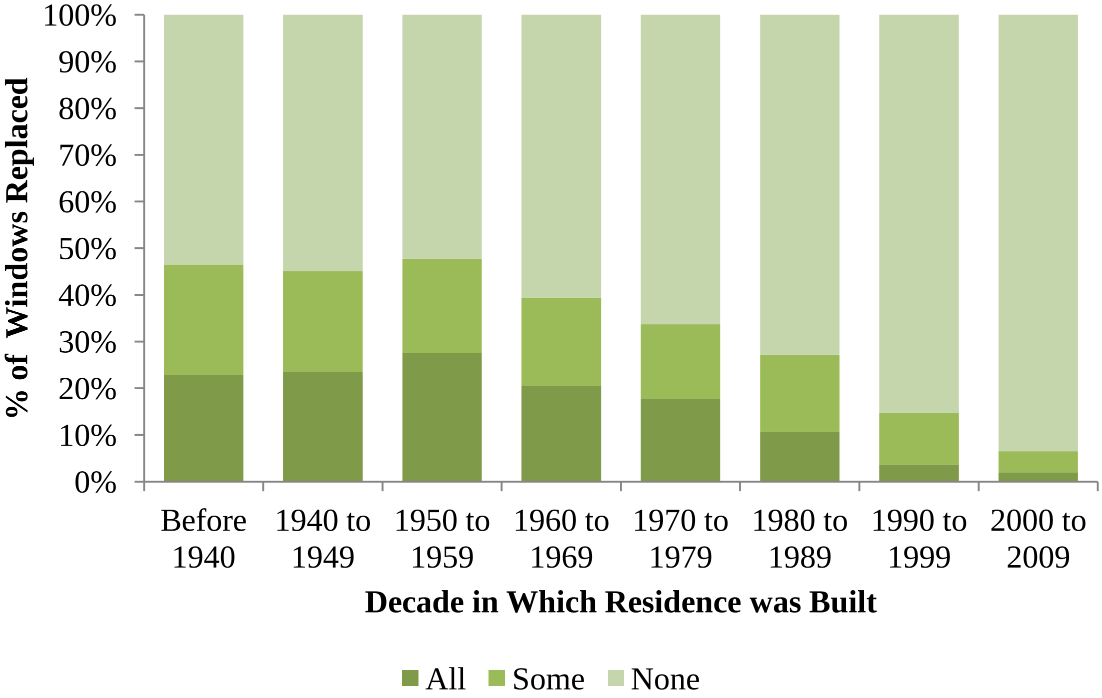

Figure 3.2: Percent of homes with replaced windows.

3.2 Methods

3.2.1 Background

There have been a number of studies on the impact of different window units on energy use [103-108], LCA [108-111], and payback period or economic performance [103, 106-108, 111]. The literature consistently suggests that increasing the number of panes in the window decreases the energy demand, however, the amount of energy savings depends strongly on the climate with more extreme climates seeing more energy savings [103-107]. Consistent with these finding, the payback periods and economic performances of efficient windows tended to be better in more extreme climates making double-pane windows a good choice in many climates, though the energy savings were often unable to make up for the initial cost of triple-pane windows [103, 106]. The articles by Asif [110] and Salazar [109] specifically address the life cycle assessment of windows with different frames. Both studies found polyvinyl chloride (PVC) frames to have worse environmental impacts than aluminum-clad frames, and Salazar's study additionally found PVC frames to be less environmental than fiberglass frames (fiberglass was not included in Asif's study). It should be noted that neither LCA study included energy use as a part of their environmental assessment. Additionally, others have looked at the impact of shading techniques and window area [104, 108] on the total energy usage of a home. Both studies found significant reductions in energy use from shading for hot climates and warm climates. To limit the number of variable in our study, we did a sensitivity analysis of shading types in Atlanta, but did not include all shading types for all seventeen cities.

Many studies have looked at the combination of energy use with economic impacts, but few studies have considered these aspects with total environmental impacts from an LCA, despite the fact that both are important factors in deciding the sustainability of windows. Additionally, results are different with each climate, and this paper provides a more comprehensive study of the environmental and economic impact of windows in the United States than previous studies.

3.2.2 Functional Unit and Scope of Study

In this study, seven window types were selected to compare different features, and the data were normalized by 1 m^2 of window and frame. The data can be looked at in yearly intervals, as well as in cumulative terms for the mean lifetime of a window of 30 years [112, 113]. The 30 year timescale was used in this analysis, which differs the other studies where the lifetime of the home is used, which is assumed to be 60 years [53]. In the case of windows, all the windows we studies were assumed to have a lifetime of 30 years and the homes were assumed to be undergoing a retrofit to upgrade windows. If the home has more than 30 years left at the point of retrofit, the pattern we see in the LCA and LCC would replicate itself, but given potential technology improvements, we chose the limit the study to the standard lifetime of the windows.

Looking at the LCA and LCC for the entire lifetime of a window gives us a quick idea of performance over time, though a yearly timeframe may be useful for a person looking for the best performing window within a shorter timeframe than 30 years. The seven window types include a low-end, single-pane window (Window 1) which creates a baseline for comparison to two simple double-pane windows and four thermally-improved, energy-efficient windows, as seen in Table 3.1.

This variety of windows allows us to compare framing materials, the impact of single versus double and triple-glazing, and the impact of high versus low SHGC. In addition to the SHGC, the U-value and visible transmittance are indicators of the energy performance of the windows. The U-value of a window represents the rate of heat loss, where lower U-values demonstrate better insulating properties by having lower heat transfer. Visible Transmittance (VT) is the fraction of visible light that passes through a window, with higher numbers indicating a high proportion of visible light.

The two simple double pane windows, windows 2 and 3, are considered to be approximately the same in terms of energy performance and cost, with the only difference being the material of the frame. Two of the energy-efficient windows tested did not actually meet the code for ASHRAE 90.1-2013 Standard [114], the specific residential ASHRAE 90.2-2007 Standard [115], the 2012 International Energy Conservation Code (IECC) [116], or for Energy Star [117] requirements for many of the climate zones; however, the energy modeling demonstrated that they were the best performers under certain parameters. In fact, during the sensitivity analysis of shading, window area, and orientation, it was discovered that for in the best case scenario for energy modeling of a home in Atlanta, the window that results in the lowest overall annual energy cost (Window 6) has a higher SHGC than is allowed by the standards. Additionally, the baseline window is higher than the standards and requirements allow, but it is used as the comparison because we are considering retrofitting older windows that may have been installed long before the code was in place.

Table 3.1: The properties of seven windows compared in this study [106].

Window Identifier	Glazing (# of panes)	Solar gain (SHGC)	U-value	Visible Transmit-tance	Coating	Frame
1	Single (1)	Clear glass (0.64)	0.88	0.65	None	Aluminum-clad wood
2	Double (2)	Clear glass (0.57)	0.52	0.59	None	Aluminum-clad wood
3	Double (2)	Clear glass (0.57)	0.52	0.59	None	Polyvinyl chloride (PVC)
4	Double (2)	High (0.50)	0.29	0.57	Low-e	Fiberglass
5	Double (2)	Low (0.20)	0.27	0.46	Low-e	Fiberglass
6	Triple (3)	High (0.41)	0.20	0.50	Low-e	Fiberglass
7	Triple (3)	Low (0.18)	0.19	0.37	Low-e	Fiberglass

3.2.3 Data Sources

To determine the environmental impacts of the product, an inventory of materials, manufacturing, and disposal is needed. Resource, manufacturing, and disposal inventory data were taken from values published by Salazar and Sowlati [109], who based their LCI on site-specific and published data acquired from three manufacturing sites in North America. For the LCC, the costs of the product are estimated using the National Renewable Energy Laboratory's (NREL) Residential Efficiency Measures Database [112], which lists average window prices, for a variety of window types in USD per square foot. A report released by the US Department of Energy (DOE) notes that this price actually includes the demolition cost of \$3 per square foot (about \$32 per square meter) [106], so this study splits retrofitting cost into the cost of the product with installation and the demolition cost at the disposal phase.

To expand the scope of this study, we also considered maintenance and energy use attributable to windows. The maintenance impacts come from the amount of latex caulk needed every eight years, as specified in ATHENA's "Maintenance, repair and replacement effects for building envelope materials" manual [118] at a current estimated price of $2 per square foot ($21.50/m^2), as is approximated by the DOE [119]. Additionally, the Window Selection Tool [120] was used to compute the total energy usage of a given home and the energy usage attributed to the type of window. The modeling methodology is discussed extensively in the next section.

In this study, all of the windows are assumed to be 30 years based on the agreement of lifetime expectations listed in the NREL's Residential Efficiency Measures Database [112] and the National Association of Home Builders Study of Life Expectancy of Home Components [113].

3.2.4 Energy Modeling

A number of factors contribute to the energy use of a home, so for comparison we need to limit the number of changing factors to focus on the effect of the windows. Data from the EIA shows that 69% of US homes are single-family dwellings and 69% of housing units are one story [52], which justifies the focus on one story single family homes for our initial effort. We used the computer program, RESFEN, which was developed by Lawrence Berkley National Laboratory (LBNL) and uses the DOE-2.1 tool to predict the effects of windows on the heating and cooling needs of residential buildings [121]. In order to make a more user-friendly program, the team at LBNL collaborated with a group at the University of Minnesota and the Alliance to Save Energy to create the Window Selection Tool based on the results from the RESFEN model [120]. The weather data are based on the typical meteorological year (TMY), which contains hourly weather data taken from typical months covering 30 years of records [122]. The RESFEN model uses the second version of the weather files, TMY2, to calculate energy needs [121].

For comparison, we also compared the energy data from this model to another energy model. We compared our DOE-2.1 results to results from EnergyPlus [123], which is a similar software, also developed by the Department of Energy. Using the graphical user interface created by NREL, named BEopt [124], we found that the heating and cooling site energy use was similar for most climates. On average, the site energy use in BEopt was 17% higher, and climates classified as cold or cool only being 10% different. This is likely attributed to the fact that warmer climates use less total energy, so differences in the energy model may be small in physical number, but larger in percent change.

We chose to use the DOE-2.1 for this analysis because the Window Selection Tool which used these inputs had an simple user interface which would be more accessible to consumers. However, such a validated model does not exist for all features of the home, so the EnergyPlus model is used in the subsequent energy analyses.

3.2.4.1 Sensitivity Analysis of Shading, Window Area, and Orientation

For the energy modeling, we made set up a base case scenario to control for outside factors in order to compare various window types in a typical home. However, to better understand the effect of other available design options, we compared the annual energy for the same set of seven chosen windows under other shading, orientation, and area conditions for Atlanta, Georgia. Shading may be another option to consider for a consumer who is retrofitting their home, so we considered the percentage of annual energy that could be saved or needed compared to our base case for the best and worst performing windows in our set. This analysis could also be used for builders or consumers before the home is built or for homes with different structural conditions, which prompted us to look at potential energy savings and costs for varied window orientations and window area as well.

The energy modeling for 20 window types was computed using the Window Selection Tool for existing construction, under a typical set of conditions. The selected conditions were typical shading, equal orientation of windows, and a moderate amount of window area (15%). For a smaller comparison set, a base case and four windows that were amongst the most energy-efficient were chosen to model for the entire LCA and LCC process. However, to understand the energy effects of other choices, a sensitivity analysis was done to determine how the best and worst windows compared to the typical case.

The amount of shading was evaluated as the other option available to most consumers looking to reduce energy costs without significant reconstruction to their home and can be seen in Figure 3.3. As compared to typical shading, maximum shading has a larger overhang of 0.6 meters versus 0.3 meters which leads to a small potential annual energy savings of about 2% for the best window choices and 1% when comparing the worst windows. The overhangs shading method involves overhangs of two feet, but that is the only shading mode involved in this option, making it slightly worse for energy efficiency than typical shading. Likewise, interior shading refers to only blinds and would result in a slightly higher energy bill than typical shading. Having no shading and the worst performing window of the set led to a 9% increase in annual energy costs as compared to typical shading, but only made a 3% difference for the best window. Although it may be prudent to upgrade the window and the shading in this case, making a change between the worst window to the best window with no shading would decrease energy costs by 27% and may be a better focus than improving the shading to give a 9% energy cost reduction.

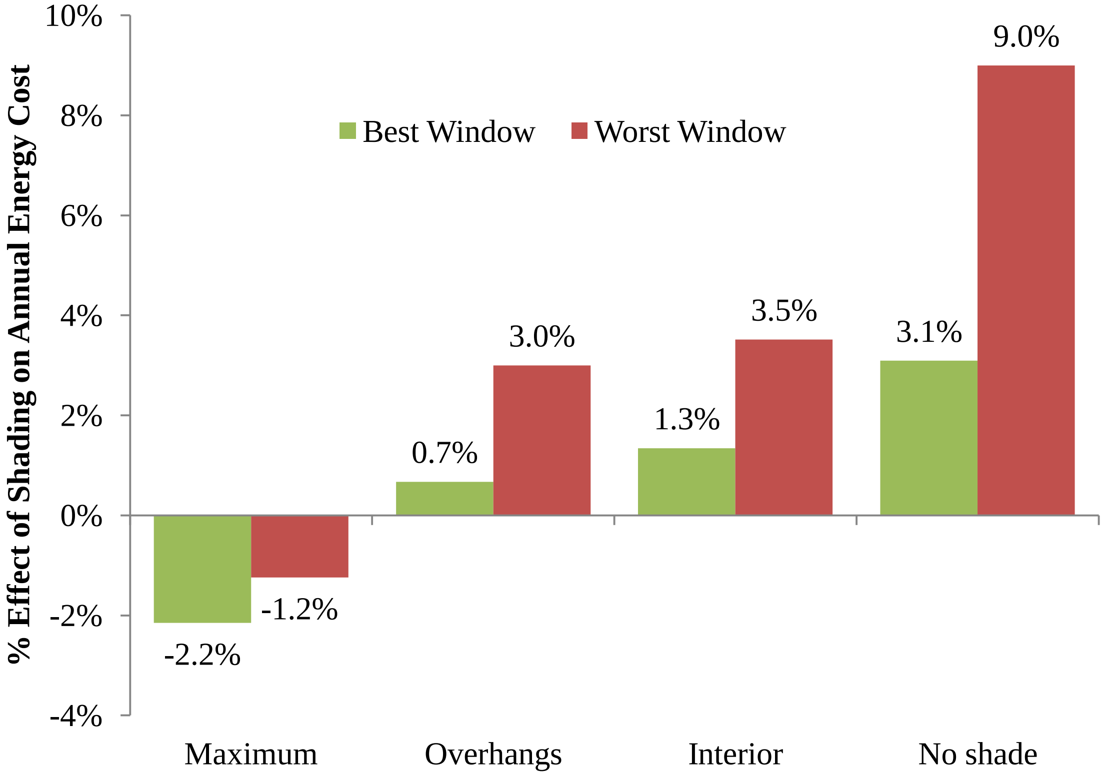

Figure 3.3: The effect of shading on the energy costs compared to the typical shading.

We analyzed how the factors of orientation and window area could affect the energy use for a home to be constructed or under major renovation, though this may not be applicable to homes looking for slight renovation. Equal orientation assumes the windows are evenly distributed on sides of the home, whereas the other directional orientations, for example a southern orientation, assume 50% of the windows are facing south and the other 50% of windows are evenly distributed on the other three sides of the home. For the base case we chose to assume moderate window area, which is the average 15% window to wall ratio [121], and compared that to a small window area (10%) and large window area (20%). Figure 3.4 shows that for the Atlanta climate, energy can be saved with a southern orientation and smaller windows. In all but one case, the structural change is more significant when comparing the worst performing windows than the best performing windows so improvements due to structure are muted when a more efficient window is chosen. However, all of the structural changes are less significant than the change from the worst window to the best performing window, which is saves over 17% of energy costs in all cases.

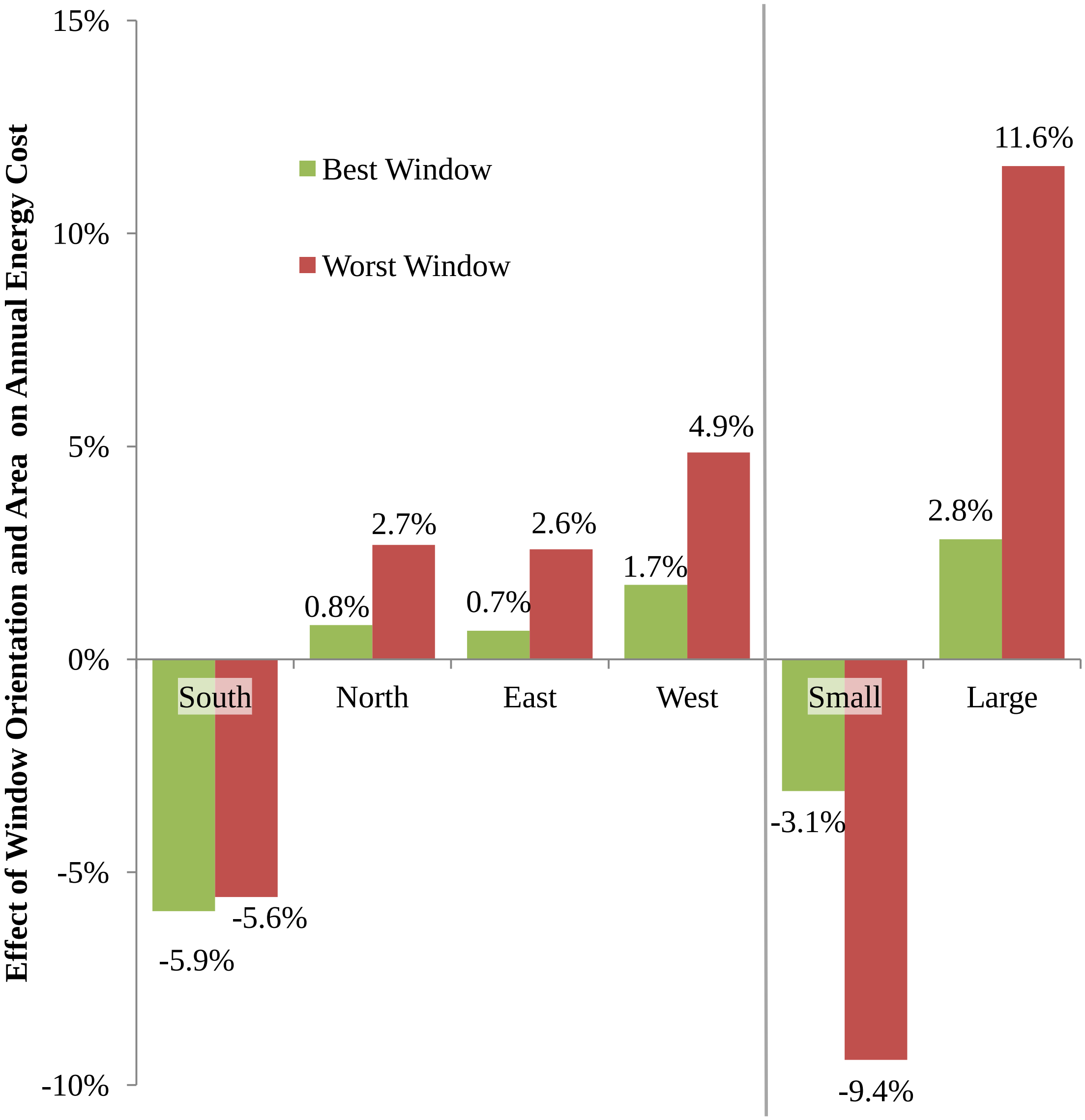

Figure 3.4: The effect of orientation (compared to equal orientation) and window area (compared to a medium 15% WWR) on the annual energy cost of the home.

As noted earlier, changing to one of the more energy efficient window results in over a 20% energy savings over the base case window in almost all cases. Although our base case window always performed worst under all circumstances, it is interesting to note that the best energy performance was not always from the same window, and could vary based on these factors. For example, in the most energy-efficient case the best window choice in Window 4 due to high-solar-gain in the winter significantly reducing wintertime energy costs. Given that our most efficient window and structural form combination had a higher solar-heat-gain coefficient than is allowed by ASHRAE 90.1-2013 Standard [114], we decided to include it in our evaluation as a potential window despite the regulation to better understand the environmental and cost impacts. The best case scenario could save about 30% of energy costs over the base case scenario if we include structural choices (south facing, small window area, and maximum shading) and best window choice. However, the sensitivity analysis proved that choosing more energy-efficient windows makes a more significant impact than changing shading, orientation, or window area option, so the rest of the study keeps these factors constant and focuses on the impacts due to windows.

3.2.4.2 Modeling Used in Analysis

After conducting the sensitivity analysis, we chose to limit the variables. Keeping simulations consistent, we assumed the home had a moderate window to wall ratio (WWR of 15%) and that windows were oriented equally around the home with a typical amount of shading. Typical shading is defined as the “average solar gain reduction by using 1’ [0.3 m] overhangs, interior shades, adjacent buildings, insect screens, and vegetation." A complete list of energy modeling assumptions for the home is located in Tables 3.2 and 3.3. Using this model, we simulated the annual energy needs for 20 varieties of windows and chose four energy-efficient windows for which to do a complete LCA and LCC. In order to isolate the change in energy usage attributable to the windows, the energy needed in the baseline scenario is subtracted from the other case, giving a negative energy which indicates an energy savings for all of the other windows. Any degradation of the energy-efficiency of the windows or effect on lighting needs was outside of the scope of this study.

Table 3.2: Energy modeling assumptions for the home for the window's study. Adapted from RESFEN 6 Manual **[121]**.

Parameter	Description
Floor Area	Existing 1-story, 158 m^2
Infiltration	SLA = 0.00054
Structural Mass	17 kg/m^2 of floor area
Internal Mass	39 kg/m^2 of floor area
Solar Gain Reduction	Typical: Interior shades (seasonal SHGC multiplier, summer = 0.70, winter = 0.80) 0.3 meter overhang Adjacent buildings 6 meters away, 67% same-height obstruction
Window Area	15% window to wall ratio
Window Distribution	Equal distribution on all four orientations
Natural Ventilation	Max ACH = 10, based on operable windows
HVAC System	Furnace and A/C
HVAC Efficiency	AFUE = 0.78 A/C SEER = 10
Thermostat Settings	Heating = 70°F, Cooling = 78°F Night setback (11PM – 6AM) = 65°F Basement: Heating = 62°F, Cooling = 85°F
Weather Data	TMY2 for each given city
Calculation Tool	DOE-2.1E

Table 3.3: Insulation[a], foundation, and duct loss assumptions for energy modeling based on location. Adapted from RESFEN 6 Manual **[121]**.

City	Ceiling R-value	Wall R-value	Foundation	Duct losses
Honolulu, HI	11	7	Slab-on grade	20%
Miami, FL	11	7	Slab-on grade	20%
New Orleans, LA	19	7	Slab-on grade	20%
Phoenix, AZ	11	7	Slab-on grade	20%
Atlanta, GA	11	7	Slab-on grade	20%
El Paso, TX	19	7	Slab-on grade	20%
San Francisco, CA	11	7	Slab-on grade	20%
Kansas City, MO	22	7	Basement	12%
Albuquerque, NM	11	7	Slab-on grade	20%
Seattle, WA	19	7	Basement	12%
Boston, MA	22	7	Basement	12%
Salt Lake City, UT	11	7	Basement	12%
Minneapolis, MN	22	7	Basement	12%
Billings, MT	19	7	Basement	12%
Duluth, MN	19	7	Basement	12%
Anchorage, AK	22	7	Basement	12%
Fairbanks, AK	22	7	Basement	12%

[a] It is assumed the basement, floor, and slab- on grade do not have insulation

The Atlanta climate was selected as the first test bed for the complete energy and carbon savings analysis given our location and the expected steady population growth of the region [125]. With the results from the energy modeling, we additionally projected the potential energy savings for the retrofitting of Atlanta’s current single-family housing stock from single-pane windows to energy-efficient windows. Using the Atlanta Regional Commission’s 10-county metro Atlanta region residential data [126] and ratio of single family homes [127], we approximate that there are about 1.32 million single-family homes in Atlanta. Additionally, the US Energy Information Administration [128] has published data on the number of Georgia homes with single pane windows versus double pane windows, which translates to approximately 43% of Georgian homes. There is a potential to retrofit about 565,000 single-family homes, and with the energy results, we can calculate how the conversion of all of these homes from single-pane windows to more energy-efficient windows could impact the total energy use of the metro area and the CO_2 emissions. Emissions are based on the assumption that the electrical grid provides cooling energy with an emission factor provided by Southern Company [129] and natural gas provides the heating energy with an emission factor reported by the Environmental Protection Agency [130].

3.2.4.3 Influence of Climate and Location on Energy

Seventeen US cities were chosen to represent different international climate zone with a variety of source electricity mixes. Cities are from a mix of climate zones 1-8, 15 states, and moist, dry, and marine areas, as shown in Table 3.4. More detailed information about each city's climate is located in Appendix A. The same seven windows were compared for the same style one-story home, with equal window orientation, 15% WWR, and typical shading. Total cost savings were compared to understand the best overall window for energy savings, however it should be noted that the cost of energy and electricity mixes vary from city to city and that variability was factored into the cost and environmental analysis. While energy mixes will likely change over the 30 year lifetime, predicting the change in energy sources is outside the scope of this study; however, with a variety of energy mixes (located in Appendix C), observations can be made on how different mixes of energy fare. Energy and environmental impacts were also analyzed for each city, which gave insights into how environmental impacts differed both by climate and location.

Table 3.4: Cities and their climate zones included in this dissertation.

Climate Zone	Climate	City
1	Very hot	Honolulu, HI
1A	Very hot, moist	Miami, FL
2A	Hot, moist	New Orleans, LA
2B	Hot, dry	Phoenix, AZ
3A	Warm, moist	Atlanta, GA
3B	Warm, dry	El Paso, TX
3C	Warm, marine	San Francisco, CA
4A	Mixed, moist	Kansas City, MO
4B	Mixed, dry	Albuquerque, NM
4C	Mixed, marine	Seattle, WA
5A	Cool, moist	Boston, MA
5B	Cool, dry	Salt Lake City, UT
6A	Cold, moist	Minneapolis, MN
6B	Cold, dry	Billings, MT
7A	Very cold, moist	Duluth, MN
7	Very cold	Anchorage, AK
8	Subarctic	Fairbanks, AK

Figure 3.5: Map of cities used in energy modeling.

3.2.5 LCA Method

For this study, inventory data were taken from an LCA report on North American windows [109], in which the values for material composition of various window types were gathered directly from manufacturers. Similar to the previous study, the analysis was still into life cycle stages: resources, manufacturing, use, and disposal (or end-of-life). Installation is excluded from this study due to insufficient data. Otherwise the LCA methodology is the same.

3.2.6 Uncertainty Analysis

The uncertainty analysis was conducted using the built feature in SimaPro. Whenever US data were available it was used, such as for dominating factor of energy processes. However, given the ecoinvent database is European, much of the background material data were based on European data and our inventory data were Canadian. Given lack of US window inventory and background data, we assumed the process data were similar for the resources, manufacturing, and disposal of window frames, but made corrections by adding uncertainty factors to all the of the data to estimate the range of possible values. Corrections for the geography and differences in process, as well as year the data were collected were accounted for using the uncertainty factor criteria. A Monte Carlo simulation is run, which uses the uncertainty factors to randomize the values of user input [92, 93], then outputs the distribution of the resulting outputs. Results from the 1,000 iterations are reported showing the range of values within a 95% confidence interval, and median value, and for the first and third qualities to show the range of values within the 50% confidence interval. Due to the extensive resources needed for the uncertainty analysis, the analysis was only completed for the test bed city of Atlanta.

3.2.7 LCC Method

Similar to the flooring study, the LCC is split into three phases, the cost of the product to the consumer (P), the cost of the use phase (U) attributed to energy cost (E) and maintenance cost (M), and the end-of-life, or disposal cost (D). It should be noted that financing of windows may occur, but this is outside of the scope of this study.

Most commonly, the payback period for an energy technology is calculated using a simple payback period. A simple payback period does not consider the changing value of money and is the initial cost divided by the annual energy savings. For the purpose of comparing our study to other studies, we calculated the simple payback period for the window. Similar to our flooring study, though, we present the life cycle costing in terms of a modified payback period which accounts for the nominal discount rate.

The present value of total cost is calculated based on the method developed by the National Institute of Standards and Technology for LCCs [94]. In the case of cost of product and cost of disposal, the present value (PV) is computed by considering the given cost calculated for the year it was purchased (n) or disposed of ($n+t$, where t is the lifetime of the window), taking into consideration the discount rate (d). The long term discount rate comes from the US Office of Management and Budget’s 30-year nominal discount rate (3.9%) [95]. The use phase, however, is more complicated and considers caulking cost (M) to be added in every m number of years as well as energy savings (E) occurring each year. The sum of the phases results in the total cost for the window’s lifetime (PV_n) and is the total economic impact (CI). Payback period can be determined by looking at the yearly cumulative totals to find where any window costs less than Window 1. Equations 3.1–3.4 express how to solve for these values numerically.

$$PV_P = \frac{P}{(1+d)^n} \tag{3.1}$$

$$PV_U = M(1+d)^{-\left\lfloor \frac{n+t}{m} \right\rfloor} + E\left(\left[\frac{1-(1+d)^{-(n+t)}}{d}\right] - \left[\frac{1-(1+d)^{-(n)}}{d}\right]\right) \tag{3.2}$$

$$PV_D = \frac{D}{(1+d)^n} \tag{3.3}$$

$$PV_n = PV_P + PV_M + PV_D = CI \tag{3.4}$$

In addition to the three phases of cost, we can consider the additional resale value that would be added to a home by retrofitting windows. Based on regional averages on the percentage of cost recouped for window renovations [131], we can estimate the resale value increases from retrofitting and how that changes over time in Equation 5, where (PV_R) is the present value of the resale value and ($(\%)_R$) is the percentage of cost recouped. As a separate analysis, the resale value can be subtracted from the cost of the window retrofit.

$$PV_R = \frac{P \times (\%)_R}{(1+d)^{n+t}} \tag{3.5}$$

We looked at the effect of utility costs increasing at a greater rate than inflation. This rate is predicted in the EIA’s 2015 Annual Energy Outlook [132] for every five years from 2015 to 2040. We wanted to fill in all of the years and predict to 2045 so we could analyze for the entire 30 year lifecycle of a window, so we plotted the exponential trend line for energy prices for electricity and natural gas based on our data and used the equation to approximate annual growth. Because this growth value was considered above the nominal discount rate, computing the changing cost of energy was relatively straightforward, and shown in Equation 3.6. The cost at a given time is based on the cumulative sum of the electricity price (*Elec*) and natural gas price (*NG*), accounting for their annual growth in cost ($(\%)_{gElec}$ and $(\%)_{gNG}$ respectively). This use cost substitutes for the previous use phase cost, which only accounts for the nominal discount rate.

$$PV_U = M(1+d)^{-\left\lfloor\frac{n+t}{m}\right\rfloor} + \sum_{0}^{n}\left(Elec \times (\%)_{gElec} + NG \times (\%)_{gNG}\right) \tag{3.6}$$

Lastly, we investigated the current rebates for windows and what the rebates would need to reach for a favorable adoption rate. The current tax rebate for retrofitting windows is a maximum of \$200 for the home [133]. Based on national averages [131], we would expect replacing all of the windows in the home to cost over \$10,000, making the rebate offered < 2% of the cost of a retrofit. For some climates with large energy savings, this \$200 rebate may make justifying the retrofit easier, however, if energy savings are not high, the rebate may not make much of a difference in comparison to the initial cost. Anderson and Newell studied the adoption rate of technology recommended in energy audits in manufacturing plants, and found that the probability of adoption dropped drastically with an increasing payback period [134]. The mean payback period for adopted projects was 1.29 years, and the maximum was 9 years. These results were for manufacturing, though, so we would except homeowners to have more of an investment in their home, and would expect them to consider the resale value. A study on residential decision making for energy efficient technologies investigates the importance of behavioral factors in adoption [135]. Such factors go beyond a simple payback period and look at the influence of neighbors on adoption, values and attitudes, and diffusion of information on technology. Given proper diffusion of information on increased incentives and access to cash-flow for a retrofit, we would expect adoption of energy efficient technologies to increase. No specific payback period is given for which homeowners would chose to retrofit, so we estimate that retrofitting is unlikely to occur if the payback period is longer than 10 years. We tested two rebate or incentive methods: firstly, a tax rebate of a set total value for a home as is currently used, and secondly, a percentage of initial cost rebate, which could make more efficient, higher cost windows more favorable.

The financial scenarios were studied in combination as well. For instance, we investigated the scenario of an increased rebate rate along with the resale value added by windows. The results of the financial scenarios provide a diversity of results which may be of interest based on the homeowners’ current situation.

3.2.8 Single Scoring

The three pillars of sustainability include environmental protection, economic development, and societal development [136]. Societal impacts were excluded from assessment due to a lack of standardization in the field, although human health is considered a factor in the environmental LCA. Given the current issues with SLCA, we only used the LCA and LCC results to create an overall performance score to compare window choices.

Obligatory assessment methods in ISO 14042 include classification and characterization; optional elements include normalization, ranking, grouping, and weighting. There is no accreditation available to verify that an LCA method or software has met the ISO standard. However, weighting is supported by SimaPro, and can be a more effective way to communicate environmental performance to a general audience. To create an overall score, we need to account for the improvements in environmental and economic performance. We based our method on the recent paper by Cetiner [57], which compares the impacts of various insulations in a home to the current system, and expands upon the method we developed for comparing flooring options [137]. The four energy-efficient windows and two simple double-pane windows are compared to the performance of the baseline (b): Window 1. The environmental impact score from the SimaPro analysis is defined as NI and the economic impact determined in the LCC analysis is defined as CI. Both scores are normalized by the baseline value. However, unlike in Cetiner's paper, we isolated the windows from the impact of the whole building, and had environmental and cost savings due to energy improvements that were larger than the total environmental impact or cost of the window in some cases. In order to adjust the environmental and economic scores so that all values are positive, each score is adjusted by adding the environmental and economic impacts from the maximum impact from energy in the LCA (signified by $_{Emax}$). With the normalized values, we can compare the overall performance based on different weightings (w) of economic and environmental performance.

$$NP_i = \frac{(NI_b - NI_i + 2NI_{Emax})}{NI_b + NI_{Emax}} \tag{3.7}$$

$$CP_i = \frac{(CI_b - CI_i + 2CI_{Emax})}{CI_b + CI_{Emax}} \tag{3.8}$$

$$P_i = NP_i \times w_N + CP_i \times w_C \tag{3.9}$$

3.3 Results and Discussion

3.3.1 Influence of Climate and Location on Energy Results

In terms of overall energy cost savings, triple-glazed windows performed better than their double-glazed counterparts. Matching the results of the literature [103, 106], the windows with a low SHGC performed better in very hot, hot, warm, or mixed climates, such as Honolulu, Phoenix, Atlanta, and Kansas City, than the high SHGC windows. The reverse was true for the marine, cool, cold, very cold, and subarctic climates of San Francisco, Boston, Billings, Duluth, and Fairbanks. The hot and cold climate extremes saw larger savings monetarily, with Phoenix saving over 2750 kWh of cooling energy, which is more expensive than heating energy, and Fairbanks saving over

15,400 kWh of heating energy per home per year. When comparing energy savings for the best windows in each scenario to the total energy usage in the baseline scenario though, energy savings are in a close range from 22% – 35%, both in terms of kWh and in terms of USD, because the cities with the highest savings from improved windows also have the highest energy use overall. Full results are located below in Table 3.5, and it should be noted that because cooling energy costs more than heating energy per kWh and the cost of energy varies by city, energy savings do not directly correspond to economic savings across cities.

Table 3.5: Annual savings for each window type as compared to Window 1.

	Annual Combined Heating and Cooling Savings									
	2&3		4		5		6		7	
Cities	kWh	$	kWh	$	kWh	$	kWh	$	kWh	$
Honolulu	336	126	520	196	2353	887	1014	382	2425	914
Miami	432	45	722	74	2242	254	1159	125	2326	263
New Orleans	1161	53	2096	94	2217	159	2331	119	2372	167
Phoenix	1364	113	2514	205	3252	353	2943	260	3450	371
Atlanta	2237	113	4111	205	3060	215	4217	226	3329	230
El Paso	1770	79	3255	142	2588	208	3435	173	2807	219
San Francisco	1993	67	3860	129	866	38	3550	121	1076	45
Kansas City	3631	138	6562	247	5163	259	6764	271	5603	277
Albuquerque	2906	97	5394	176	3249	183	5342	193	3587	196
Seattle	3176	121	6009	228	4185	167	6094	234	4577	182
Boston	4217	201	7532	358	5339	295	7569	370	5807	318
Salt Lake City	3483	115	6517	212	4706	204	6653	229	5133	219
Minneapolis	5407	156	9668	276	7501	257	9931	295	8142	277
Billings	5076	146	9039	259	6700	229	9191	273	7274	246
Duluth	6863	190	12264	338	9160	268	12479	348	9952	290
Anchorage	5950	299	11149	558	7795	395	11325	568	8561	434
Fairbanks	7896	395	14743	738	12275	626	15499	779	13411	682

3.3.2 LCA Results

To understand the environmental impacts of each window, simulations were run for both the midpoint impacts and the endpoint impacts using the World ReCiPe H methodology. The midpoint analysis gives results for 18 environmental metrics, which are quantities that have measurable units. Complete midpoint indicator results for Atlanta are located in Table 3.6. Negative values indicate a reduction in impacts due to the potential energy savings, which were input as negative "avoided" values. For Atlanta, Window 1 performs the worst in 33% of the midpoint categories, and Window 6 performs worst in 39% of the categories. While this is an indication of how each window performs, we will see that due to the weighting of various metrics and with the large number of categories, it is difficult to determine which window is the best overall window. It is possible to balance these metrics based on the local situation, but for the purposes of consistency for each city we compare the windows using a single endpoint score.

Table 3.6: The results for all 18 midpoint environmental metrics for seven window types.

Impact category	1	2	3	4	5	6	7
Climate change (kg CO_2 eq)	335.15	149.75	406.80	242.30	-1487.53	-59.39	-1390.42
Ozone depletion (kg CFC-11 eq**)**	7.26E-05	6.97E-05	2.68E-05	2.21E-05	-1.90E-05	2.27E-05	-9.03E-06
Terrestrial acidification (kg SO_2 eq**)**	0.99	-0.89	0.15	-0.79	-14.96	-4.04	-14.94
Freshwater eutrophication (kg P eq**)**	0.057	0.055	0.108	0.129	0.118	0.243	0.235
Marine eutrophication (kg N eq**)**	0.043	0.033	0.058	0.044	-0.111	0.044	-0.076
Human toxicity (kg 1,4-DB eq**)**	109.45	82.43	246.97	273.17	89.17	303.06	161.50
Photochemical oxidant formation (kg NMVOC**)**	0.81	0.28	0.51	-0.02	-5.03	-1.04	-4.89
Particulate matter formation (kg PM-10 eq**)**	0.43	0.01	0.12	-0.11	-3.44	-0.83	-3.39
Terrestrial ecotoxicity (kg 1,4-DB eq**)**	0.017	-0.001	0.037	0.032	-0.088	0.011	-0.081
Freshwater ecotoxicity (kg 1,4-DB eq**)**	5.02	3.78	12.86	13.06	5.72	12.76	7.11
Marine ecotoxicity (kg 1,4-DB eq**)**	4.32	3.90	11.56	11.80	9.24	12.77	10.80
Ionising radiation (kg U_{235} eq**)**	86.60	-48.59	-41.91	-47.57	-680.04	-116.20	-602.93
Agricultural land occupation (m^2a**)**	-7.12	-7.21	3.40	3.92	3.37	5.31	4.89
Urban land occupation (m^2a**)**	0.81	0.86	2.19	1.72	1.42	2.06	1.83
Natural land transformation (m^2**)**	0.009	0.006	0.012	0.019	0.014	0.029	0.025
Water depletion (m^3**)**	3.14	3.58	2.92	3.01	1.03	4.20	2.68
Metal depletion (kg Fe eq**)**	0.75	0.37	3.23	3.61	1.60	3.95	2.40
Fossil depletion (kg oil eq**)**	37.21	11.19	16.58	-52.46	-390.11	-130.41	-390.26

The midpoint method we used is different from that used in either the Salazar [109] or Asif [110] paper. If we exclude the use phase from the midpoint score calculations, as was done in the other paper, we can draw some comparisons. Our inventory data were based on the Salazar paper, so we would expect the result to be very similar. In a few of the metrics we can compare, such as climate change and aquatic acidification, we found that our results were on the same order of magnitude, though they did not match perfectly. However, for the majority of the midpoint factors, PVC was the worst performing window frame and in our study, excluding the use phase, fiberglass was the worst performing window frame. Upon investigation of the data, we discovered most of the impacts in our case could be attributed to the energy for manufacturing, for which fiberglass is greatest. Because Salazar's study is based in Canada, it is likely this was less significant in their study because the majority of electricity in Canada is generated by hydroelectricity (58%) and nuclear (14%), which have lower environmental impacts in most midpoint categories than the US electricity mix of coal (39%) and natural gas (27%) [138]. Asif's paper did not report midpoint categories, but we did find similar trends to the embodied energy reported for the two matching frames, with PVC frames causing close to twice the environmental impact as the aluminum-clad frame.

The single environmental score was calculated for all seven windows, and broken into phases of the life cycle to understand the driving forces in environmental impacts. Results for Atlanta are shown in Figure 3.6, and are given in points, where one point is equal to one thousandth of an average person's yearly environmental load and a higher number indicates a worse environmental impact and negative values indicate avoided impacts, as has been done in previous LCA studies [139]. As seen in Figure 3.6, Window

1 has the lowest impacts due to resources, manufacturing, and disposal due to the framing materials and one pane of glass. If we consider the single-pane was previously installed and we could choose to leave it for another 30 years, we would only consider the use phase and disposal in its' environmental score, giving it a lower score of 1.72 Points per square foot. However, the environmental impact from a comparative energy savings completely offset all other phases for three of the energy-efficient windows. Windows 5 and 7 have lower-solar-gain glazing, which in Atlanta saves significant cooling costs in the summer and would be the most environmental choices for this scenario.

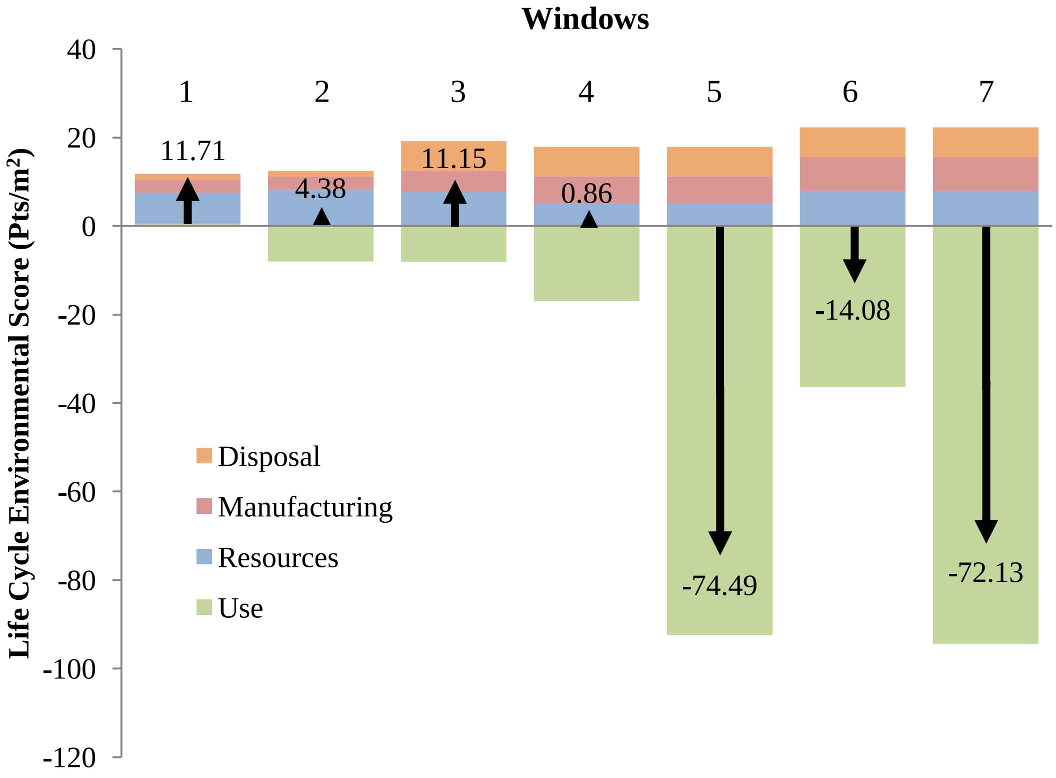

Figure 3.6: Life cycle environmental scores of seven window types.[a]

[a] Shown broken into life cycle phases, where the numbers and the arrows in the figure represent the total, and a negative value indicates avoided environmental impacts as compared to Window 1.

We looked into how the life cycle assessment would be different in other cities. For this analysis, we assumed that the resources, manufacturing, and disposal were constant for each window, and the use phase due to energy use was the only factor that changed. Environmental impacts due to energy depended on both the amount of heating and cooling energy saved, but also the environmental impacts of the energy mixes in each state. Electricity mixes were based on the state electricity generation sources published by the EIA [140]. The environmental impacts for the use phase of each city are located in Table 3.7. Windows 5 and 7 always have the greatest environmental impact avoidance due to the reduction in electricity needed for cooling with , even in climates with relatively smaller cooling reductions, which would indicate the electricity sources in most states are less environmental than the natural gas needed for heating. This additionally means there is a larger environmental impact reduction in warmer areas with higher cooling needs.

The energy mixes were a factor as well. Miami and Honolulu had similar cooling and overall energy reductions for Window 5 and 7, yet these reductions translated to a 50% increase in environmental impact avoidance in Hawaii where 75% of the electricity comes from petroleum compared to Florida where 64% of electricity comes from natural gas. Atlanta and Kansas City also had similar cooling reductions for Windows 5 and 7, but because 83% of Missouri’s electricity comes from coal and Georgia has a more distributed mix of energy sources (with 39% from natural gas and 27% each from coal and nuclear), Kansas City saw more dramatic environmental impact avoidance. The two marine cities, San Francisco and Seattle had both relatively small reductions in cooling needs and more environmental energy mixes, with California being 64% natural gas and

19% renewable and Washington being 77% hydroelectric, and therefore saw very minute environmental impact avoidance from retrofitting windows.

Table 3.7: The environmental impacts in Points per square meter for the use phase due to energy savings of each window (Window 2 and 3 have equal energy savings) for each city. Negative values indicate impact avoidance.

Window	2 & 3	4	5	6	7
Honolulu	-30.87	-48.06	-218.42	-93.97	-225.12
Miami	-22.93	-37.68	-142.88	-66.86	-147.75
New Orleans	-15.95	-25.77	-98.29	-45.86	-101.61
Phoenix	-51.51	-92.32	-215.45	-129.97	-224.12
Atlanta	-9.61	-18.61	-93.97	-38.70	-96.77
El Paso	-23.21	-39.19	-125.93	-64.46	-130.11
San Francisco	-0.53	-0.85	-2.74	-1.48	-2.82
Kansas City	-29.81	-48.66	-157.52	-80.68	-163.39
Albuquerque	-19.92	-31.64	-124.90	-56.29	-128.59
Seattle	-0.62	-0.91	-2.85	-1.58	-2.94
Boston	-5.31	-8.32	-32.42	-15.46	-33.47
Salt Lake	-27.72	-45.88	-134.03	-72.54	-138.88
Minneapolis	-9.66	-14.64	-54.69	-26.76	-56.66
Billings	-11.99	-18.77	-63.89	-32.37	-66.10
Duluth	-4.23	-5.98	-19.94	-10.64	-20.57
Anchorage	-1.39	-1.98	-3.24	-2.45	-3.35
Fairbanks	-1.49	-2.53	-6.15	-3.76	-6.33

3.3.3 Uncertainty Analysis Results

The single scores for environmental impact are an average score for the simulation; however, there is uncertainty in both the foreground and background data. To account for this uncertainty, we ran a Monte Carlo simulation with 1,000 trials for each window. First, we calculated the p-values based on our results to find that the p-value was less than 0.0001 in all cases which indicated the data strong suggests that there is a relationship between the window options. We plotted the distribution of the simulation data in four quartiles, shown in Figure 3.7. Energy savings had significant uncertainty, which is shown by the larger distribution of values of the two windows that save the most energy, Windows 5 and 7. Additionally, we ran Monte Carlo simulations to directly compare each window to one another. Window 1 was the worst performing window in 100% of the trials as higher values represent a higher environmental impact, with the exception of Window 3. Window 3's PVC frame caused considerable more environmental impacts than the aluminum-clad frame without gain significant or certain energy savings, making this a less environmental choice than Window 1 in over 90% of trials. Windows 2 lowest values are close to 4's highest values as seen in Figure 3.7; however, 4 is the better window in 94% of trials. Windows 5 and 7 are the closest to each other, and the Monte Carlo analysis indicates that 5 is the best window in 70% of trials, and therefore 7 is the best window in 30% of trials. Their overall performance is very similar environmentally, making both good environmental choices in Atlanta, so economics will be a significant factor in determining overall performance.

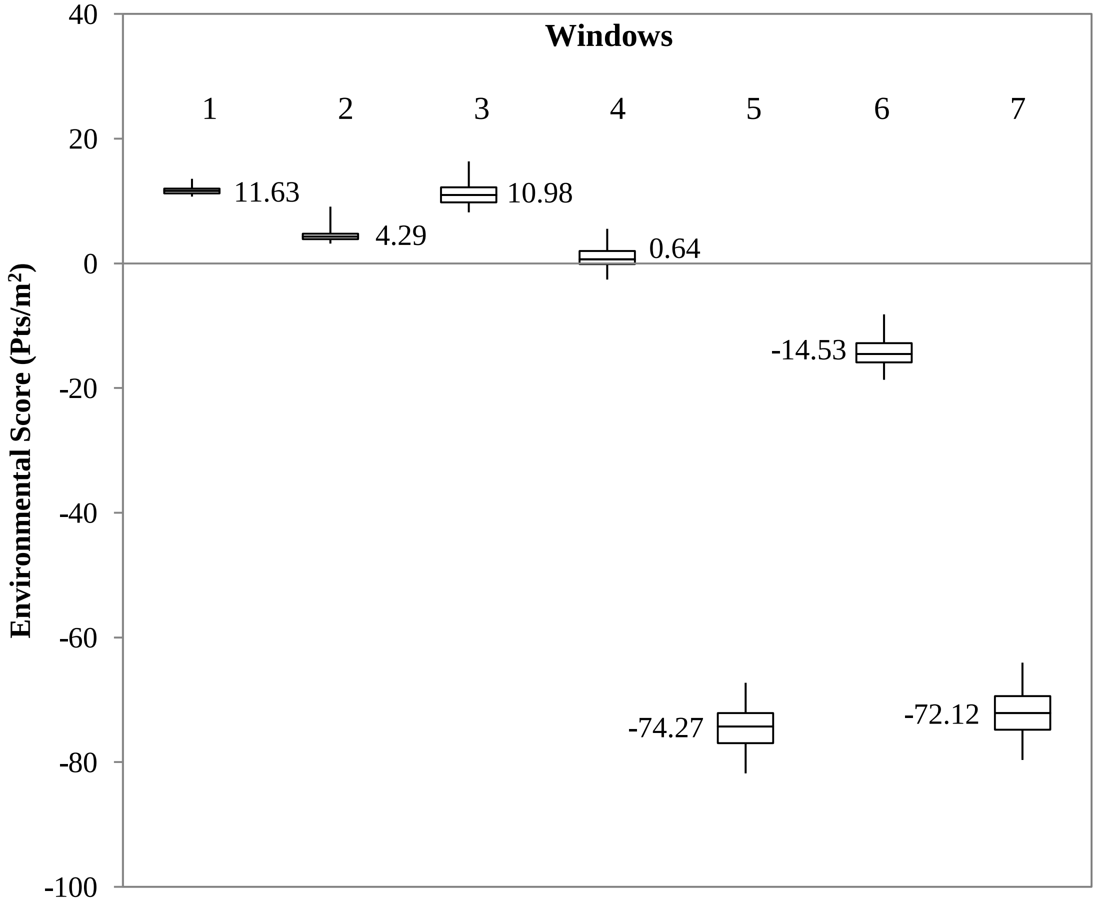

Figure 3.7: Distribution of single score results from the Monte Carlo simulation for seven window types.

3.3.4 LCC Results

We started by looking at the simple payback of windows for all of the cities. This measure is based solely on the initial cost of the window and the annual energy savings. When we compared the incremental costs of a window over window 1, we found the simple payback was low, with all cities having windows which would payback in less than 10 years. The triple-glazed windows only had a payback of under 10 years in the two polar climate extremes of Honolulu, Hawaii and Fairbanks, Alaska. These results are shown in Table 3.8. These results are similar to those shown in previous papers [103, 106], however, knowing that the value of money changes over time, we went into further depth, exploring the impacts of accounting for a discount rate.

Table 3.8: Simple payback of windows as an incremental cost over Window 1.

Simple payback	2&3	4	5	6	7
Honolulu	3	5	2	19	10
Miami	9	14	6	58	36
New Orleans	8	11	10	61	56
Phoenix	4	5	5	28	25
Atlanta	4	5	7	32	41
El Paso	5	7	8	42	43
San Francisco	6	8	42	60	209
Kansas City	3	4	6	27	34
Albuquerque	4	6	9	37	48
Seattle	3	4	10	31	52
Boston	2	3	5	19	30
Salt Lake	3	5	8	31	43
Minneapolis	3	4	6	24	34
Billings	3	4	7	26	38
Duluth	2	3	6	21	32
Anchorage	1	2	4	13	22
Fairbanks	1	1	3	9	14

For the LCC analysis, window costs over their 30 year lifetime in Atlanta are determined and normalized by square meter and are shown in Figure 3.8. For the sake of the life cycle costing analysis, Windows 2 and 3 are considered to be equal because the initial cost and energy savings are approximately the same. All of the double-pane windows, (2-5), were less expensive for the lifetime of a window than installing a single-pane window when annual energy saving are considered. Of these windows, Window 4 is the cheapest, even though the energy savings are greater for Window 5 because the initial cost of Window 4 is about $32 cheaper per square meter. Over the life of window, saving about $139 per square meter over the baseline window may not seem significant; however for the home this was based on, there are about 18.5 square meters of window area, leading to a savings over $2,500 for the least expensive of the windows, 4. Savings would be even greater when rebates for energy-efficient windows are considered. Currently, consumers can file for tax rebates of energy-efficient windows for up to $200 in a year [141]. The lower the discount rate is, the more savings can be realized due to annual energy savings, and inversely the higher the discount rate is the less cost-effective are the energy-efficient windows.

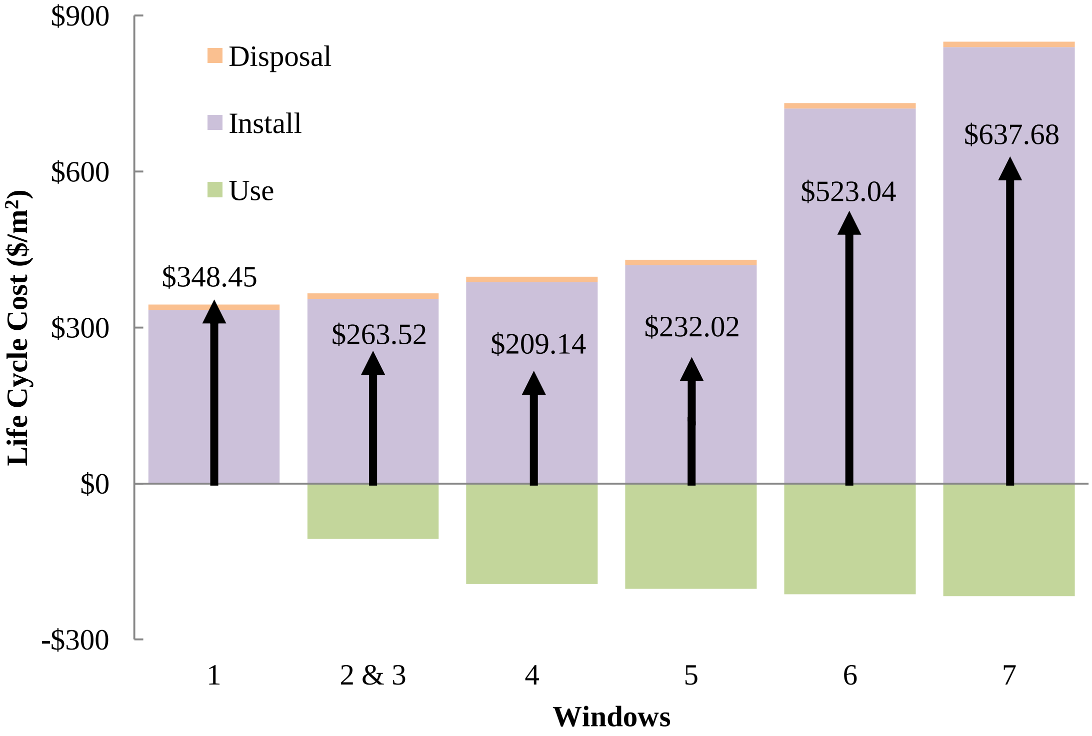

Figure 3.8: The present value life cycle cost of the seven windows.[a]

[a] Shown broken into life cycle phases, where the numbers and the arrows in the figure represent the total, and a negative value indicates energy savings as compared to Window 1.

We looked at the modified payback period, where Window 1 costs \$348.45/m^2, and the life cycle cost for each window in each city, shown in Table 3.9. All cities see a payback from Windows 2 & 3, which are the cheapest double-pane windows due to energy savings as compared to Window 1. Only four of the cities studied do not have retrofitting options that payback in five years or less, so retrofitting single-pane windows with other single-pane windows would not make sense in most situations. Even though these tend to be the quickest to payback, they are never the cheapest window when considering the entire lifetime. For all cities, either Window 4 or 5 is the cheapest window when considering the 30 year lifetime due to energy savings accrued over time. The lowest LCC in warmer climates tends to come from Window 5, which has a low-solar gain coefficient, whereas cooler climates tend to achieve the lowest LCC using Window 4, a high-solar gain window. Figure 3.9 displays how the life cycle costs of the windows change over time in the two most extreme climates we studied, Fairbanks and Honolulu, in a moderate climate, San Francisco, and in our base case city, Atlanta. The cheapest window choice for a retrofit depends heavily on the climate and how long the homeowner plans to use the windows or live in the home.

Table 1.9: Payback period in years and life cycle cost (LCC) in USD for the 30 year lifetime for each window type as compared to Window 1 (at a LCC of $348.45/m^2).

Window	2 & 3		4		5		6		7	
Cities	Payback Period	LCC	Payback Period	LCC	Payback Period	LCC	Payback Period	LCC	Payback Period	LCC
Honolulu	4	$251.23	6	$217.65	2	($401.07)	N/A	$376.09	14	($6.67)
Miami	12	$327.55	20	$332.61	8	$195.26	N/A	$618.18	N/A	$607.41
New Orleans	10	$320.01	15	$313.66	14	$284.82	N/A	$623.88	N/A	$697.08
Phoenix	4	$263.50	6	$209.14	6	$102.04	N/A	$491.05	N/A	$504.83
Atlanta	4	$263.50	6	$209.14	9	$231.96	N/A	$523.02	N/A	$637.66
El Paso	6	$295.58	9	$268.45	10	$238.64	N/A	$572.97	N/A	$647.99
San Francisco	7	$306.88	10	$280.73	40	$398.81	N/A	$621.94	N/A	$811.93
Kansas City	4	$239.93	5	$169.53	8	$190.52	N/A	$480.61	N/A	$593.42
Albuquerque	5	$278.57	7	$236.49	11	$262.21	N/A	$554.13	N/A	$669.74
Seattle	4	$255.97	5	$187.51	13	$277.28	N/A	$515.49	N/A	$682.87
Boston	3	$180.62	4	$65.01	7	$156.62	N/A	$387.40	N/A	$554.78
Salt Lake City	4	$261.67	6	$202.58	10	$242.41	N/A	$520.22	N/A	$647.99
Minneapolis	3	$223.03	4	$142.30	8	$192.46	N/A	$458.01	N/A	$593.42
Billings	3	$232.39	5	$158.23	9	$218.83	N/A	$478.78	N/A	$622.59
Duluth	3	$190.95	4	$83.85	7	$182.13	N/A	$408.06	N/A	$581.15
Anchorage	2	$88.26	2	($123.36)	5	$62.43	18	$200.86	N/A	$445.52
Fairbanks	2	($2.15)	2	($293.00)	3	($155.22)	12	$2.05	21	$211.84

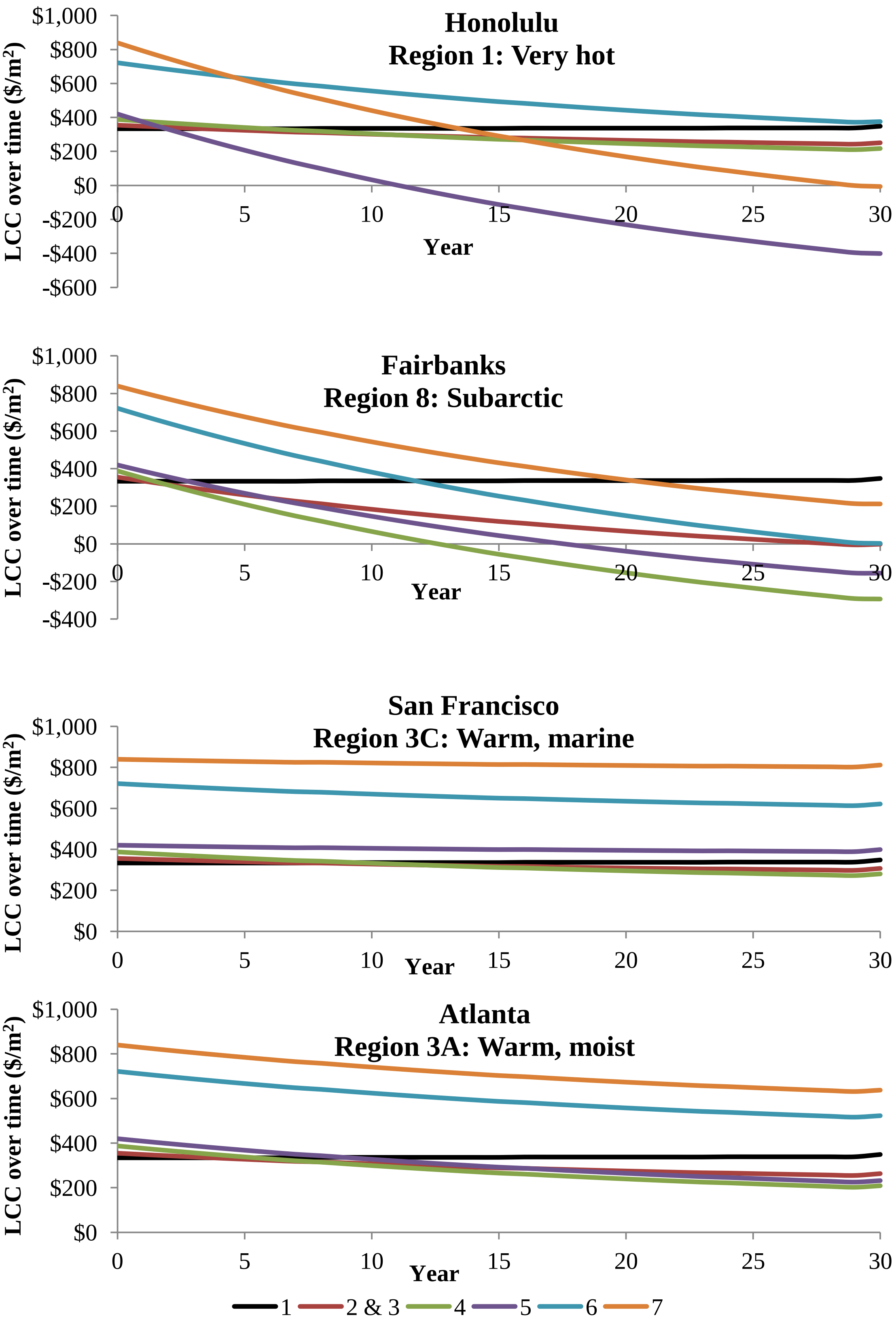

Figure 3.9: LCC over time considering nominal discount rate, compared to Window 1.

However, if we are considering leaving the single-pane window that was previously installed for the entire lifetime, in essence the do nothing scenario, the cost of Window 1 would be considered $14.75 for maintenance costs and disposal at 30 years, and none of the windows would payback in Atlanta. In this scenario where we consider Window 1 a sunk cost, only a few climates would see a payback on the windows being the most extreme climates and expensive energy cities of Honolulu, Anchorage, and Fairbanks. The payback period is longer than in the Carmody [106] or Jaber [103] studies largely because both used a simple payback formula which did not account for the discount rate, as we did in this study. Similarly though, energy savings and payback periods were shorter in more extreme climates or places with expensive energy.

In the scenario of leaving single-pane windows in places compared to retrofitting options, the economic case does not work for the majority of cities we studied. There is another consideration for many homeowners, though, and that is the added resale value from improved windows. When replacing windows with midrange or upscale windows, about 70% of the cost is recouped on average for US and in the Pacific region, which sees the highest recoup, about 90% of the cost is recouped [131]. In the scenario with resale value subtracted from the cost, Phoenix, Boston, and Duluth also have windows which completely recover their install cost in addition to Honolulu, Anchorage, and Fairbanks. Because the resale value is also diminishing over time with the discount rate, most cities still are unable to completely recoup the cost of window installs, but the life cycle cost is significantly lower. To represent the way resale value impacts the cost over time, the cost of each window is plotted for the two most extreme climates, Honolulu and Fairbanks, the most moderate climate, San Francisco, and the test bed climate, Atlanta in Figure

3.10. The extreme climates have a continuing downward trend because energy savings is greater than the loss in resale value over time, but in the more moderate climates life cycle costs tend to be lower at the 1 year mark when resale value is highest.

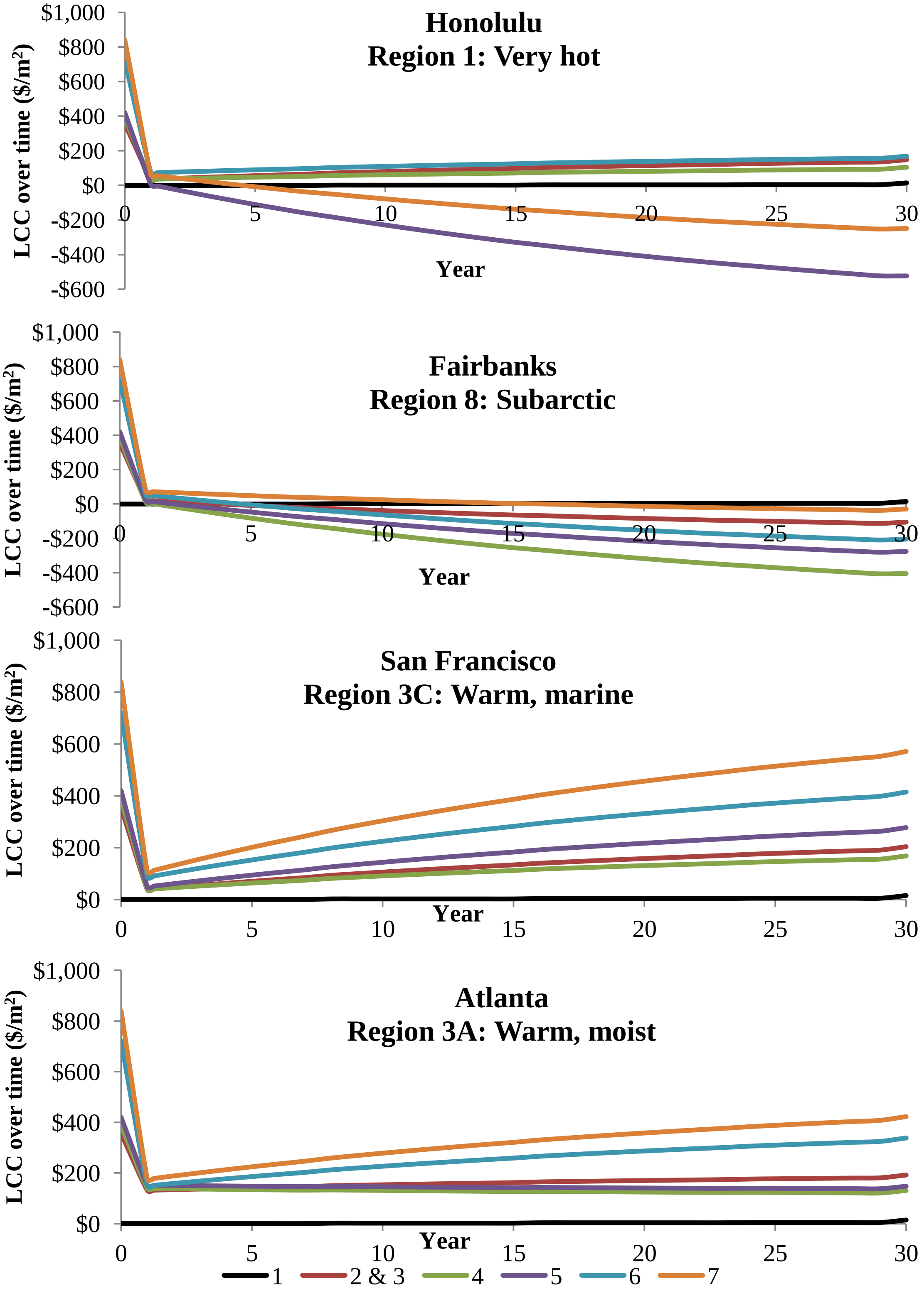

Figure 3.10: LCC over time including resale value for four climates.

We considered that energy prices increase at an inflation rate greater than the inflation accounted for in the nominal discount rate. Because all of the windows lead to an energy savings, the increasing cost of energy would lower the payback period. When we considered leaving Window 1 in place and did not account for any cost related to it, we found previously that only three cities had window options which would payback in the 30 year installation time frame. When we add in the consideration that energy prices are increasing at a higher inflation rate, however, that consideration alone means that only five cities do not payback in the time frame and 12 do payback. If we consider the homeowner may want to sell the home at some point within the 30 year installation, the payback period of the windows will be shortened. We can see the impact of the energy prices is a greater downward slope over time by comparing Figure 3.11 to the energy price with resale value results in Figure 3.10. The increase in price of energy savings also means a greater energy savings over time due to energy improvements. For the extreme climates of Honolulu and Fairbanks this means a decreased life cycle cost for the retrofit; from -\$523 to -\$1,262 and from -\$406 to -\$1,212 respectively. The energy savings led to more than double the savings over the 30 year time frame. In the case of Atlanta and San Francisco, this effect is muted because there are less energy saving to begin with, but the LCC is reduced from \$131 to -\$88 in Atlanta and \$168 to \$27 in San Francisco. Although the windows do not payback in San Francisco, increasing cost of energy does lower the life cycle cost significantly. It should also be noted that the growth in the cost of energy is based on national averages, and may be greater in some regions than in others.

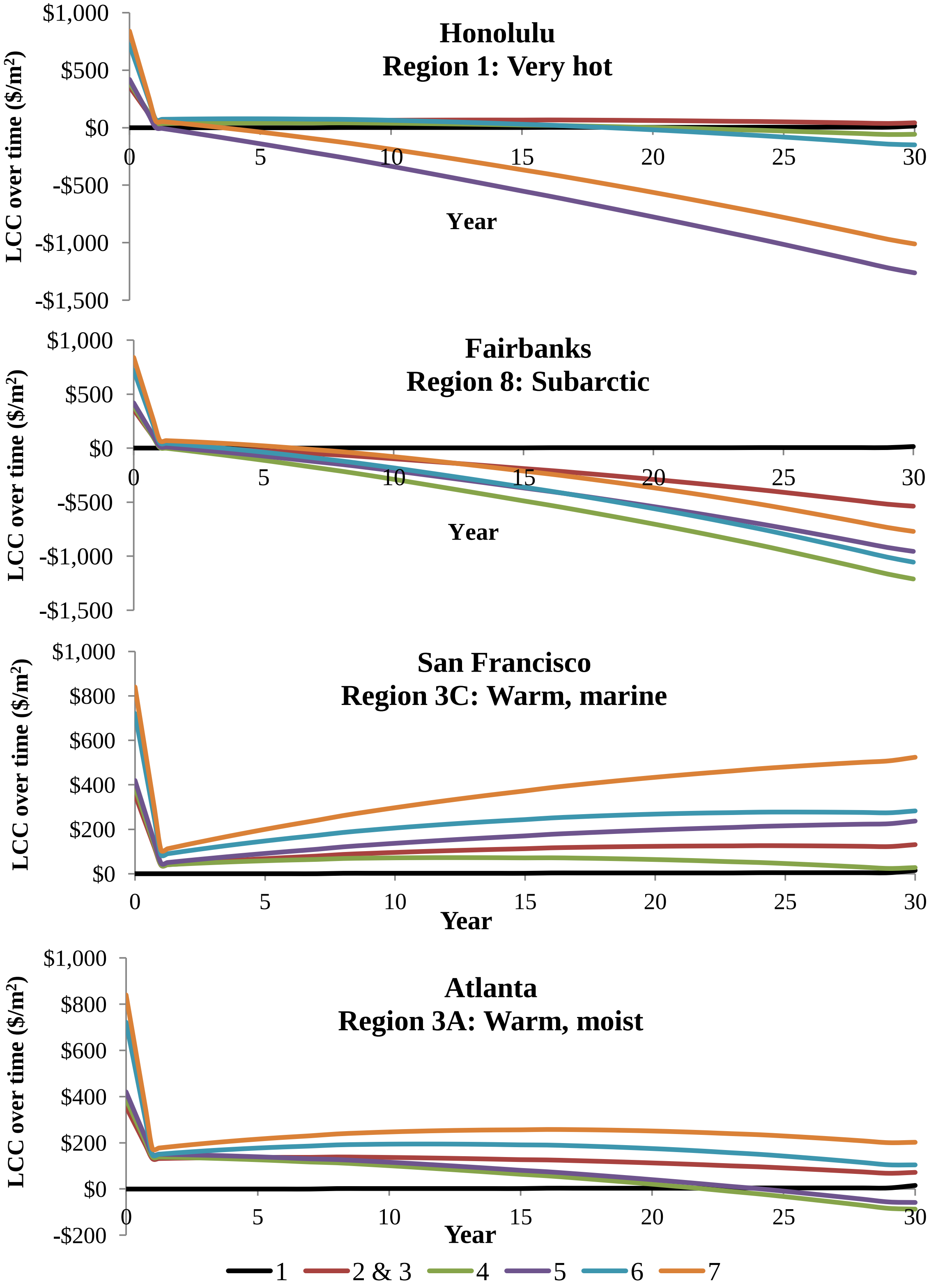

Figure 3.11: LCC over time considering resale value and inflated energy prices.

Lastly, we looked at what kind of rebate would be needed for each city to have a window which had a payback period of less than 10 years. We assumed that energy prices were increasing at a rate higher than US inflation, as was done in the last piece of the study. With the current rebate in place, which is about $10 per square meter, only two cities have a payback under 10 years. We tested rebates, increasing by $5 per square meter to see what values would be needed for other cities. Then we test percentage rebates in intervals of 5%. The results are shown in Table 3.10. The results show that in order to get achieve a payback period of less than 10 years, even when accounting for increased energy prices, drastically higher incentives would be needed.

Table 3.10: Rebates needed by city to achieve a payback period of 10 years or less.

Cities	Cost Rebate Needed	% Rebate Needed
Honolulu	Current ($10/m^2)	0%
Miami	$280/m^2	70%
New Orleans	$325/m^2	80%
Phoenix	$225/m^2	55%
Atlanta	$270/m^2	70%
El Paso	$305/m^2	75%
San Francisco	$315/m^2	85%
Kansas City	$280/m^2	80%
Albuquerque	$290/m^2	75%
Seattle	$255/m^2	70%
Boston	$180/m^2	50%
Salt Lake City	$265/m^2	70%
Minneapolis	$230/m^2	60%
Billings	$240/m^2	65%
Duluth	$190/m^2	50%
Anchorage	$60/m^2	20%
Fairbanks	Current ($10/m^2)	0%

3.3.5 Single Score Results

To understand how each energy-efficient window performs compared to the baseline, single-pane window, we have normalized the environmental and economic scores into one score. This is not a direct measure of performance, but can be used when considering the tradeoffs between economics and environmental impacts. Five ratios are given in Table 3.11, two of which consider only one impact, one which considered both impacts equally, and the 75/25 ratio for both economics and environmental impacts. The results are given in performance as compared to the baseline Window 1, where positive numbers are improved performance and negative numbers are diminished performance. For Atlanta, the economically best window is 4, but for all other ratios listed, 5 is the best overall window. It does relatively well economically, but also does substantially better environmentally than Windows 4 and 6. Depending on the consumer, they could use such a score to weigh their options when considering which window to buy.

Table 3.11: Overall performance as a percentage improvement over Window 1 based on normalized economic and environmental scores in Atlanta.

	Performance for different weighted economic/environmental ratios (%)				
Window	0/100	25/75	50/50	75/25	100/0
2	29%	25%	22%	18%	15%
3	22%	-13%	-49%	-84%	-120%
4	28%	27%	26%	25%	25%
5	80%	65%	50%	35%	21%
6	37%	20%	3%	-14%	-31%
7	77%	45%	13%	-19%	-51%

When looking at weighting environmental and economic performance equally for all cities, Window 5 performs best for all but three cities: San Francisco, Seattle, and Anchorage. Electricity saved by installing Window 5 and less resources needed for the double-pane window than its' triple-pane counterpart, Window 7, leads to it having one of the lowest LCA scores throughout the cities, in addition to it being cheaper than Window 7. In the three cities, Window 2 performed best, which is surprise because it does not comply with the previously mentioned codes. It is a lower cost window, and in these cities improvements in energy efficiency are offset by the lowed impacts in resources and manufacturing. The single score results for all 17 cities, balanced equally for environmental and economic scores are in Tables 3.12 and 3.13, compared retrofitting Window 1 and leaving Window 1 as is, respectively.

Table 3.12: Overall performance as a percentage improvement over Window 1 for 17 cities.

Single Score	Window 2	Window 3	Window 4	Window 5	Window 6	Window 7
Miami	8.45%	-60.61%	10.93%	55.25%	-5.53%	20.67%
Honolulu	10.21%	-9.56%	14.06%	75.48%	16.09%	59.50%
New Orleans	9.17%	-96.89%	11.69%	46.31%	-12.42%	4.76%
Phoenix	16.66%	-27.90%	28.02%	61.71%	14.69%	33.59%
Atlanta	21.80%	-48.58%	26.34%	50.43%	3.17%	13.15%
El Paso	12.40%	-65.27%	18.52%	51.61%	-1.88%	14.37%
San Francisco	1.49%	-149.35%	-12.51%	-18.93%	-63.54%	-79.38%
Kansas City	16.97%	-38.97%	26.54%	55.75%	8.65%	22.90%
Albuquerque	13.10%	-70.07%	19.26%	49.89%	-3.63%	11.15%
Seattle	5.51%	-81.50%	-5.22%	-6.84%	-48.51%	-58.83%
Boston	16.25%	-28.41%	21.86%	41.47%	0.89%	8.45%
Salt Lake	16.37%	-53.15%	25.79%	51.37%	4.74%	15.32%
Minneapolis	15.95%	-38.26%	22.04%	46.97%	1.86%	12.66%
Billings	16.29%	-41.91%	23.23%	46.92%	2.14%	11.72%
Duluth	15.86%	-34.44%	18.15%	31.96%	-6.57%	-4.37%
Anchorage	14.58%	-29.26%	11.18%	4.63%	-21.89%	-32.92%
Fairbanks	16.35%	-17.32%	18.02%	21.25%	-5.99%	-8.89%

Table 3.13: Overall performance as a compared to Window 1 not being replaced for 17 cities.

Single Score	Window 2	Window 3	Window 4	Window 5	Window 6	Window 7
Miami	-56.29%	-64.18%	-54.11%	7.43%	-100.43%	-71.00%
Honolulu	-9.58%	-11.90%	-5.07%	67.95%	-5.10%	45.78%
New Orleans	-87.33%	-102.21%	-83.37%	-39.57%	-166.19%	-160.25%
Phoenix	-25.62%	-30.03%	-10.30%	31.77%	-41.77%	-22.74%
Atlanta	-43.74%	-53.23%	-32.30%	-7.99%	-94.95%	-97.19%
El Paso	-59.66%	-69.27%	-49.53%	-9.66%	-110.72%	-102.63%
San Francisco	-279.06%	-388.57%	-339.79%	-357.38%	-526.70%	-578.07%
Kansas City	-35.76%	-42.10%	-18.93%	10.40%	-67.16%	-62.43%
Albuquerque	-63.54%	-74.22%	-50.56%	-20.98%	-122.68%	-123.73%
Seattle	-216.39%	-311.44%	-270.30%	-263.77%	-399.15%	-416.75%
Boston	-34.24%	-46.54%	-21.93%	0.58%	-63.39%	-60.19%
Salt Lake	-48.34%	-56.80%	-30.98%	-8.08%	-92.19%	-96.18%
Minneapolis	-38.61%	-48.23%	-25.24%	1.01%	-73.14%	-70.26%
Billings	-40.88%	-50.23%	-26.28%	-3.71%	-78.89%	-80.15%
Duluth	-46.53%	-65.06%	-39.61%	-21.34%	-88.08%	-90.15%
Anchorage	-146.84%	-228.73%	-185.93%	-187.80%	-271.23%	-282.81%
Fairbanks	-80.06%	-127.92%	-91.61%	-75.57%	-138.63%	-134.77%

If we look at the second scenario of leaving Window 1 in place as compared to other windows, 11 of the 17 cities do not have a retrofit option that performs better when environmental and economic impacts are equally weighted. The economic payback is not there for upgrading windows except in the most extreme climates of Alaska and Honolulu. With over 40% of the US residential building stock having single-pane windows, this may be hindering the retrofitting of windows around the country.

Comparing the payback of the energy-efficient windows to previously installed windows shows that without accounting for other factors, the current economic case for retrofitting single-pane windows does not work out in most cities. However, if we consider the potential effects of retrofitting all of the current single-family homes with single-pane windows in metro Atlanta, we can see economic energy savings for the city and potential avoidance in spending more on energy infrastucture, as well as avoidance of environmental impacts for the city. By accounting for solely the energy savings, Window 7 would reduce CO_2 by the greatest amount in Atlanta, by over half a million metric tons annually. All four energy-efficient windows show savings near a half million metric tons, but similarly Windows 5 and 7 perform better in this analysis, where cooling is provided by electricity and heating is provided by natural gas. The simple double-pane windows, Windows 2 and 3 reduce CO_2 emissions as well, but by about half as much. However, if heating and cooling are both provided by electricity, Windows 4 and 6 save the most CO_2 because they reduce the heating energy needed by a much higher margin than Windows 5 and 7, and natural gas has a lower emission factor than the grid in Georgia. Additionally when all energy is provided by electricity all windows save over or close to million metric tons of CO_2. The CO_2 reductions from energy-efficient windows equates to a reduction of about 3% of the CO_2 emissions from the 10-county region's residential sector when natural gas provides heating or 6-9% when heating comes from electricity. Additionally, by switching to energy-efficient windows, the collective annual savings for all of the households in metro Atlanta would be about $130 million.

3.4 Conclusions

Energy-efficient windows show significant economic and environmental advantages over traditional single-pane windows when all are compared for installation. For homeowners planning to leave previously installed single-pane windows in past their lifetime expectancy of 30 years, however, the economics score only works in extreme climates with expensive energy sources. The current rebate for windows works out to be close to $11 per m^2 of window, assuming all 18.5 m^2 of windows are installed in the same year, which is not large enough to push any additional cities into seeing a payback from retrofits. Increasing the incentives for retrofitting single-pane windows could make retrofitting more viable in additional cities.

All cities saw reductions in energy use by replacing their single-pane windows with any double or triple pane windows. Although it is beyond the scope of this study, we can estimate that climate change would likely increase energy savings in many climates. The most extreme climates saw the largest energy savings, and the Intergovernmental Panel on Climate Change reports that climate change will likely lead to more extreme climate conditions and events [142], with relatively higher temperatures overall. Extreme climates in this study had relatively more energy savings, and warmer climates had particularly large environmental impact reductions, which we could predict would intensify with climate change.

Energy-efficient window do offer other benefits aside from annual energy savings though. High-quality energy-efficient windows reduce drafts in the winter and sunlight in the summer, reduce peak loads for energy usage, reduce condensation and therefore mold growth, reduce ultraviolet damage, and provide better daylighting [143, 144]. Better insulating windows also lead to noise and acoustics reduction [145].

Homeowners will likely see efficient windows reduce their energy bill annually, but it is also worth considering added resale value and the time in which it would be best to invest in upgrading windows. Newly constructed homes can take advantage of even greater energy reductions by planning to have a smaller area of south-facing windows with maximum shading, but having the most energy-efficient window for each home can make a substantial difference no matter the orientation, size, or shading. Retrofitting and designing metro Atlanta homes with energy-efficient windows could lead to half a million metric tons of CO_2 being avoided annually. Incentives, educational programs, and regulations may all be ways to encourage a transition away from the cheapest windows to increasingly energy-efficient windows as Atlanta and the US work to become more sustainable. Additional studies could be done to understand policies and incentives which could lead to a transition of the US' residential building stock away from single-pane windows.

CHAPTER IV

INTERACTION BETWEEN ENERGY AND CLIMATE IN CHOOSING A SUSTAINBLE ROOFING OPTION

4.1 Introduction

Energy requirements of a building can be significant during its life time. As per the U.S. Department of Energy [146], primary energy consumption in the residential sector was about 22 quadrillion Btu in 2010. This number has increased by 31% in the last twenty years. Of this energy demand, about 43% is due to space heating and cooling. Today, it is common for consumers to opt for energy saving solutions like LED lights, energy efficient appliances, or conducting energy saving behavior such as turning off lights in unused rooms. However, the choice of construction materials for the envelope of their house has a significant impact on the energy requirements as we saw in the last section with windows. Different materials have different heat transfer capacities and surface albedo properties.

The climate condition where the home is built has an impact on the energy use. Roofs are a place of significant heat transfer in the house and thus affect the energy demand of the house. We modeled the energy use of homes in the same 17 climate zones as were studied in the windows chapter to understand how different materials, colors, and levels of insulation would affect energy usage in the home. With the exception of two cities, all the cities saw an annual site energy reduction over 30% by improving their roofing systems from the base case (and the other two cities saved just under 20%).

4.2 Methods

4.2.1 Background

We looked at trends in roofing materials over time, and found that asphalt and composition shingles were overwhelmingly the most used roofing material. Composition shingles may vary slightly in components based on the manufacturer and specification, but are primarily made of asphalt. The energy model and environmental inventory used in this study refers to asphalt shingle, so for the rest of the section, we will use asphalt to refer to both asphalt and composition shingles. In Figure 4.1, we can see that asphalt has been the most popular option of home, no matter what decade they were built. Other popular options include metal, wood shingles and ceramic or clay tiles.

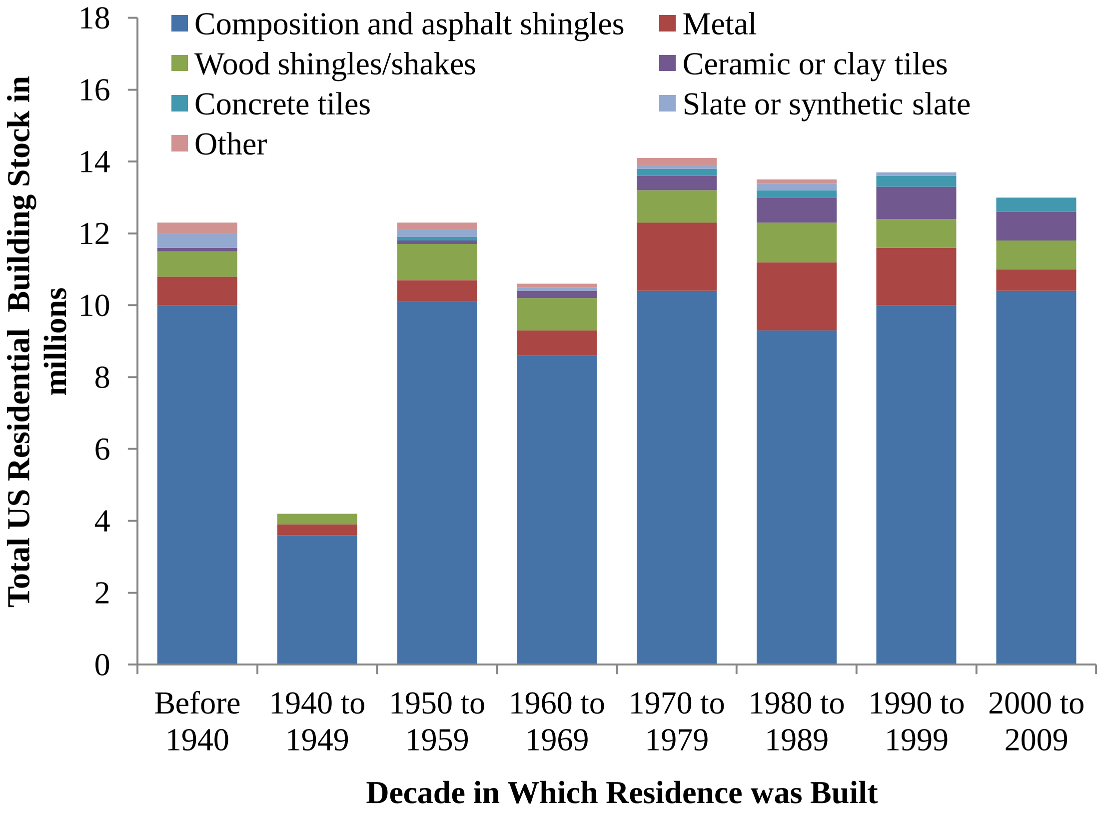

Figure 4.1: Roofing material used for US home based on decade in which it was built.

Past studies have found that reflective roofs can lead to reduced indoor summer temperatures [147-149] and energy use [148-152]. Cool roofs and radiant barriers are all methods to reflect or absorb the energy from light hitting the roof. Cool roofs refer to either white roofs, which are often used for flat roofs which cannot be seen from the ground, or cool-colored roofs, which increase solar reflectivity but still look like traditional roofing [153]. Darker roofs increase the temperature in the home through a mixture of conduction and convection of energy in the attic or ceiling area, as well as the temperature of the surrounding air through the convection. The heating of surrounding air is particularly troubling in urban areas due to the density of buildings, and is a contributing factor in the heat island effect. Heat island effect causes built up areas to be hotter than nearby rural areas. During the evenings, the annual mean air temperature of a city with 1 million people or more can be 22°F higher than its surroundings [154]. Increasing the roofing material's albedo, which is the fraction of solar energy reflected from the Earth, helps in reducing the urban heat island [147, 151, 152, 155] and hence has increasingly become a part of the solution to this problem. Radiant barriers are another option for homeowners. They are placed inside the roof and can also reduce radiant heat from the sun by reflecting the heat out of the roof [156].

Another way to reduce heat transfer to and from the home is through reducing the conduction of energy. Greens roofs and ceiling and attic insulation are both ways to absorb the energy and lower conduction. Unlike radiant barriers and cool roofs which reduces heat gain all year (beneficial in the summer but not in the winter), insulating methods have the advantage of reducing heat gain in the summer and lowering heat loss in the winter. Green roofs use vegetation which absorbs energy and green house gas emissions and used evapotranspiration to reduce the temperature of the roof and surrounding air [157]. However, due to relatively high costs and maintenance needed for these roofs, few single family dwellings have implemented a green roof [158], and therefore will not be included in this study. Ceiling or attic insulation is required by code for new construction in the US, and as such most homes have some level of insulation. From the EIA’s *Residential Energy Consumption Survey*, we know that 21% of the US homes are considered to be poorly insulated or have no insulation [52], which would lead to increased energy demand for the home [159]. The trend over time has been that newer homes have more insulation, but the majority of homes are still not classified as well insulated. In Figure 4.2, we can see that older homes are in the greatest need of added insulation, but the majority of home built before 2000 have adequate insulation, poor insulation or no insulation.

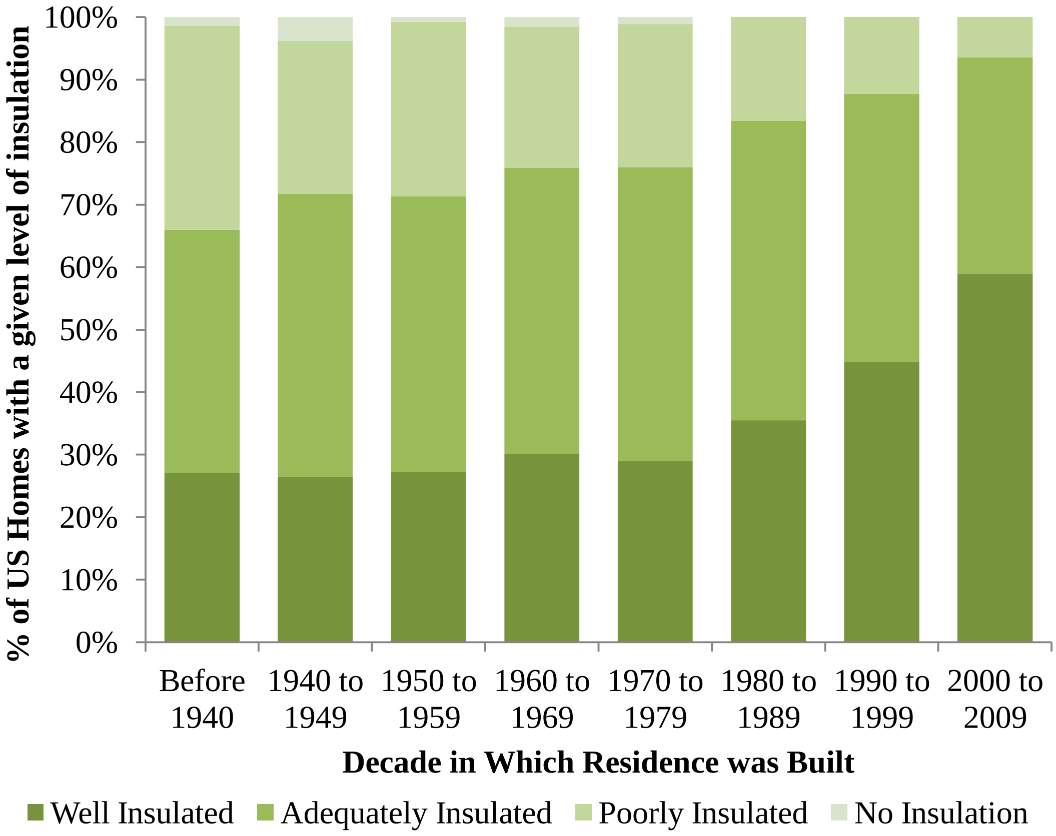

Figure 4.2: Level of insulation in US homes based on decade in which the home was built.

This study aims to evaluate various roofing options based on the energy they save and then perform a life cycle analysis to compare their overall environmental impacts. All US climate zones are studied by selecting 17 US cities to understand the critical role of climate on energy demand. In addition, this study takes into account the monetary savings due to reduced energy consumption and compares the overall life cycle costs to understand the sustainable performance of different roofing options.

4.2.2 Energy Modeling

It should be noted that originally we intended to use DOE-2.1 through a user interface developed by Oak Ridge National Laboratory and Lawrence Berkeley National Laboratory named the Roof Savings Calculator [160]. This interface, similar to the Window Selection Tool in the last chapter, focuses on one housing component and its impact on energy. It is relatively simple and could allow consumers to quickly estimate how changing components of their roof could affect their energy use. However, for more than a year, and present moment (June 15th, 2015), the model is undergoing validation due to discrepancy in results with previous roofing studies and models, and therefore results from energy simulations using the tool cannot be cited.

Instead of the Roof Savings Calculator, we used an energy modeling software developed by the DoE called EnergyPlus, which was briefly discussed in the previous chapter on windows. NREL created a user interface that makes this program simple to use, without a consumer or developer having to learn programming, but does still require downloading the interface and the energy modeling software (rather that working on a website as is the case with the Window Selection Tool and the Roof Savings Calculator). This model computes a number of factors, including the energy use and energy savings for the entire home. Within the program, there are numbers of variables which can be changed to best simulate the home, including factors all the way from building envelope materials to using set temperatures for the summer and winter seasons.

The program also has inputs for weather files and utility costs. We used the TMY3 files for our simulations, which are similar to the TMY2 files used for the windows study. They are however updated and more accurate, including weather data from 1990 – 2005, compared to TMY2 which covers 1961-1990 [161]. The utility costs can also be varied based on national average, state average, user-specified, or detailed rates. For each city we used detailed rates based on the utility company that would be servicing that city. Detailed rates are not available for natural gas though, so state averages are used in those instances.

Once the inputs are completed, the model can be run in three modes: design mode, which only compares the current design to one other selected design option; parametric mode, where the initial design can be compared the combination of any selection made; or optimization mode, which uses all of the variables to find the best solution for the home. Based on our desire to compare a number of roofing options, we chose to ran the model in parametric mode, changing only the variables within the roofing section. The modeling assumptions for BEopt can be seen in Table 4.1 and assumptions are based on what was modeled for the windows with RESFEN [121] and defaults for existing homes in BEopt when the RESFEN assumptions were unavailable.

Table 4.1: Modeling assumptions for roofing study.

Category		Selected Input
General home characteristics	Total floor area	158 m^2
	Bedrooms	3
	Baths	2
	Age of home	Varies based on city
	Foundation type	Varies based on city
	Floors of living space	1
	Wall height	2.4 m
	Attic	Unfinished
	Roof type	Gable
	Roof pitch	6:12
	Roof structure	Truss, cantilever
	Orientation	North
	Neighbors	At 6.1 m
Walls	Wood stud	R-7 fiberglass batt
	Wall sheathing	OSB
	Exterior finish	Vinyl, light
Ceilings/roof	Unfinished attic	Uninsulated, vented
	Roof material	Asphalt shingles, dark
	Radiant barrier	None
Foundations/ Floors	Space	Uninsulated
	Carpet	80%
Thermal mass	Floor mass	Wood surface
	Exterior wall mass	1.3 cm drywall
	Partition wall mass	1.3 cm drywall
	Ceiling mass	1.3 cm drywall
Windows & doors	Window area	15% equally orientated
	Windows	Single-pane, non-metal frame
	Interior shading	Benchmark
	Eaves	0.6 m
	Overhangs	None
Airflow	Air leakage	7 ACH50, 0.5 Shelter coeff.
	Mechanical ventilation	Exhaust
	Natural ventilation	Benchmark

Table 4.1 [cont]

Category		Selected Input
Space conditioning	Central air conditioner	SEER 10
	Furnace	Gas, 78% AFUE
	Duct leakage	15% for basements, 20% for crawlspace or slab
	Ceiling fan	Benchmark
	Cooling set point	76 F
	Heating set point	71 F
	Humidity set point	60% relative humidity
Water heating	Water heater	Benchmark, gas
	Distribution	Uninsulated copper
Lighting	Lighting	34% CFL hardwired, 24% CFL Plug-in
Appliances & Miscellaneous	Appliances & Miscellaneous	All benchmark

4.2.2.1 Sensitivity Analysis to Reduce Variables

In order to maintain consistency, the only home variables which were changed for the energy model related to roofing. Even within this section, there are 43 insulation choices, 13 roofing material choices, and the option to have a radiant barrier or not. With all of those options selection in parametric modes, we are able to calculate 1,092 scenarios for energy use for all of the potential roofing combinations. This many points, however, is not only difficult to analyze and compare, but also takes a significant amount of time to run on the computer. We needed to reduce the number of points tested for all 17 cities. To get a sense of which factors may be driving energy savings, we ran all of the point for Atlanta, our test bed city and analyzed trends for Atlanta.

To understand the trends, we focused on one input option at a time, including level of insulation, roofing material, roofing color, and use of a radiant barrier. Keeping all other factors equal, we took one input at a time and found averages to understand potential trends. Figure 4.3 displays the impact of materials and colors in terms of energy savings and annualized energy costs. After analyzing the data, we found that in terms of energy use, color and material made almost no difference for Atlanta. Changing dark roofing in for white roofing only led to a savings of 0.06% for asphalt and 0.2% for clay tile. Changing from asphalt to tile led to, at most, an extra savings of 0.13%, as else equal. We found the trend to be similar for the radiant barrier, with the barrier decreasing energy use by 0.7% on average. According to the model, clay tiles were significantly more expensive for the time period we tested and radiant barriers added in cost that was greater than the potential savings.

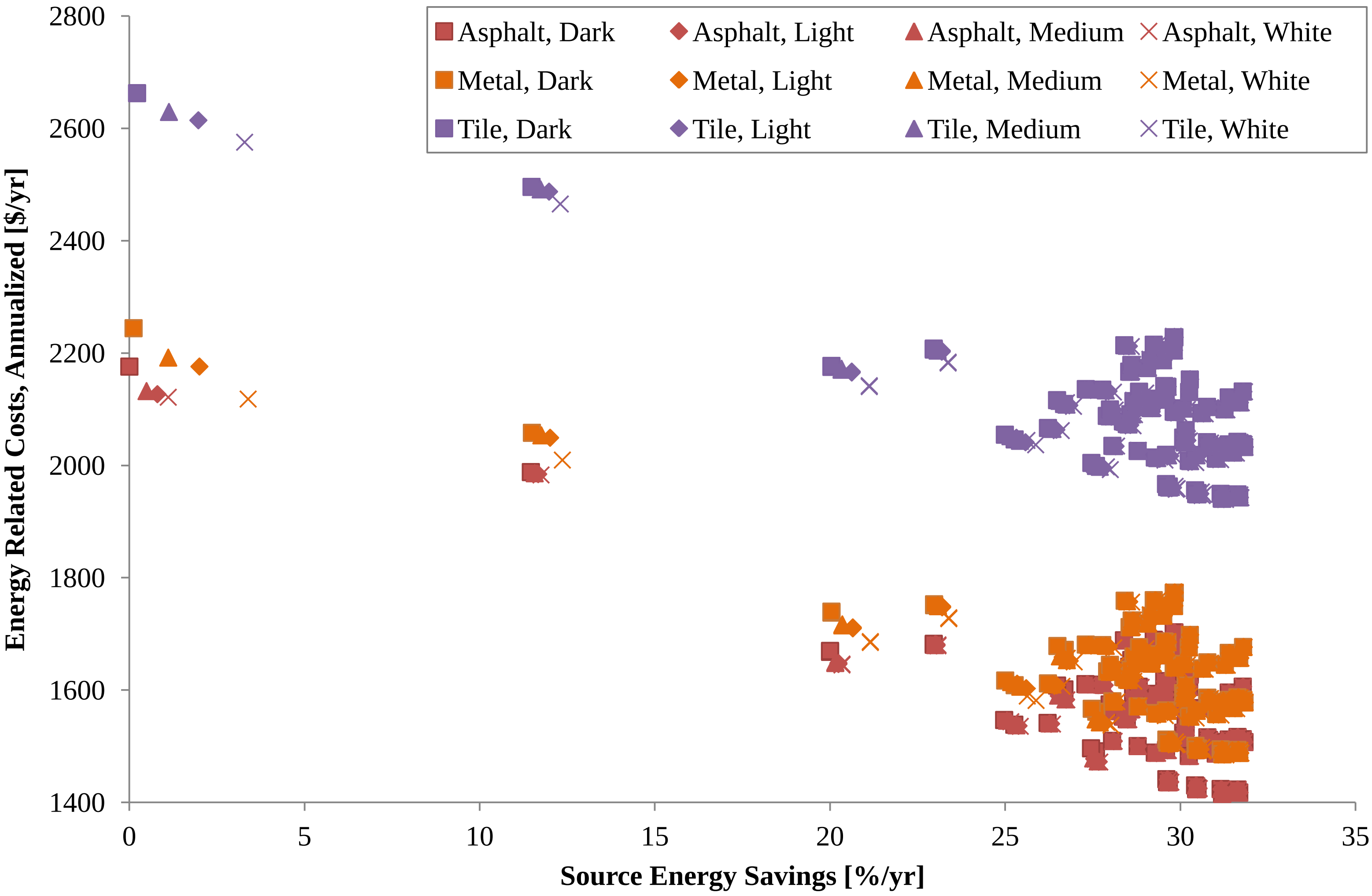

Figure 4.3: Energy simulation results for 1,092 roofing system scenarios in Atlanta.

Having tested all the other factors, we looked lastly at insulation. This factor proved to be the most influential in bringing about energy savings. Looking at Figure 4.4 we plotted the change in energy savings as related to the insulating R-value for roofing and ceiling insulation. These insulations simply vary as to where they are installed in the roofing system: either directly to the roof or above the ceiling in an attic. With this data, we can see a definite trend, with increasing insulation leading to increasing energy savings, but not in a linear fashion. Instead the trend seems to be approaching a limit, where in the case of Atlanta increased insulation has diminishing returns. Additionally, we can note that ceiling insulation performs slightly better that roofing, but this difference is close to negligible.

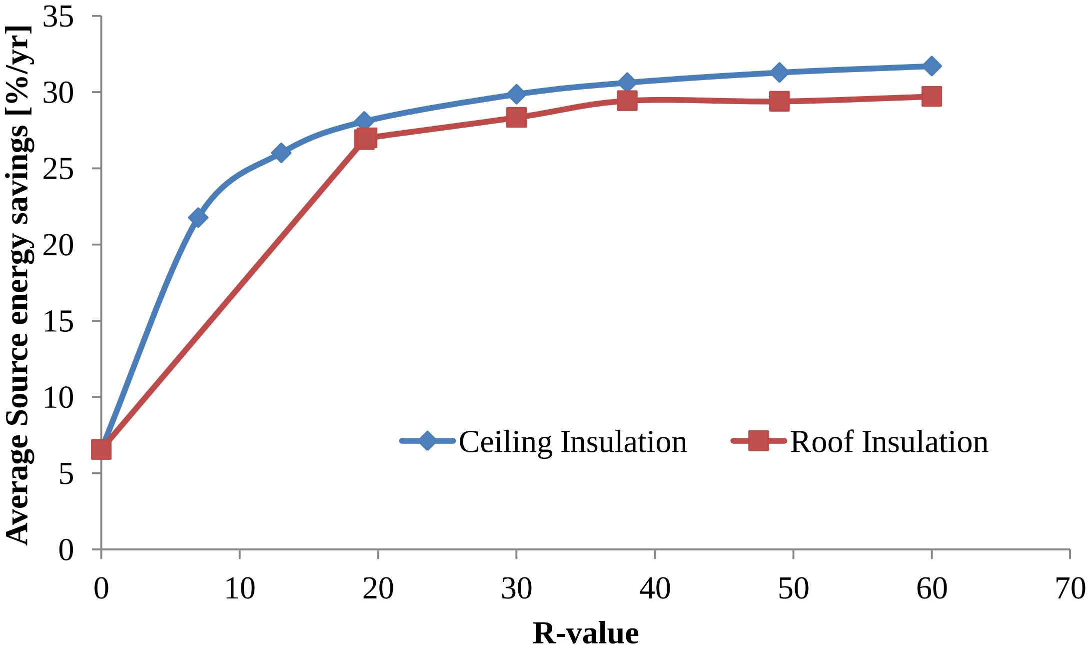

Figure 4.4: Correlation between energy savings and R-value.

The complete investigation of Atlanta's roof helped us to narrow down the factors for our study. We found the level of insulation to be the most important in reducing energy use of the home. In our model, we assumed that the homes had attics and so ceiling insulation was something that could be used. For all of the cities studied we chose to look at 4 levels of insulation: no insulation, the previously installed insulation as assumed by the RESFEN model [121] (between R-11 and R-22 depending on the city), the required insulation for the home to be up to code [116], and R-60, which is the highest level of insulation we could model. Exact assumptions for insulation, as well as age of home and foundation type used in the modeling are listed in Table 4.2. Because the model only had certain levels of insulation available to test, and those levels were close to, but not exactly matching the cost data available from the NREL Retrofit Database [112], we had to choose levels of insulations which most closely match our data, so LCA and LCC assumptions are listed separately in the table.

We did wonder if materials or color could potentially have more of an impact in extremely cold or hot climates. To test this theory, we test asphalt shingles and clay tile in dark and white. Asphalt and composition shingles are used for 64% of US homes [52], but in locations of extreme heat and sunlight, asphalt can melt, so clay tiles were provided as an alternative. We did not have the inventory information on metal roofing to add it to this study. For each of the 17 locations, there are 16 energy use data points which are used to understand the impact of roofing choices on energy, the environment, and economics.

Table 4.2: Factors which vary by city for energy simulation.

Cities	Age of home [162]	Level of Insulation	
		Previous for LCA (and LCC)	Required
Honolulu, HI	37	R-13 (R-11)	R-30
Miami, FL	29	R-13 (R-11)	R-30
New Orleans, LA	32	R-19 (R-19)	R-38
Phoenix, AZ	27	R-13 (R-11)	R-38
Atlanta, GA	29	R-13 (R-11)	R-38
El Paso, TX	32	R-19 (R-19)	R-38
San Francisco, CA	37	R-13 (R-11)	R-38
Kansas City, MO	39	R-19 (R-21)	R-49
Albuquerque, NM	27	R-13 (R-11)	R-49
Seattle, WA	39	R-19 (R-19)	R-49
Boston, MA	49	R-19 (R-21)	R-49
Salt Lake City, UT	27	R-13 (R-11)	R-49
Minneapolis, MN	39	R-19 (R-21)	R-49
Billings, MT	27	R-19 (R-19)	R-49
Duluth, MN	39	R-19 (R-19)	R-49
Anchorage, AK	37	R-19 (R-21)	R-49
Fairbanks, AK	37	R-19 (R-21)	R-49

4.2.2.2 Influence of Climate and Location on Energy

We used the same US cities with close to the same modeling assumptions for the roofing and windows study. Section 3.2.4.3 covers the information on the locations selected. The energy mixes in the case of this study were directly selected within the program. For each city, we chose the detailed utility rates for electricity, selected the utility rate and their rate which would apply for a home, which helps give us a good estimate of cost for a particular location. Once again, we used the energy mixes from January 2015 [140] to find which energy sources were reduced based on locations, which is needed for the LCA.

4.2.3 Functional Unit and Scope of Study

As in previous studies, 1 m^2 of material is the standard we use to compare results. For roofing, however, this is a little more complicated. We are using ceiling insulation which lays flat on the ceiling above the floor area. However, the roofing material is applied to a roof which we assume is not flat, therefore 1 m^2 of ceiling would not equate to 1m^2 of roofing. We chose to use 1m^2 of ceiling as our functional unit because this unit is easier to conceptualize because we tend to think in floor area of a home rather than roofing area of a home. This means that the roofing materials are multiplied by a factor of 1.118, which is the amount of roofing material needed for 1m^2 of ceiling space based on a roof pitch of 6:12. Steeper pitches would need to be multiplied by a larger factor and vice versa, but for consistency, all roofs in this study were assumed to have a standard pitch of 6:12. Additionally, shingles are installed in layers which overlap. This material need is included with the LCA and LCC data as well.

As mentioned previously, four levels of insulation and two roofing materials in two different colors were chosen, which gave us 16 energy scenarios for 17 cities. It was determined to be outside of the scope of this study and the scope of the model to study the impact of time and environmental conditions on the effectiveness of cool roof coatings or to investigate different kinds of coating [163]. Within the LCA and LCC study of the materials, the underlayment for the roofing was also studied. The lifetime of all the materials used in the study is listed in Table 4.3. Insulation lasts the lifetime of the home, however it should be noted that when retrofitting insulation, you can leave the current insulation and add additional insulation on top of previous insulation to reach a certain R-value. This is crucial, because this reduced the amount of material need thereby reducing costs and environmental impacts from added insulation. We chose to use blown-in cellulose in this study because it was slightly cheaper, had similar energy impacts, is a more natural product made largely of recycled newspaper (which would hypothesize would be more environmental), and by being blown-in it can be added to in order to increase R-value easily. We studied this as compared to fiberglass in the last LCA study on insulation. Additionally, we should note clay tiles last the lifetime of the home, but the underlayment needs to be replaced about every 15 years. Asphalt should be replaced every 20 years, but after 20 years the first layer can be considered new underlayment and left in place, meaning the no new underlayment is needed and at 40 years both the underlayment and asphalt should be replaced. Because of the varied timescales, we chose to look at this study in terms of the lifetime of a home, which is approximately 60 years [53] as was done in the flooring study. We also will look at how these values change over time though, to understand what the best options are depending on the remaining life of the home.

Table 4.3: The insulation and roof covering options studied and their lifetimes.

Level of insulation	None	Previous	Required	R-60
Type	Blown-in cellulous			
Lifetime	Life of home			
Roofing material	Asphalt, dark	Asphalt, white	Clay tile, dark	Clay tile, white
Lifetime	20 years		Life of home	
Roofing install	Underlayment		Underlayment	
Lifetime	40 years		15 years	

The options we studied, create 16 roofing systems for each cities. This is a large amount of data to comprehend for 17 cities. In order to make the results section understandable, we have elected to create a shorthand for all of the systems, which can be seen in Table 4.4. The first piece of the string indicates the level of insulation, then the roofing material, then the color. This notation will be used throughout the rest of the chapter for the specific roofing systems.

Table 4.4: Notation for roofing systems in roofing chapter.

Order	Level of insulation	Roofing material	Roofing color	Notation
1	None	Asphalt	Dark	0AD
2			White	0AW
3		Tile	Dark	0TD
4			White	0TW
5	Previous	Asphalt	Dark	PAD
6			White	PAW
7		Tile	Dark	PTD
8			White	PTW
9	Required	Asphalt	Dark	RAW
10			White	RAD
11		Tile	Dark	RTD
12			White	RTW
13	R-60	Asphalt	Dark	60AD
14			White	60AW
15		Tile	Dark	60TD
16			White	60TW

4.2.4 Data Sources

The life cycle assessment begins with collecting the inventory data that will provide the inputs into the assessment program. In the case of roofing, roof covering and insulation data were both available through the BEES database [41], which was also used in the flooring study. The data from the BEES database documented the inventory for the resource, manufacturing, installation, and end-of-life phases. However, we were limited in which materials we could compare based on the data that was available. For instance, we would have liked to compare metal roofing to asphalt and clay, which the energy model showed had similar energy use savings; however, the BEES database did not have information for metal roofing components and we could not find other inventory to the necessary detail in the literature. We did have two primary materials we could compare for insulation, cellulose and fiberglass, but in order to keep the number of variables reasonable to report, we limited our study to just cellulose. The last study on wall insulation looks at the environmental differences within these two options, and although the R-values are generally higher in ceiling insulation, we would expect the trends in environmental impacts to be the same.

Also it should be noted that the inventory for the insulation is given in percentages of a given weight, which can be calculated based on the density of the product and the thickness of product needed to achieve a specific R-value. Only R-38 values were given in the database. We did have the values for the thickness of the insulation needed from within the input screen on the BEopt model [124], so we could estimate the inventory of the insulation. The values of thickness and R-value which were given were perfectly linear.

For the life cycle costing, we used the NREL Retrofit Materials Database [112], which was used in the windows study. We did not have specific information on disposal costs, however, so this was assumed to be integrated in the installation costs and not separated for the study. Roofing material and insulation prices were given, though the price for insulation depended on the previous level of insulation. Any previous level of insulation reduces the cost of a higher insulation value because insulation can be added on top of the previous insulation to increase the R-value, and the insulation should not need to be disposed of or replacement during the lifetime of a home.

4.2.5 LCA Method

The LCAs were conducted in a similar manner to those in the previous studies, using the same method, ReCiPe Hierarchist, in the SimaPro software. Unlike the previous methods, however, insulation can be added incrementally. For example, if a home had no insulation, getting the insulation value up to R-60 would require adding 0.42 m (about 17 inches) of blown cellulose to the ceiling. If a home already had insulation installed which reached a value of R-38, only 0.13 m (about 4 inches) of cellulose would need to be added to reach R-60. The potential for upgrading to R-60 from no insulation versus upgrading to R-60 from R-38 is drastically different in terms of material needed, energy saved, and as we will talk about in the next section, cost. The difference in potential added a great deal of complexity to this study, but we felt this complexity made the study more interesting and applicable to the general public. Given the disparity in environmental effects based on the current level of insulation, we chose to look at three scenarios for the insulation:

1. No insulation to previously required level, currently required level, and R-60.
2. Previously required level to current required level and R-60.
3. Currently required level to R-60.

Using the results from the three scenarios, we can inspect whether retrofitting the ceiling to add more insulation is worthwhile environmentally and economically.

Due to time and computing constraints, a short Monte Carlo uncertainty analysis was conducting on the LCA of Atlanta’s roofing options, where 100 trials were run for each of the roofing systems. As with previous studies, the uncertainty of each input was added to the input file, and we can see the range and distribution of the environmental impact values.

4.2.6 LCC Method

The LCC method is similar to the method used in the flooring assessment with a few notable differences. The energy costing was available on an annual basis from within the BEopt program, based on the energy model and the nominal discount rate, so this was used directly in the use phase of the LCC. Also, as noted in the previous section, the cost changes depending on the amount of insulation that needs to be added. The NREL [112] retrofitting cost database we used accounted for this, so we used the appropriate numbers for three scenarios of retrofitting previously listed. The energy savings between the insulations in these scenarios was also updated. Additionally, no information was available on the cost of disposing of roofing materials, so this number was considered to be included in the retrofitting costs and was not separated out as was done in the previous two studies.

Because of the complexity of the various levels of insulation, roofing materials, and roofing color options along with the scenario study based on the current level of insulation in a home meant that we avoided some of the complicated financial scenarios which were included in the windows study. Added resale value and the changing cost of energy were not consideration within this roofing study.

4.2.7 Single Scoring

The methodology for single scoring precisely matches the method used in the windows study (Section 3.2.8). We looked at the same three scenarios for levels of current insulation for a retrofit to determine the best option for retrofitting.

4.3 Results and Discussion

4.3.1 Influence of Climate and Location on Energy Results

We began the roofing analysis by looking at the impact of climate, and specifically location on energy results. As we found in the initial study of Atlanta, insulation was by far the most important factor for gaining energy savings. For all of the cities in climate zones 1-4, with the exception of marine climates, white roofing led to a lower annual energy cost than dark roofing and the greater the insulating value was, the less pronounced the savings due to roofing color were, which is in agreement with past experiments and studies [148, 152]. The opposite is true, for the most part, for cities in climate zones 5-8 and marine climates, with a few exceptions for Minneapolis and Salt Lake City in the cases of no insulation or previous insulation. This pattern was also held true for the roofing material, with tile tending to be better in the warmer climates, and asphalt tending to be better in colder climates. These results fit the hypothesis that darker materials have better energy performance in cooler climates where heat gain is more desirable, leading to decreased heating bills where heating bills dominate the cost. Likewise, cooler materials have better energy performance in warmer climate where heat gain is undesirable, leading to increased cooling bills in areas electricity bills dominate the cost. The energy savings are shown in Table 4.5, where a positive value indicates energy savings and a negative value indicates added costs. The change in energy costs is highly dependent on the cost of energy in the city, but we can see the most energy cost savings occur in the hottest climate (Honolulu) and the coldest climate (Fairbanks).

We also looked at the change in energy demand based on the various roofing systems, as shown in Table 4.6. The first thing worth noting about this data is that, similar to the windows study, the most energy in total kWh is saved in heating climates. This is by virtue of the fact that heating a home takes more primary energy than cooling a home. In terms of total energy, adding insulation always decreases the total energy demand. For total energy, white and tile roofing only provide a benefit in five cities (Honolulu, Miami, New Orleans, Phoenix, and El Paso), though this is likely due to the dominance of heating energy. When we look at heating demand separately, insulation always reduces heating demand and tile and white roofing always increases it. Insulation also always reduces cooling demand, and white or tile materials reduce cooling demand in most circumstances, with a few exceptions in the marine climates and climate zones 7 and 8. How the cooling and heating energy are balanced in each climate affects the total energy, as well as the environmental and cost impacts.

Table 4.5: Energy savings (or added cost indicated by negative value) for roofing systems as compared to the 0AD roofing system (in $).

Roofing System	0AW	0TD	0TW	PAD	PAW	PTD	PTW	RAD	RAW	RTD	RTW	60AD	60AW	60TD	60TW
Honolulu	135	27	516	689	724	696	824	814	830	818	877	868	876	870	900
Miami	32	6	118	158	169	160	197	188	194	189	211	201	205	202	216
New Orleans	14	2	48	183	187	184	196	204	207	205	213	213	215	213	220
Phoenix	67	13	249	544	566	549	631	674	685	676	720	703	712	705	740
Atlanta	12	2	37	373	377	374	387	462	464	462	469	482	483	482	488
El Paso	25	5	86	343	349	344	366	384	388	385	399	401	404	402	413
San Francisco	1	-1	-25	252	250	252	240	310	308	309	303	323	322	323	318
Kansas City	6	1	18	435	436	435	438	496	496	496	497	504	504	504	504
Albuquerque	28	5	93	399	408	401	428	508	511	508	520	517	519	517	527
Seattle	-9	-3	-47	367	365	367	357	419	418	419	414	426	425	426	421
Boston	-3	-1	-21	583	581	582	578	661	661	661	659	671	671	671	669
Salt Lake	3	0	5	318	318	318	318	400	399	400	398	406	406	406	405
Minneapolis	5	0	12	508	509	508	509	577	577	577	577	586	586	586	585
Billings	-1	-1	-10	402	401	402	399	457	457	457	455	464	464	464	462
Duluth	-9	-2	-40	506	504	505	496	573	572	573	569	582	581	582	578
Anchorage	-14	-4	-61	645	641	644	631	732	731	732	726	743	742	743	738
Fairbanks	-11	-4	-54	843	840	842	830	956	954	955	950	970	969	970	965

Table 4.6: Energy reduction (or additional needed indicated by negative value) for roofing systems as compared to the 0AD roofing system (in kWh).

Roofing System	0AW	0TD	0TW	PAD	PAW	PTD	PTW	RAD	RAW	RTD	RTW	60AD	60AW	60TD	60TW
Honolulu	510	103	1950	2320	2452	2349	2836	2742	2804	2757	2983	2930	2956	2936	3047
Miami	504	97	1877	2426	2596	2461	3068	2863	2959	2883	3232	3056	3124	3071	3303
New Orleans	158	15	472	6552	6602	6558	6740	7306	7338	7312	7435	7614	7640	7617	7717
Phoenix	458	73	1502	7373	7538	7403	7998	9072	9160	9089	9427	9444	9517	9462	9732
Atlanta	-114	-44	-701	9790	9764	9779	9632	12093	12084	12090	12043	12618	12606	12612	12585
El Paso	15	-32	-396	10031	10042	10025	10037	11222	11233	11224	11254	11720	11729	11720	11755
San Francisco	-713	-179	-3417	9107	8866	9048	8074	11324	11219	11301	10890	11843	11767	11826	11527
Kansas City	-229	-70	-1103	14257	14201	14240	14020	16237	16211	16231	16125	16498	16472	16489	16398
Albuquerque	-384	-123	-2047	12418	12298	12377	11826	15794	15756	15785	15612	16061	16029	16052	15905
Seattle	-575	-161	-2690	14993	14855	14961	14410	17117	17049	17099	16841	17393	17337	17378	17158
Boston	-510	-129	-2173	17871	17762	17847	17437	20276	20229	20267	20088	20575	20531	20566	20413
Salt Lake	-414	-117	-1959	14724	14586	14688	14119	18498	18448	18487	18278	18786	18742	18777	18595
Minneapolis	-490	-129	-2132	23578	23464	23546	23121	26743	26693	26728	26529	27145	27101	27136	26966
Billings	-528	-141	-2302	21000	20880	20971	20504	23851	23792	23833	23622	24212	24162	24203	24012
Duluth	-774	-191	-3291	28432	28250	28388	27714	32227	32148	32213	31899	32697	32626	32682	32418
Anchorage	-821	-226	-3564	31723	31535	31673	30955	36043	35955	36020	35703	36592	36518	36574	36304
Fairbanks	-780	-243	-3452	41132	40953	41076	40366	46675	46590	46652	46335	47385	47318	47365	47098

4.3.2 LCA Results

There are 18 scores for the environmental midpoint categories, which we analyzed in Atlanta. These categories give us more tangible outcomes, such as fossil fuel depletion in kg of oil equivalent, unlike the more abstract Points which we discuss for the endpoint categories. When we looked at Atlanta, we found that environmentally the best roofing insulation value was very consistent, though the color and material did vary. The roofing systems with the lowest and best environmental impacts had R-60 insulation (with one exception). Clay tile were the best option in 11 categories (asphalt in 7 categories), and white tiles were best in 12 categories (dark in 6 categories). Overall, the best performing roof system was 60TW in half of the categories, with 60AD being best in 5 categories.

It is expected that in terms of environmental impacts the white clay tiles would perform best in most categories, with insulation lowering energy demand [159] and white, clay tiles performing better in cooling intensive climates [150]. However, the importance of each impact can be weighed differently depending on the objective or the method, so it is difficult to make overall conclusions for the midpoint data. The midpoint results are summarized in Table 4.7 and the complete quantitative results for the midpoints in Atlanta are in Appendix D.

Table 4.7: Roofing system with the lowest environmental impact by midpoint category in Atlanta. Complete results are in Appendix D.

Impact category	Lowest Impact Roofing System
Climate change (kg CO_2 eq)	60AD
Ozone depletion (kg CFC-11 eq**)**	60TW
Terrestrial acidification (kg SO_2 eq**)**	60AD
Freshwater eutrophication (kg P eq**)**	60TW
Marine eutrophication (kg N eq**)**	60TW
Human toxicity (kg 1,4-DB eq**)**	60TD
Photochemical oxidant formation (kg NMVOC**)**	60TW
Particulate matter formation (kg PM-10 eq**)**	60AD
Terrestrial ecotoxicity (kg 1,4-DB eq**)**	60AW
Freshwater ecotoxicity (kg 1,4-DB eq**)**	60AD
Marine ecotoxicity (kg 1,4-DB eq**)**	60AD
Ionising radiation (kg U_{235} eq**)**	60TW
Agricultural land occupation (m^2a**)**	60TW
Urban land occupation (m^2a**)**	60TW
Natural land transformation (m^2**)**	60AW
Water depletion (m^3**)**	60TW
Metal depletion (kg Fe eq**)**	RTW
Fossil depletion (kg oil eq**)**	60TW

We investigated, in greater depth, the single environmental scores for roofing systems in all 17 cities. Unlike previous studies, though, we studied how incremental changes in insulation could affect the environmental results, so that our results could apply to owners with all levels of insulation. Because insulation can be added upon itself to increase the insulation value, we know that the resource, manufacturing, installation, and end-of-use associated with insulation will all decrease as less is needed. However, the energy improvements for homeowners considering increasing insulation from R-38 to R-60 will be smaller than homeowners with no insulation considering retrofitting up to

R-60. To show how these factors impacted the results, Figure 4.5-4.7 display the environmental scores of all of the roofing systems, separated by life cycle phase. Figure 4.5 shows the life cycle when no insulation has been installed. It clearly shows the correlation between the use phase environmental impacts and insulation, with greatly reduced environmental impacts coming from having insulation. We see that without insulation, white clay tiles actually increase energy demand in Atlanta due to extra heating needed in the winter. Dark tile actually performs better than white tiles until the required amount of insulation is met. However, as insulation is increased, the difference between asphalt and clay tiles and the difference between dark and white colored materials becomes smaller. Also worth noting is that the total impacts related to the materials (resources, manufacturing, installation, and end-of-life) make up 1.5% or less of the total impacts once insulation is installed for Atlanta.

Figure 4.6 shows the environmental impacts assuming that the previous insulation is the assumed R-13 for Atlanta, and Figure 4.7 shows the impacts assuming the currently required level of insulation is installed (R-38 for Atlanta). We see similar trends for which materials perform best environmentally and in terms of energy savings as demonstrated in the use phase, however, the total impact is much lower. For instance, installing the top performing roofing system for Atlanta, 60TW, the total environmental impact savings are 178, 39.0, and 6.09 Pts/m^2 as compared to no insulation, R-13, and R-38 respectively. Material reductions due to a decreased need of insulation for incremental additions of insulation only led to a savings of around 0.1 Pts/m^2, which is negligible in the scope of the total impacts. We do see, however, that the material choices have a comparable more significant impact when compared to incremental insulation increases.

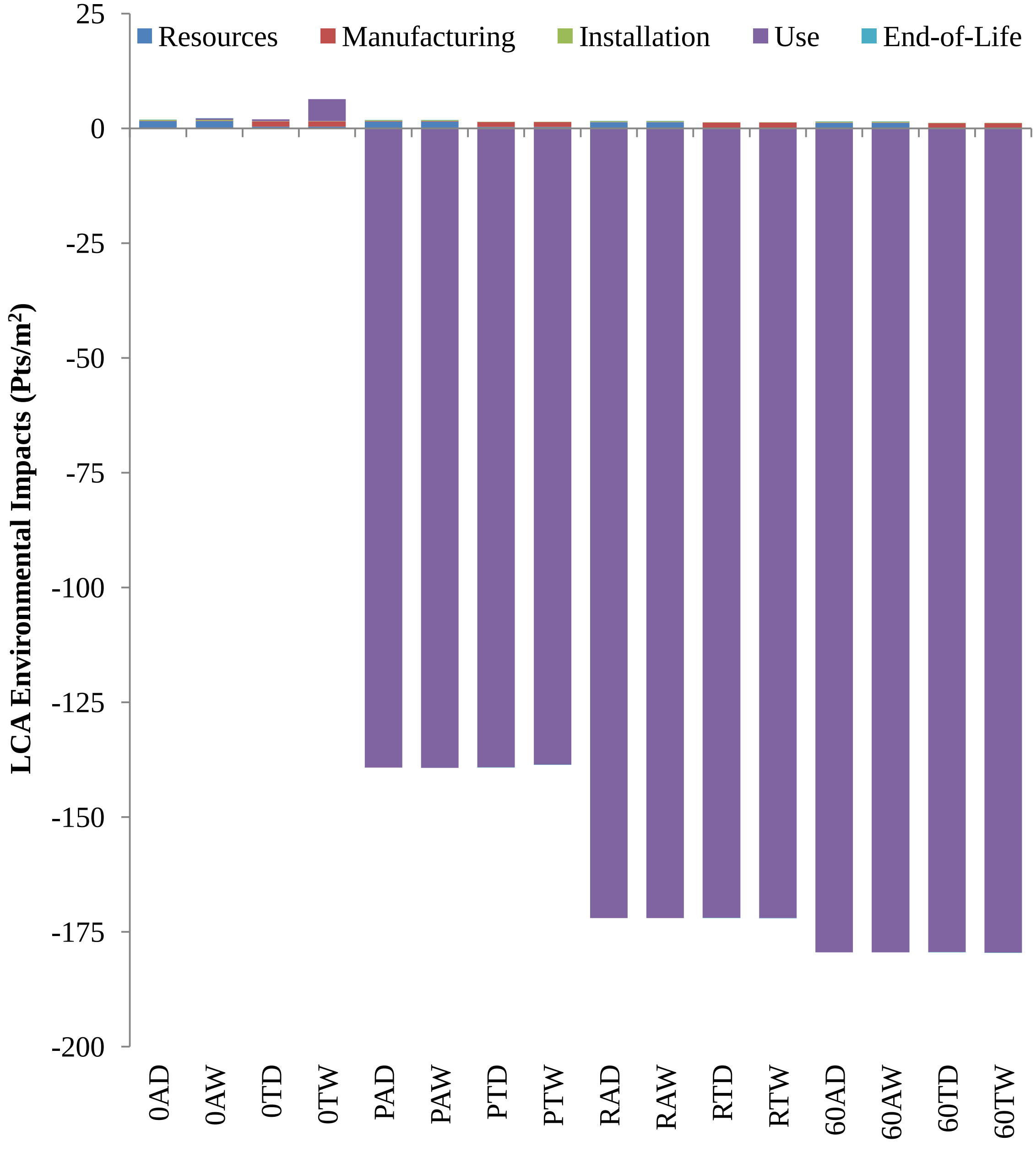

Figure 4.5: LCA results of roofing options in Atlanta when retrofitting from no insulation.

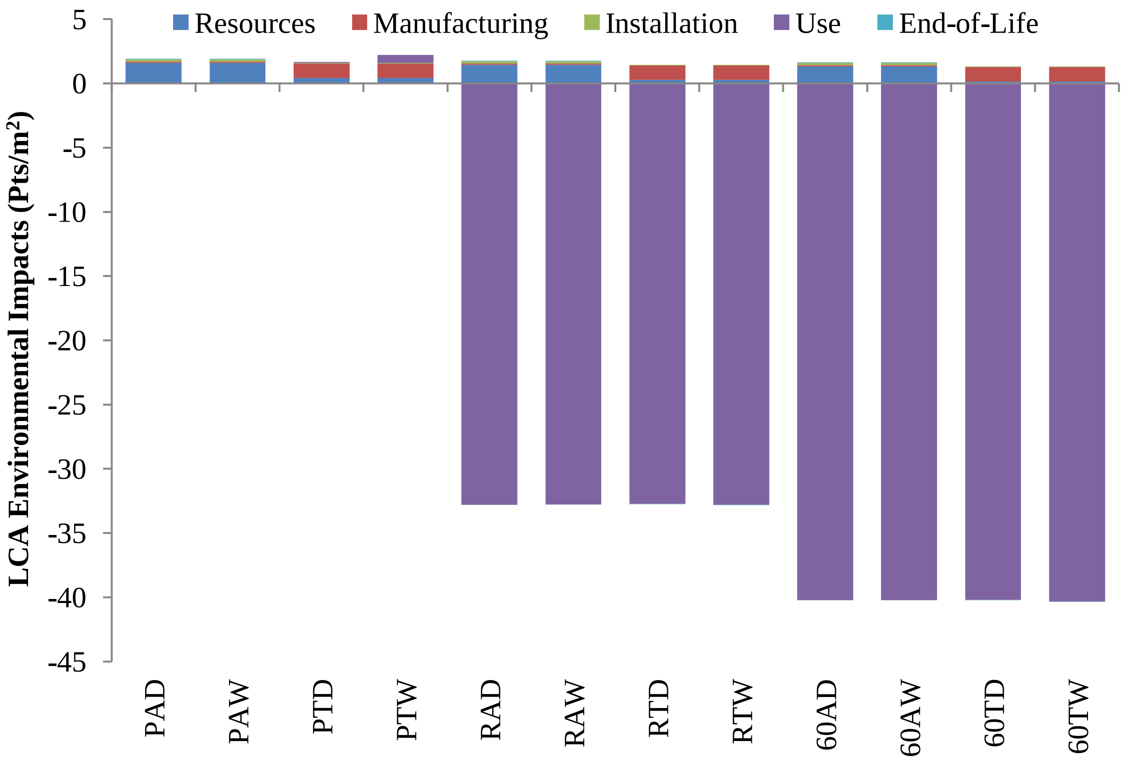

Figure 4.6: LCA results of roofing options in Atlanta when retrofitting from the previous assumed insulation, R-13.

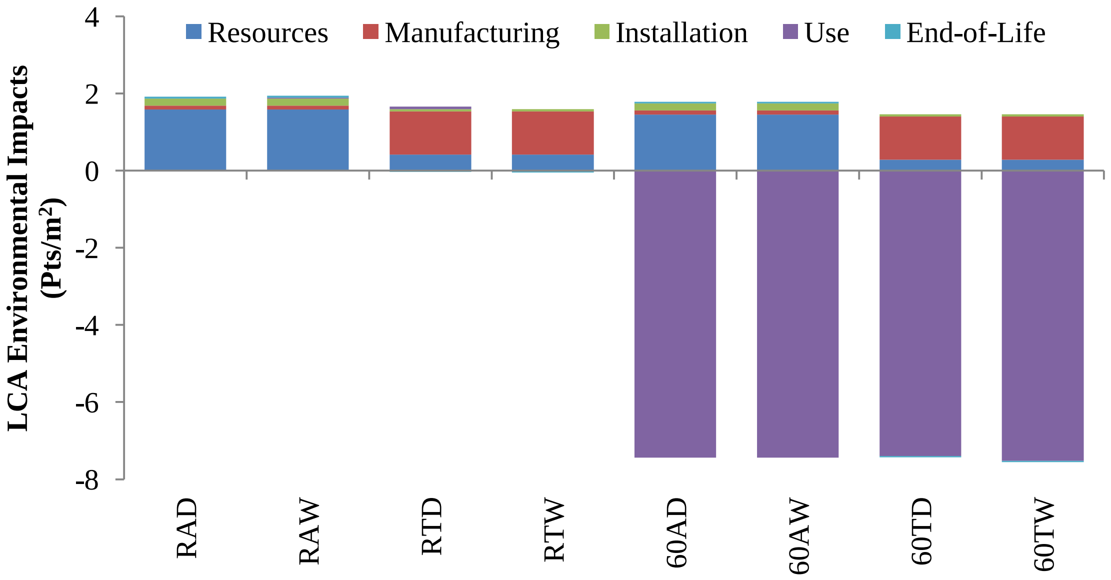

Figure 4.7: LCA results of roofing options in Atlanta when retrofitting from the currently required insulation, R-38.

Like in the windows study, the materials values for the phases remain the same across all of the cities (with slight adjustments based on previously installed insulation and currently required insulation values). Given that information, we chose to only display the use phase impacts from energy use for all 17 cities in Table 4.8, assuming that no insulation is currently installed. The heating was assumed to be provided by natural gas, and the electricity was provided by the grid mix for each state [140]. Unlike the windows study, we see that the environmental impact generally decreases with cooling degree days in a climate. Increasing insulation led to very substantial reduction in heating energy, and also improved cooling demand but to a lesser extent, which explains the environmental improvement gains to retrofitting a roofing system in cooler climates. The more moderate, marine climates of San Francisco and Seattle do see smaller reductions than other cities within their climate zone because their energy reductions are smaller, but unlike in the windows study. They are not the smallest reductions because the heating demand reduction dominates with increased insulation. With incremental insulation retrofits, these values are also reduced in a similar fashion to that seen with Atlanta. Next we wanted to look at the best performing roofing systems for each city, based on total LCA scores.

Table 4.8: Scores for use phase of roofing for all roofing systems and 17 cities (in Pts).

City	0AW	0TD	0TW	PAD	PAW	PTD	PTW	RAD	RAW	RTD	RTW	60AD	60AW	60TD	60TW
Honolulu	-9.9	-2.0	-37.9	-45.0	-47.5	-45.5	-55.0	-53.2	-54.4	-53.5	-57.8	-56.7	-57.3	-56.9	-59.0
Miami	-8.2	-1.6	-30.6	-38.4	-41.1	-38.9	-48.7	-45.4	-46.9	-45.6	-51.3	-48.4	-49.4	-48.6	-52.3
New Orleans	-3.6	-0.5	-11.7	-96.1	-97.1	-96.3	-100.0	-107.1	-107.8	-107.3	-109.8	-111.7	-112.3	-111.8	-113.8
Phoenix	-10.0	-1.8	-34.6	-121.0	-124.4	-121.7	-134.2	-149.0	-150.8	-149.4	-156.3	-155.3	-156.8	-155.6	-161.1
Atlanta	0.3	0.4	4.8	-139.2	-139.2	-139.1	-138.6	-172.0	-172.0	-171.9	-172.0	-179.4	-179.4	-179.4	-179.5
El Paso	-3.3	-0.2	-6.2	-152.9	-153.8	-153.0	-157.0	-171.1	-171.8	-171.2	-173.4	-178.8	-179.3	-178.9	-180.6
San Francisco	9.9	2.5	46.9	-121.7	-118.4	-120.9	-107.6	-151.3	-149.9	-151.0	-145.4	-158.3	-157.2	-158.1	-154.0
Kansas City	-2.3	-0.1	-5.5	-234.3	-234.5	-234.2	-234.8	-266.8	-266.8	-266.8	-266.8	-271.0	-271.0	-275.9	-265.8
Albuquerque	-1.3	0.3	4.0	-203.1	-203.5	-203.0	-202.6	-258.3	-258.7	-258.4	-258.9	-262.8	-263.0	-262.8	-263.3
Seattle	8.8	2.4	39.5	-195.0	-193.0	-194.5	-186.6	-222.7	-221.7	-222.4	-218.8	-226.2	-225.5	-226.1	-223.0
Boston	6.6	1.7	28.1	-246.3	-244.9	-246.0	-240.7	-279.4	-278.8	-279.3	-277.0	-283.7	-283.1	-283.5	-281.5
Salt Lake	0.4	0.5	7.9	-236.9	-236.3	-236.7	-233.2	-297.4	-297.0	-297.4	-295.6	-302.1	-301.8	-302.0	-300.4
Minneapolis	5.4	1.5	24.5	-332.7	-331.3	-332.3	-327.2	-377.4	-376.8	-377.2	-374.7	-383.1	-382.5	-382.9	-380.8
Billings	5.4	1.5	25.1	-302.0	-300.6	-301.6	-296.3	-343.1	-342.4	-342.9	-340.3	-348.3	-347.7	-348.2	-345.9
Duluth	10.0	2.5	43.2	-396.0	-393.6	-395.5	-386.4	-448.7	-447.6	-448.5	-444.3	-455.5	-454.5	-455.3	-451.7
Anchorage	11.2	3.1	48.4	-429.5	-427.0	-428.8	-419.1	-488.0	-486.8	-487.7	-483.4	-495.4	-494.5	-495.2	-491.5
Fairbanks	10.6	3.3	47.0	-556.6	-554.1	-555.8	-546.2	-631.5	-630.4	-631.2	-626.9	-641.1	-640.2	-640.8	-637.2

Table 4.9 summarizes the roofing systems which do best in the LCA for each city and from no insulation, the assumed previously installed insulation, and the currently required level of insulation. In terms of which systems do best, no matter what level of insulation is currently in place, R-60 is always the most environmental choice, as are clay tiles. White tiles are also the best choice environmentally in warmer climates due to cooling savings, specifically climate zones 1-3, excluding the marine climate, San Francisco. Dark tiles are the most environmental choice in cooler climates due to heating demands, including climate zones 5-8. Climate zone 4 is mixed in the results depending on the heating and cooling savings in that city.

Table 4.9: Summary of best environmental roofing systems by city and total LCA value achieved in Points/m^2.

City	No Insulation		Previous Insulation		Required Insulation	
	LCA	Value	LCA	Value	LCA	Value
Honolulu	60TW	-57.84	60TW	-12.77	60TW	-4.46
Miami	60TW	-51.13	60TW	-12.66	60TW	-5.58
New Orleans	60TW	-43.13	60TW	-16.30	60TW	-5.18
Phoenix	60TW	-112.56	60TW	-38.78	60TW	-10.65
Atlanta	60TW	-159.91	60TW	-39.03	60TW	-6.09
El Paso	60TW	-179.44	60TW	-26.37	60TW	-8.07
San Francisco	60TD	-156.86	60TD	-35.11	60TD	-5.30
Kansas City	60TD	-274.69	60TD	-40.31	60TD	-7.85
Albuquerque	60TW	-262.09	60TD	-58.41	60TW	-3.74
Seattle	60TD	-224.86	60TD	-29.75	60TD	-2.18
Boston	60TD	-282.34	60TD	-35.88	60TD	-2.90
Salt Lake City	60TD	-300.80	60TD	-63.77	60TD	-3.37
Minneapolis	60TD	-381.74	60TD	-48.93	60TD	-4.38
Billings	60TD	-347.00	60TD	-44.93	60TD	-3.92
Duluth	60TD	-454.05	60TD	-57.94	60TD	-5.32
Anchorage	60TD	-493.98	60TD	-64.36	60TD	-5.99
Fairbanks	60TD	-639.64	60TD	-82.96	60TD	-8.09

Lastly, we looked at the environmental scores over time for roofing options in Atlanta, as shown in Figure 4.8. It is difficult to compare the 16 different trend lines, but we can note some overall trends in the data. Retrofitting the roofing material or color without adding insulation would increase the detrimental environmental impact of roofing over the baseline case of 0AD. The data is grouped strongly based on the insulating value of the ceiling, to the extent that the differences between the roofing color or roof covering material is indistinguishable on the total scale of the impacts. Likewise the impacts of the creation and disposal of the roofing materials through the lifetime of the home are negligible compared to the energy savings. The LCA impacts decrease with every passing year of the life of the home due to the annual energy savings.

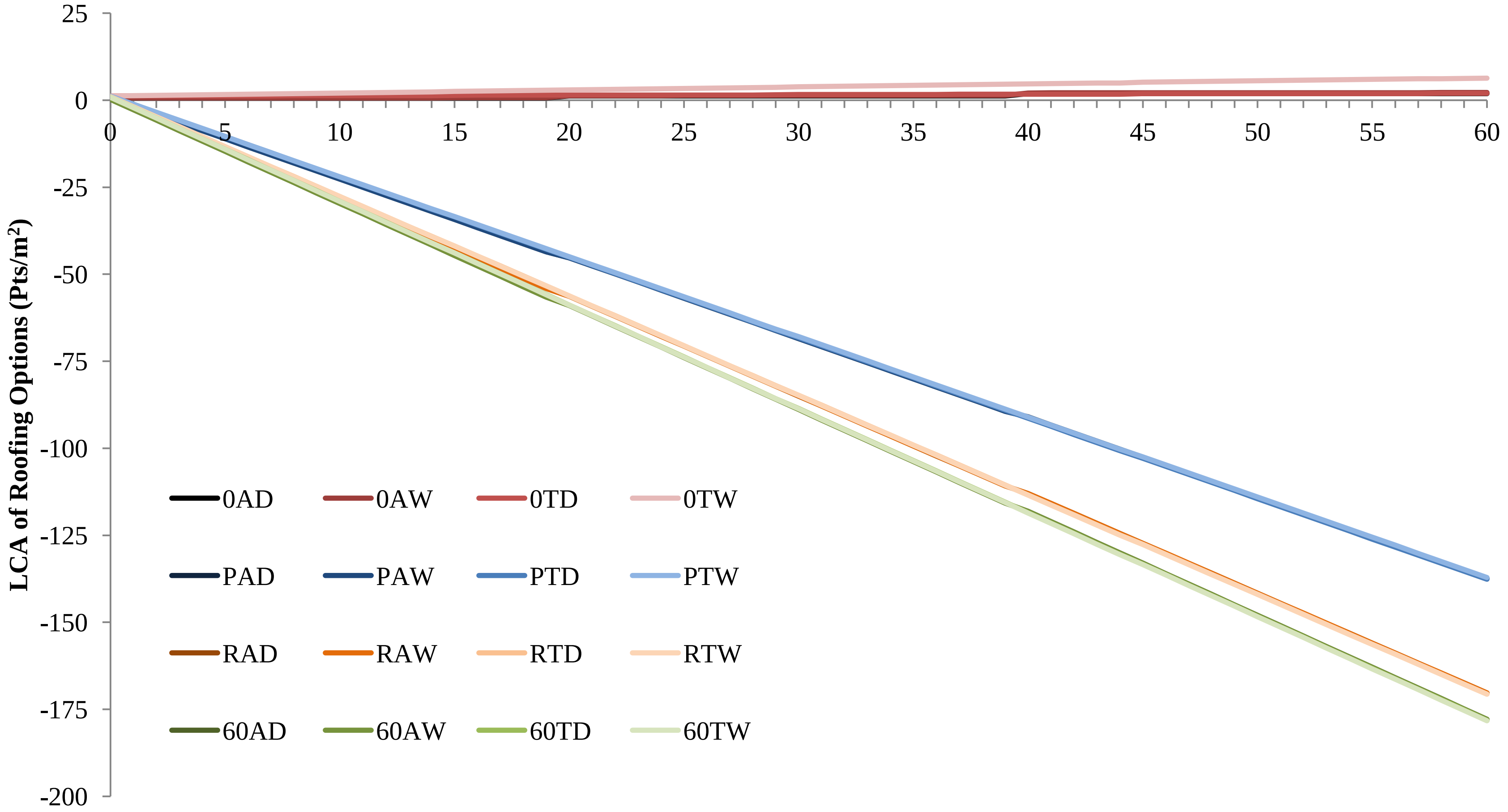

Figure 4.8: Environmental scores for roofing options in Atlanta over life of home.

4.3.3 Uncertainty Analysis Results

As with any assessment of data, it is imperative to understand the uncertainty of the input data and the results. We conducted an assessment of the roofing results, using the Monte Carlo assessment in SimaPro. This assessment was conducted Atlanta, and the results are shown in the box plot in Figure 4.9. The plot shows the distribution of the total environmental impacts for each roofing systems when it is assumed no insulation is currently installed. The numbers indicate the median value of the data, also shown as the center line in the box. We can see that the uncertainty of the first few systems is very low and the uncertainty increases with increasing energy demand changes. All of the inputs are assigned an uncertainty factor, but because energy use is the factor that is greatest in magnitude for this data, the increase in magnitude also leads to an increase in the uncertainty of the data. However, compared to previous studies, the uncertainty of the roofing values is relatively low because even though energy use is high in magnitude, its' uncertainty factor it relatively low when compared to maintenance options in the flooring study.

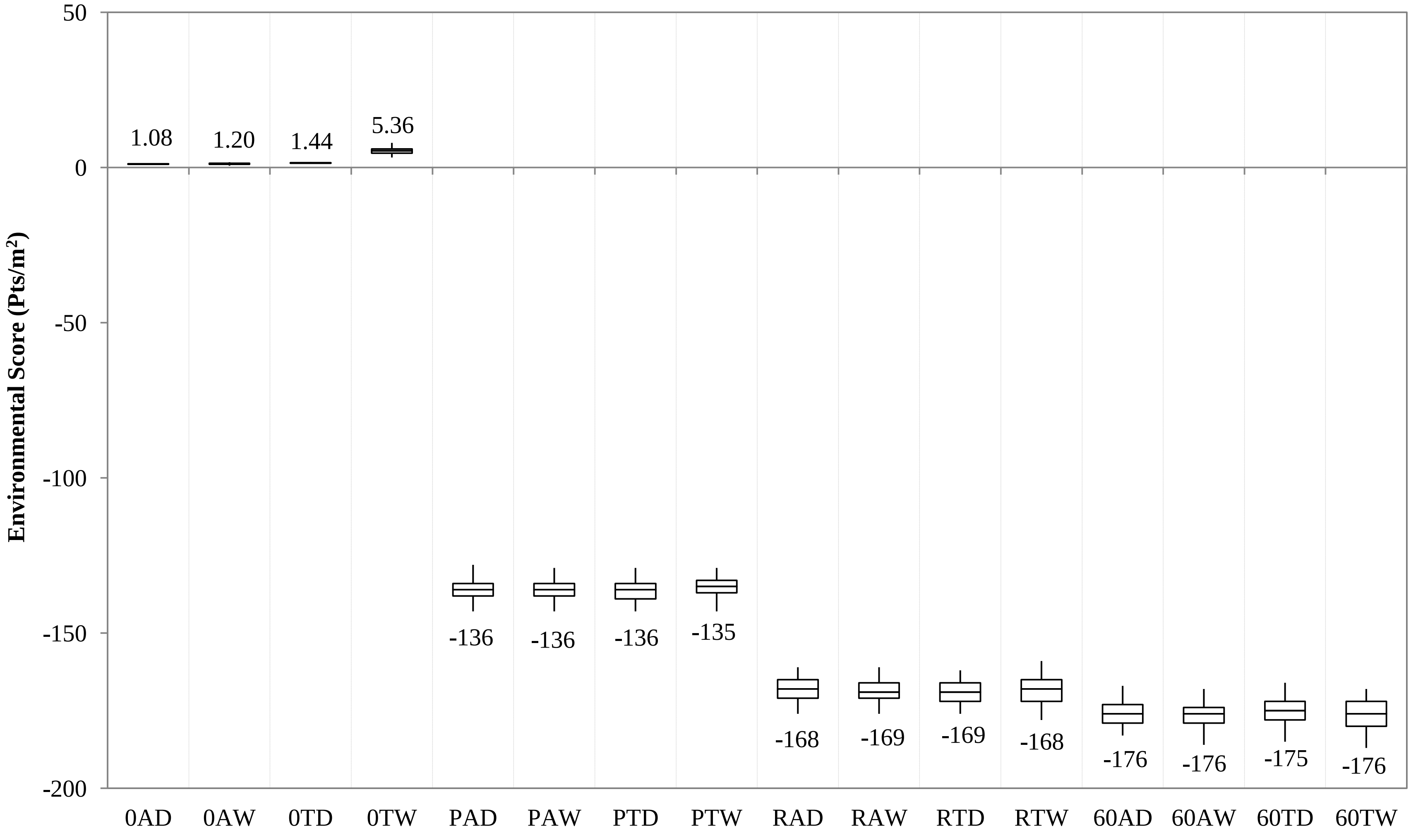

Figure 4.9: Uncertainty of environmental scores from roofing LCA, when no insulation is currently installed.

4.3.4 LCC Results

We started the LCC by looking at the simple payback period, shown in Table 4.10. This assessment simply looks at the cost of the retrofit divided by the annual energy savings to determine the amount of time needed for the retrofit to pay for itself. We assumed that the installation of the 0AD system was already occurring because asphalt roofing should be replaced every 20 years and this would be the time most homeowners would be looking at their options for roofing. The retrofit costs were assumed to be the incremental values above the cost of 0AD.

The information we found on roofing indicated that white roofing had approximately the same costs as dark roofing, so in climates that require more cooling than heating, they see an instant payback from selecting a white or cool-colored roof. The payback period for tile is much greater than for asphalt because the initial costs are significantly higher and the energy savings are not much higher than that for asphalt when there is any insulation. We can see that retrofitting up to the insulation which was assumed in the model to be previously installed has a payback period of 5 years or less in all cities. Likewise, installing the currently required insulation has a payback period of 8 years or less in all cities. The payback for R-60 insulation is slightly longer, but is under 10 years for all cities except Miami and New Orleans.

Table 4.10: Simple payback period roofing system upgraded, compared to 0AD.

City	0AW	0TD	0TW	PAD	PAW	PTD	PTW	RAD	RAW	RTD	RTW	60AD	60AW	60TD	60TW
Honolulu	0	238	12	1	1	10	10	1	1	9	9	2	2	10	10
Miami	0	1005	53	3	3	43	43	6	6	40	40	11	11	42	42
New Orleans	0	2586	131	5	5	42	42	8	8	41	41	11	11	43	43
Phoenix	0	470	25	1	1	13	13	2	2	11	11	3	3	12	12
Atlanta	0	3932	173	2	2	21	21	4	4	19	19	5	5	20	20
El Paso	0	1397	74	2	2	22	22	4	4	22	22	6	6	23	23
San Francisco	0	N/A	N/A	2	2	30	30	5	5	28	28	7	7	29	29
Kansas City	0	11170	344	2	2	19	19	4	4	18	18	5	5	19	19
Albuquerque	0	1262	68	1	1	19	19	4	4	17	17	4	4	18	18
Seattle	N/A	N/A	N/A	3	3	23	23	5	5	23	23	6	6	23	23
Boston	N/A	N/A	N/A	2	2	14	14	3	3	14	14	4	4	15	15
Salt Lake	0	46685	1193	2	2	25	25	5	5	23	23	6	6	24	24
Minneapolis	0	15173	530	2	2	16	16	3	3	16	16	4	4	17	17
Billings	N/A	N/A	N/A	2	2	21	21	4	4	21	21	5	5	21	21
Duluth	N/A	N/A	N/A	2	2	17	17	4	4	17	17	4	4	17	17
Anchorage	N/A	N/A	N/A	2	2	13	13	3	3	13	13	3	3	14	14
Fairbanks	N/A	N/A	N/A	1	1	10	10	2	2	10	10	3	3	10	10

For the LCC, we looked at the same scenarios as in the LCA. Right away we see that the materials and installation cost is a much more important factor than the environmental impacts related to the material. Looking at Figures 4.10-4.12, we see that cost savings from the use phase are higher for tile roofing in Atlanta, but the cost of retrofitting from asphalt to tile is much greater than the amount saved from energy costs. When compared to a roof with no insulation, retrofitting by adding insulation completely pays for the entire roof retrofit over the life of the home.

Again, Figures 4.11 and 4.12 show us that the incremental addition of insulation brings substantially smaller energy savings than the upgrading to the same level of insulation from no insulation. The material and installation savings from using the currently installed level of insulation and adding a higher value of insulation on top of it is about \$5/m^2 on average, but compared to the roofing material costs of the asphalt roof (\$78) or the clay tile roof (\$126), this value is not pronounced. If a roofing retrofit is occurring anyway, choosing a white roof does make sense for Atlanta, assuming the cost is equal, as well as adding insulation if none is in place. Adding an incremental amount of insulation, however, depends on how quickly the home owner is looking to see a return on investment because the energy savings are smaller which makes the payback period longer.

The LCC over time compared to a non-insulated roof can be seen in Figure 4.13. Like the environmental assessment, savings are greater over time with increased insulation; however, for costing we see a distinct difference between tile and asphalt.

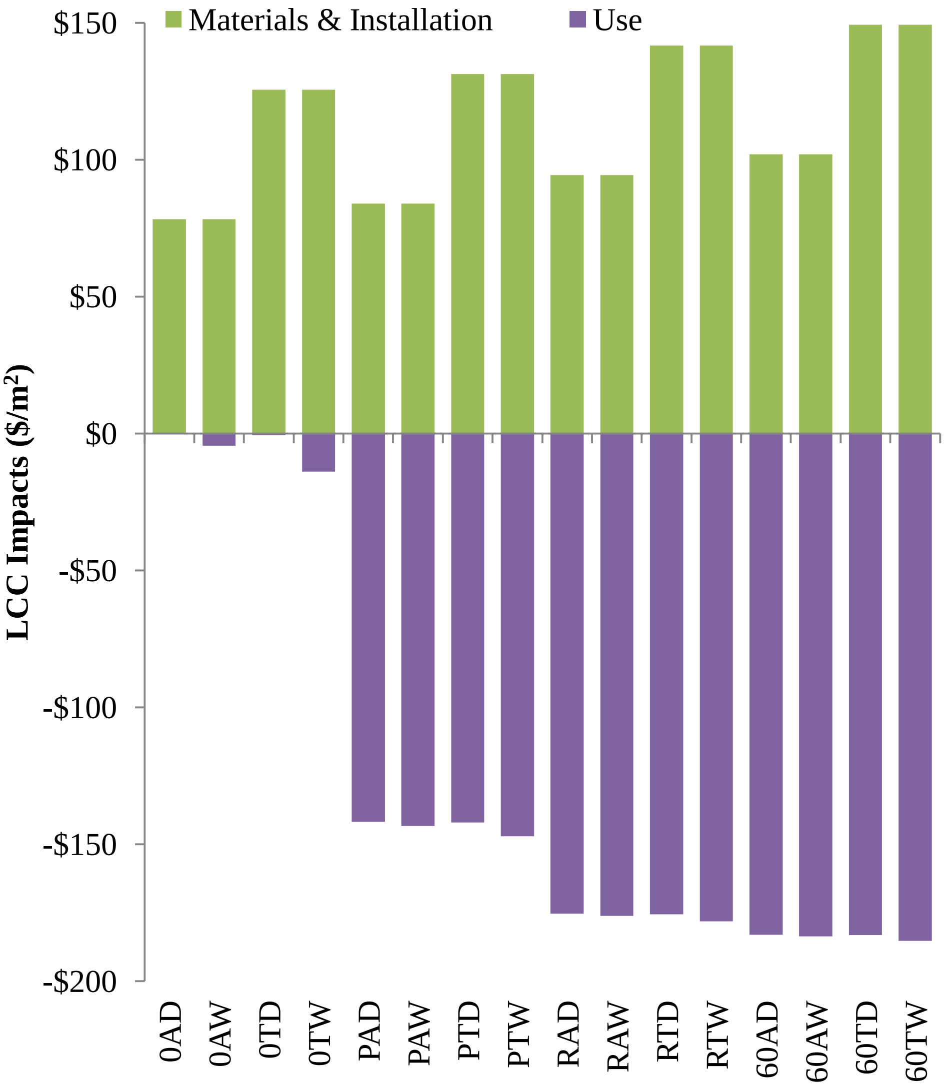

Figure 4.10: LCC results of roofing options in Atlanta when retrofitting from no insulation.

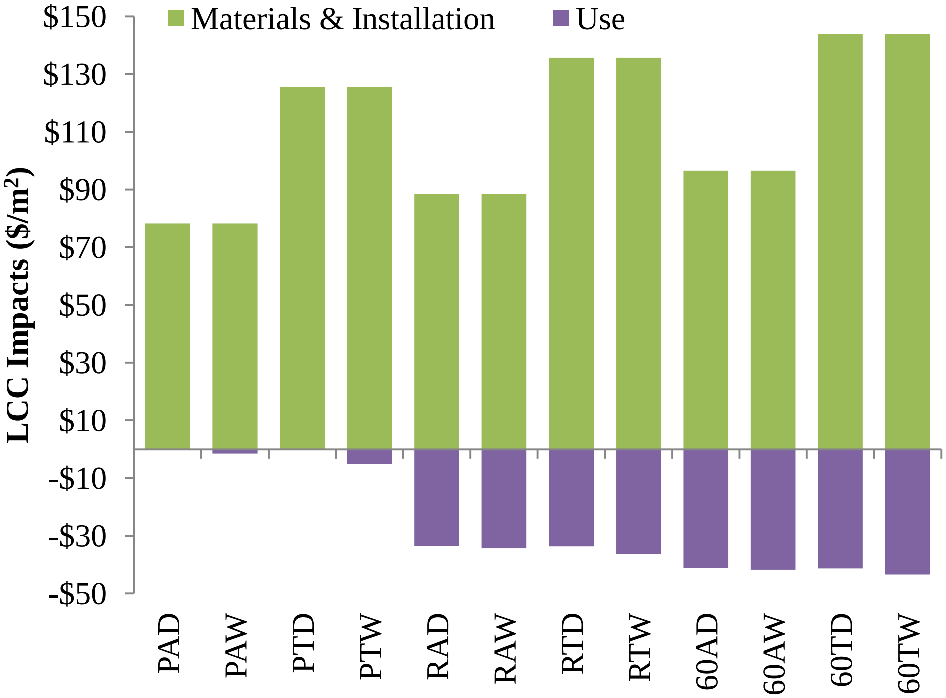

Figure 4.11: LCC results of roofing options in Atlanta when retrofitting from the previous assumed insulation, R-13.

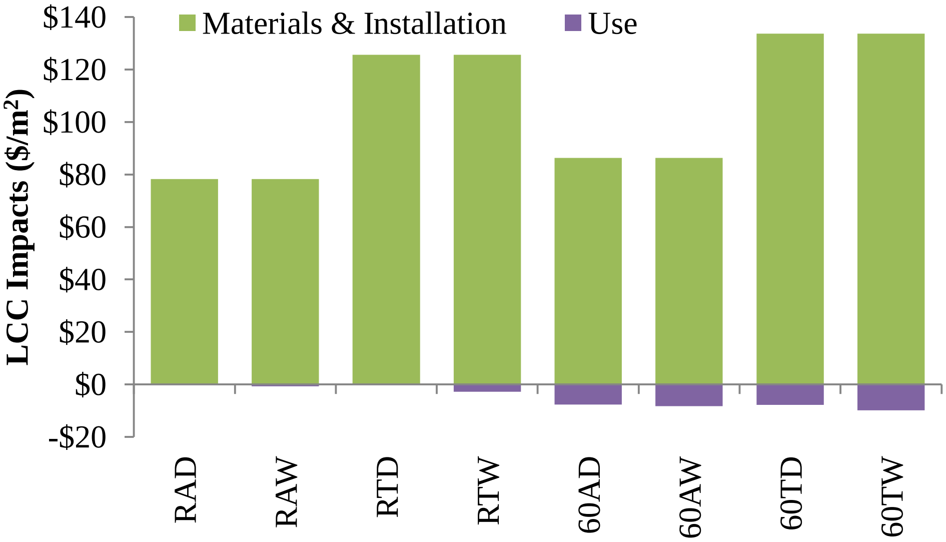

Figure 4.12: LCC results of roofing options in Atlanta when retrofitting from the currently required insulation, R-38.

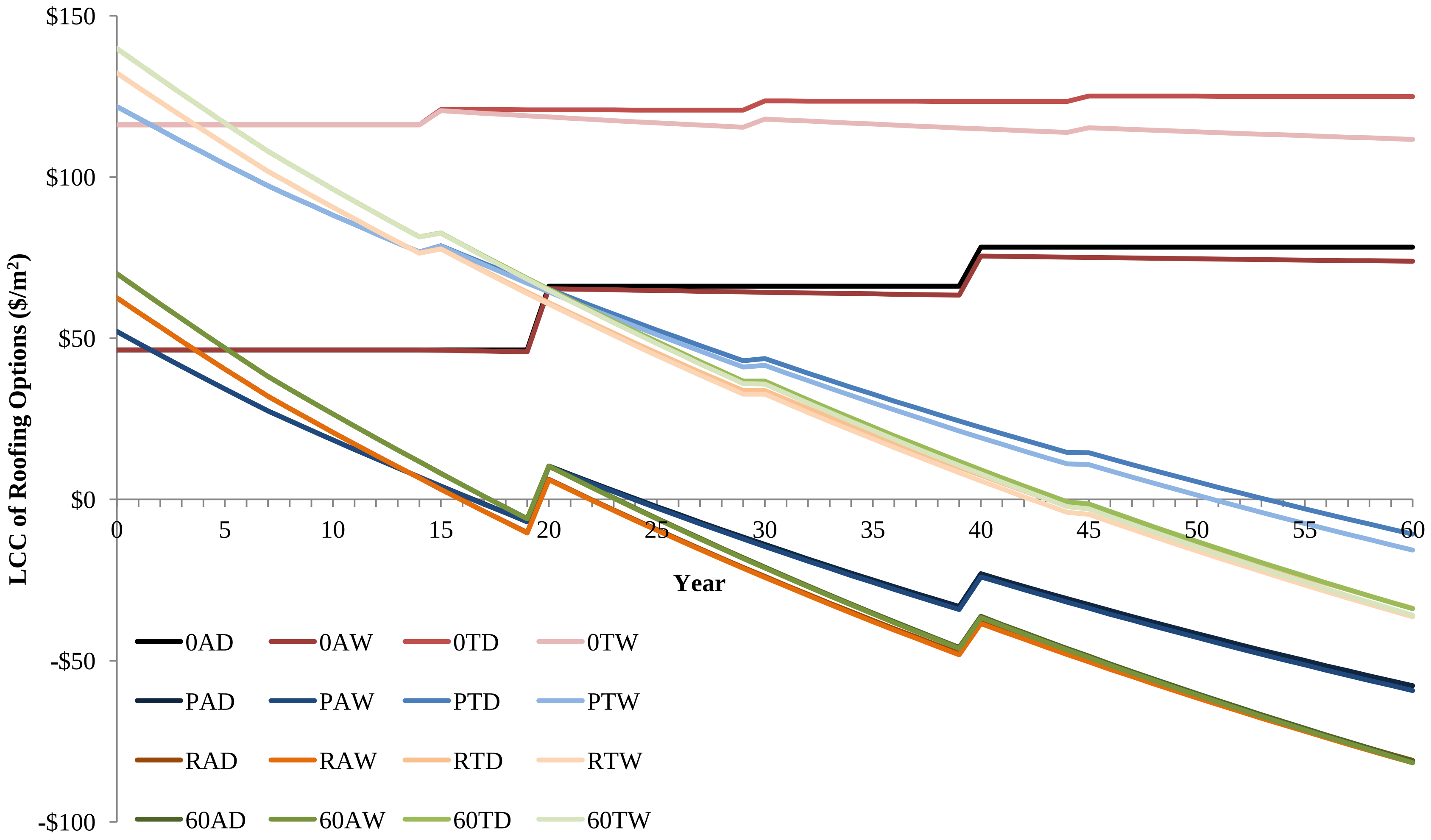

Figure 4.13: Cost of roofing options in Atlanta over life of home.

We have discussed the impact of climate and location on these results in the section 4.3.1, given the use phase (energy savings) is only factor that would change. Table 4.11 summarizes how these values change depending on the amount of insulation currently present in the home for each city. Overall, we can see the currently required amount of insulation is the most effective option in almost all cities, with exceptions including cities with expensive energy costs and/ or cities which have the potential to save substantial amounts of energy from retrofitting. The potential for savings is much greater when no insulation is installed, though insulation additions still pay for themselves in many cities over the lifetime of the home, even when the addition is incremental.

Table 4.11: Summary of best economic roofing systems by city and LCC value achieved in $\$/m^2$.

City	No Insulation		Previous Insulation		Required Insulation	
	LCC	Value	LCC	Value	LCC	Value
Honolulu	60AW	-$230	60AW	$25	60AW	$66
Miami	RAW	$18	RAW	$72	RAW	$76
New Orleans	RAW	$16	RAW	$77	RAW	$78
Phoenix	60AW	-$169	60AW	$33	60AW	$72
Atlanta	60AW	-$82	RAW	$54	RAW	$78
El Paso	RAW	-$53	RAW	$68	RAW	$77
San Francisco	RAD	-$23	RAD	$67	RAD	$78
Kansas City	RAW	-$91	RAW	$66	RAW	$78
Albuquerque	RAW	-$96	RAW	$50	RAW	$77
Seattle	RAD	-$62	RAD	$69	RAD	$78
Boston	RAD	-$153	60AD	$59	RAD	$78
Salt Lake City	RAD	-$54	RAD	$61	RAD	$78
Minneapolis	RAW	-$121	RAD	$63	RAD	$78
Billings	RAD	-$76	RAD	$68	RAD	$78
Duluth	RAD	-$120	RAD	$64	RAD	$78
Anchorage	RAD	-$180	60AD	$55	60AD	$78
Fairbanks	60AD	-$267	60AD	$44	60AD	$77

4.3.5 Single Score Results

Finally, we investigated which roofing systems were the best choices based on the LCA results, the LCC results, and for a 50/50 balance of the results for all the cities and summarized the results in Table 4.12. It is interesting to note that in many cases, the best overall roofing system is neither the best environmental system nor the best economic system. When equally balancing environmental concerns with economics, retrofitting to R-60 is always the best overall option across all cities and scenarios. Due to their relatively higher cost, tile is never the best overall solution.

The results in Table 4.12 also show us that assuming the cost is about the same for a white roof as for a dark roof, climate zones 1-3, with the exception of San Francisco, will see the best overall sustainability from white roofing. Homes in climate zones 5-8, plus the San Francisco, are more sustainable with dark roofing. The most environmental roofing option varies within climate zone 4.

Table 4.12: Best roofing systems for all 17 cities in three insulation scenarios.

City	No Insulation			Previous Insulation			Required Insulation		
	LCA	LCC	Overall	LCA	LCC	Overall	LCA	LCC	Overall
Honolulu	60TW	60AW	60AW	60TW	60AW	60AW	60TW	60AW	60AW
Miami	60TW	RAW	60AW	60TW	RAW	60AW	60TW	RAW	60AW
New Orleans	60TW	RAW	60AW	60TW	RAW	60AW	60TW	RAW	60AW
Phoenix	60TW	60AW	60AW	60TW	60AW	60AW	60TW	60AW	60AW
Atlanta	60TW	60AW	60AW	60TW	RAW	60AW	60TW	RAW	60AW
El Paso	60TW	RAW	60AW	60TW	RAW	60AW	60TW	RAW	60AW
San Francisco	60TD	RAD	60AD	60TD	RAD	60AD	60TD	RAD	60AD
Kansas City	60TD	RAW	60AW	60TD	RAW	60AD	60TD	RAW	60AD
Albuquerque	60TW	RAW	60AW	60TD	RAW	60AW	60TW	RAW	60AW
Seattle	60TD	RAD	60AD	60TD	RAD	60AD	60TD	RAD	60AD
Boston	60TD	RAD	60AD	60TD	60AD	60AD	60TD	RAD	60AD
Salt Lake City	60TD	RAD	60AD	60TD	RAD	60AD	60TD	RAD	60AD
Minneapolis	60TD	RAW	60AD	60TD	RAD	60AD	60TD	RAD	60AD
Billings	60TD	RAD	60AD	60TD	RAD	60AD	60TD	RAD	60AD
Duluth	60TD	RAD	60AD	60TD	RAD	60AD	60TD	RAD	60AD
Anchorage	60TD	RAD	60AD	60TD	60AD	60AD	60TD	60AD	60AD
Fairbanks	60TD	60AD	60AD	60TD	60AD	60AD	60TD	60AD	60AD

4.4 Conclusions

From the results of our analysis, we found that the driving factor in the potential energy savings of a roofing system was the R-value of the insulation. In balancing environmental and cost impacts, the highest level of insulation is recommended, no matter which city we studied. However, when we looked at cost only, this was not often the case; rather the required amount of insulation would suffice to create energy savings but would cost less than R-60. Roofing materials and color choices mattered more at the low end of the spectrum, when no insulation was installed and a white roof could lead to energy savings in a cooling dominated home. White roofs actually raise the costs and environmental impacts in colder climates though, due to the increased heating needs in the winter, which dominate their energy bills and environmental impacts. For homeowners who need to replace their roofing, understanding the best color for their roof may be worth investigating based on climate. Based on our assessment, though, the energy savings are so close in most cases that retrofitting a roof that is still in good quality would not make sense unless no insulation could be installed. Comparatively, adding insulation is a relatively cheap investment to reduce energy costs over time.

Environmentally, R-60 insulation and tile roofs were always best, and white roofs were best in hot climates due to decreased electricity demand and dark were best in cold climates due to decreased heating demand. Economically, asphalt was a better roof, with similar trends in color, though the maximum insulation did not always minimize cost. In terms of the sustainability based economic and environmental metrics, R-60 insulation with asphalt roofing is always the best performing system.

The aesthetics of the roofing options are a factor that is difficult to account for quantitatively. White roofs are more popular for flat roofs where the roofing cannot be seen [153]. Cool-colored roofing options are considered to be equal in the energy model though, and there are attractive cool-colored roofing options available for homeowners.

This study could be extended to understand the multitude of economic scenarios we investigated in the windows study, such as the impact of increasing energy prices, accounting for resale value, and looking into rebates. Increasing energy prices would mean greater energy savings and a lower life cycle cost. We briefly looked into the resale value of retrofitting the roof, and a roof replacement would recuperate around 68% on average in the US [131]. This may be another consideration for the homeowner depending on how long they intend to live in the home. Lastly, homeowners can file for tax rebates related to improving the thermal envelope of their home at a rate of 10% of the costs (not including labor) and a maximum of $500 total [133]. For the credits to apply the insulation value would have to meet the required R-value or above, as defined by the International Energy Conservation Code [116] which would include the required and R-60 values in this paper. Such incentives would shorten the payback period for retrofits and may make such options for viable for homeowners. The payback period for retrofitting roofing was short, so it would be interesting to study what may be stopping homeowners from retrofitting their roofs and what incentives or education programs may affect the adoption of efficient roofing.

Further studies could be done to understand how a changing climate may affect these results. With increasing climate extremes the results could be more dramatic [142], although an increase in heating degree days would likely decrease the need for insulation.

CHAPTER V

EFFECT OF WALL INSULATION VALUE ON ENERGY USE, ENVIRONMENTAL IMPACTS, AND COST OVER TIME

5.1 Introduction

We conducted a brief, final study on the impact of wall insulation's R-value and material properties on the energy use in a home across the same 17 cities which were studying in Chapters III and IV. The method we developed for finding a sustainability metric was based on a paper about retrofitting insulation [57]. Cetiner's paper focused on incorporating energy modeling into LCA and LCC and then creating a sustainability metric. Four insulation materials are studied for application in the wall, floor, and ceiling for one climate in Turkey. The testing conditions for our roofing system was different, however, we can note that our results were on the same order of magnitude as the Cetiner study found. To complete our study on the building envelope elements, which can be readily retrofitted, we investigated how wall insulation could impact the LCA, LCC, and overall sustainability of a home.

5.2 Methods

5.2.1 Background

In the previous study on roofing, we saw that insulation was the most critical variable in the energy performance of the home related to the roofing system. Using a similar methodology, we wanted to look at the impact of various levels and types of wall insulation on the energy performance of the home. In the previous study, we noted that the majority of homes reported having adequate, poor, or no insulation. We saw that newer homes had a better level of insulation, but there is still a significant amount of building stock that could consider retrofitting to upgrade their insulation. In Figure 5.1, we can see the number of homeowners that have retrofitted the insulation in their home and the number that have not depending on the age of their home [52]. The percentage of retrofits is higher in an older home, which makes sense considering they were also the homes with less insulation. Even so, 65% of homes are not considered well insulated and only 20% of homeowners have added insulation to their homes. In this study, we hope to understand if adding insulation would be worthwhile in terms of environmental impacts, cost impacts, and overall sustainability of a home.

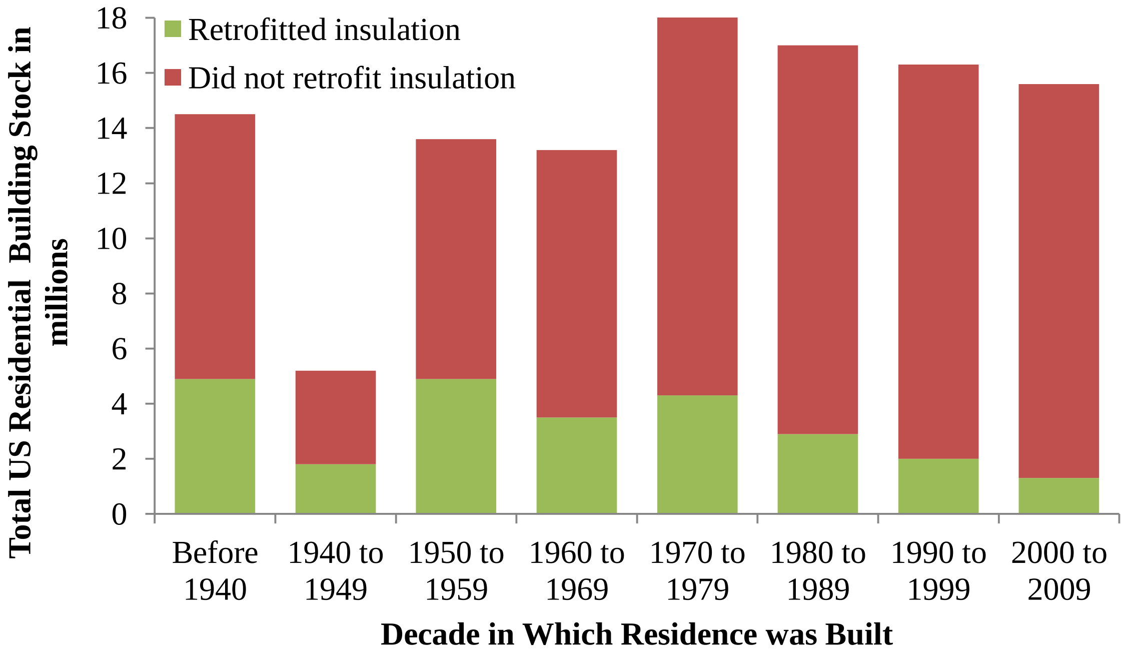

Figure 5.1: Amount of homeowners who have added insulation to their home, based on the decade the home was built.

Looking at the literature, we found a number of studies on insulation choices beyond Cetiner's study [57]. Among the studies, we found a number of LCAs which compared insulation materials [164-169], insulation thicknesses [166], and wall system impacts [164, 165]. The LCA of wall insulation is well covered in the literature, and we found that three of these studies also incorporated LCC and energy modeling in their assessments [57, 165, 166]. None of these studies looked at the diversity of climates we investigated, but the studies do give us an idea what our results may look like. The previous studies found, in general, that increased levels of insulation reduce energy demand, but this may be a trade-off with the total cost, and a lower level of insulation may give the optimal solution.

5.2.2 Functional Unit

To stay consistent with the roofing and flooring study, we chose our functional unit to be 1 m^2 of livable floor space. Choosing this unit makes comparing total impacts between flooring and roofing simple, and also is a straightforward way for a homeowner to understand the impact these components could have on a house of varying size. Additionally, energy usage is a major component in this study, and those metrics are often expressed as kWh or therms per square meter. The amount of insulation is not precisely equal to the square meter space of the home though, so we accounted for this issue by finding the square meters of wall space per square meters of floor space. For this, we assumed the wall height 2.4 meters (8 feet), which would equate to approximately 125 meters of wall space for our standard 158 square meter single-family home. The insulation costs and environmental impacts were multiplied by a factor of about 0.8 to ensure consistency with energy impacts. We used 60 years as the lifetime of the home and the insulation [53, 112].

5.2.3 Energy Modeling

Similar to the roofing study, BEopt was employed to find the energy improvements from insulation retrofits. The model was run, replicating the method that was used in the roofing study, except with set inputs for the roofing section and varying wall insulation inputs. The roofing inputs were set to be the amount of insulation which was assumed to be previously installed by city (see Table 4.2 in Section 4.2.2.1) and the roofing material was set as dark asphalt. The ability to retrofit wall insulation and to what possible R-value depends on the wall frame. The most common wall frame for US homes (over 70%) for the late 20th century was 2x4s with 16 inch spacing [170]. Our testing conditions involved looking at the difference between having no insulation to R-13 insulation, and the difference between R-7 fiberglass insulation (which is the assumed insulation for the RESFEN model [121]) and R-13 insulation. Two materials are tested for the R-13 insulation: fiberglass and cellulose. Because of current energy codes, we cannot test for no insulation being upgraded to R-7, which is less than the code requires [116].

5.2.3.1 Influence of Climate and Location on Energy

The study of insulation materials and levels is conducted across the same 17 cities as are studied in the windows and roofing studies.

5.2.4 LCA Method

The LCA method for the insulation study remains the same as the method used in the windows and roofing studies. Due to time constraints, we focused on endpoint environmental impacts and did not run the midpoint impacts or uncertainty analysis, though we would expect the trend to resemble those from the roofing study.

5.2.5 LCC Method

The LCC method for the insulation study remains the same as the method used in the windows and roofing studies. We again focused on total LCC results for the primary analysis of materials and installation costs and energy costs over time (with a discount rate). We also looked at the simple payback period for a quick assessment of the impact of time on the results.

5.2.6 Single Scoring

The single scoring method for sustainability performance in the insulation study remains the same as the method used in the windows and roofing studies.

5.3 Results and Discussion

5.3.1 Influence of Climate and Location on Energy

Using the BEopt energy model, we found the annual energy and cost results for the standard home in all 17 cities. The trends in our results closely resemble those that we found in the roofing study: energy improvements generally increase as the number of heating degree days increase, as can be seen in Table 5.1. We did find that the energy and cost savings for insulation improvements were the same for both fiberglass and cellulose, so we have abbreviated the table to only show the insulation options. All climates see improvements from increased insulation. The cost savings for a city depend heavily on the price of energy, so this trend varies more than the overall energy decreases. For example, Honolulu saves the smallest amount of total energy when adding insulation to a home with no insulation, but the annual cost savings are higher in Honolulu than in two other climate because energy is much more expensive in Honolulu. Additionally, we see that the total annual energy savings and annual energy costs when considering R-7 is being upgraded to R-13 is about 14% of the energy savings possible from considering no insulation is being upgraded to R-7.

Table 5.1: Annual energy savings in energy and cost going from no insulation to R-13 and from R-7 to R-13.

	No insulation to R-13		**R-7 to R-13**	
	Energy (kWh)	Cost ($)	Energy (kWh)	Cost ($)
Honolulu	215	$106	26	$12
Miami	455	$48	53	$6
New Orleans	2898	$98	415	$14
Phoenix	3211	$334	459	$48
Atlanta	5641	$279	830	$41
El Paso	4891	$186	715	$26
San Francisco	6505	$209	966	$31
Kansas City	6815	$280	1017	$41
Albuquerque	7626	$247	1135	$36
Seattle	8182	$290	1234	$44
Boston	9155	$412	1350	$60
Salt Lake	8191	$232	1217	$34
Minneapolis	11589	$333	1722	$49
Billings	10609	$282	1571	$41
Duluth	14432	$375	2150	$56
Anchorage	15705	$477	2385	$72
Fairbanks	19056	$580	2895	$88

5.3.2 LCA Results

We conducted an LCA of the insulation’s environmental impacts. For this, we again looked at the resources, manufacturing, installation, use, and end-of-life phases. We found that the use phase dominated the impacts again, and the impacts of the two insulation options were indistinguishable when plotted together. Since the energy impacts are the same for both options, we isolated the environmental impacts caused by the insulation material for Figure 5.2 to better understand the environmental differences between fiberglass and cellulose. The environmental impacts of both types of insulation are comparatively small compared to the other studies we have done. Interestingly, we see that based on the material impacts, cellulose is actually negative, which is attributed to the avoidance of newspaper to the landfill in order to make cellulose. The manufacturing, installation, and end-of-life all had smaller impacts than the recycling newspaper into a new product. For fiberglass, we can see that manufacturing in the primary factor. In context, however, all of these numbers are small. The difference between the environmental impact of the two insulations do matter though because the energy savings are the same for both materials, so we know that overall cellulose will be the more environmental option in all cases.

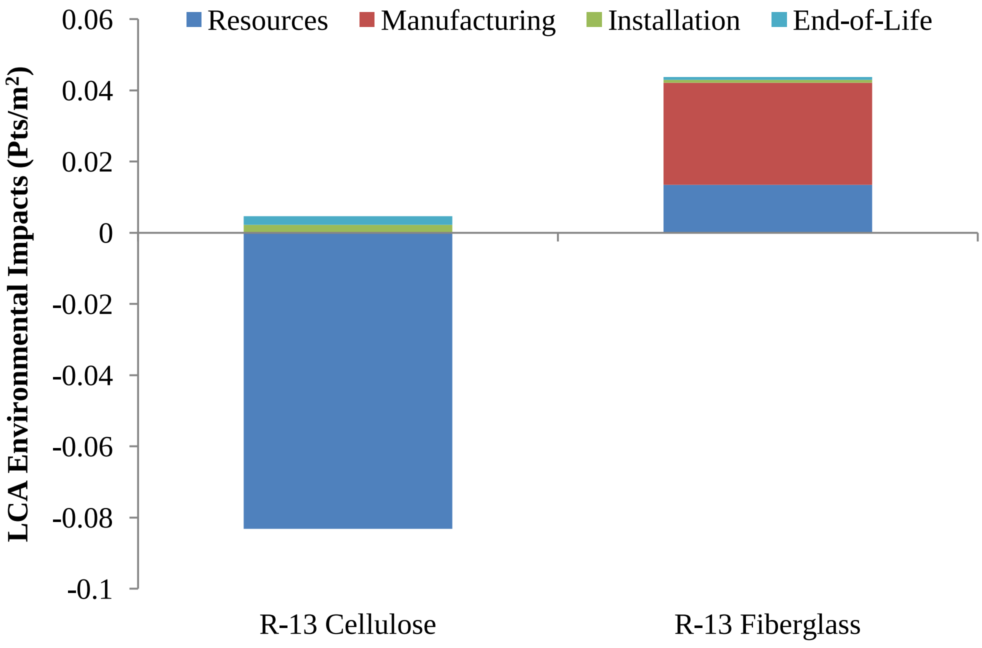

Figure 5.2: LCA impacts of R-13 insulation, not including the use phase.

In Table 5.2, we show the LCA environmental scores which can be attributed to the energy savings for all 17 cities. The numbers are much larger for most cities than the environmental impacts from the materials. The impacts were more substantial in the colder climates and less substantial when compared R-7 to R-13 than when comparing no insulation to R-13.

Table 5.2: Environmental impacts from the use phase for insulation in 17 cities (in Pts/m^2).

	No insulation to R-13	R-7 to R-13
Honolulu	-4.17	-0.50
Miami	-6.92	-0.81
New Orleans	-39.75	-5.67
Phoenix	-49.38	-7.08
Atlanta	-76.34	-11.22
El Paso	-68.12	-9.93
San Francisco	-85.99	-12.77
Kansas City	-98.58	-14.71
Albuquerque	-108.29	-16.01
Seattle	-106.87	-16.14
Boston	-122.98	-18.13
Salt Lake	-117.98	-17.42
Minneapolis	-157.83	-23.43
Billings	-145.98	-21.59
Duluth	-196.04	-29.22
Anchorage	-208.74	-31.70
Fairbanks	-253.26	-38.47

5.3.3 LCC Results

The life cycle costing was conducted in the same manner as it was for the roofing and windows study. When we were choosing the insulation material for the roofing study, we chose cellulose because we hypothesized that it would have a better environmental impact based on the materials and the cost was less for ceiling cellulose than ceiling fiberglass [112]. One point of interest, though, is that for the study of wall insulation, we found that the cost of cellulose was more expensive than fiberglass. The difference between the two materials was small, \$20.42 to \$18.71 for cellulose and fiberglass respectively [112], but because the energy cost savings were again the same, this means this price difference means that fiberglass is always the better economic choice.

To get a quick idea of return on investment of insulation systems, we looked at the simple payback period of the options for all of the cities. Table 5.3 shows these results. We can see that cellulose tends to take a little longer to payback, which follows from the slightly increased cost over fiberglass. We can also note that the payback period gets shorter, in general, as climate zone and number of heating degree days increase. For eight cities, there is an option where the simple payback period is 10 years or lower when no insulation is currently installed. The savings are lower, however, when upgrading from R-7 to R-13, and there are not any cities that would see the return on investment on this upgrade in less than 10 years.

Table 5.3: Simple payback period for wall insulation retrofits in years.

Cities	**No insulation to R-13**		**R-7 to R-13**	
	Cellulose	Fiberglass	Cellulose	Fiberglass
Honolulu	31	28	100	79
Miami	68	62	208	164
New Orleans	33	30	90	71
Phoenix	10	9	26	20
Atlanta	12	11	30	24
El Paso	17	16	46	37
San Francisco	15	14	40	32
Kansas City	12	11	30	23
Albuquerque	13	12	34	27
Seattle	11	10	28	22
Boston	8	7	20	16
Salt Lake	14	13	36	28
Minneapolis	10	9	25	20
Billings	11	10	29	23
Duluth	9	8	22	17
Anchorage	7	6	17	13
Fairbanks	6	5	14	11

We looked at the materials and installation phase as compared to the use phase in Atlanta, which is displayed in Figure 5.3. We found that the materials and installation phase were more important in the LCC assessment than in the LCA. The use phase savings were about twice of the materials and installation costs the no insulation upgrade and the materials and installation costs were more than the use phase savings when upgrading from R-7. The differences in material and installation costs are hard to distinguish on the plot, but this small difference makes fiberglass the more economic choice in both cases.

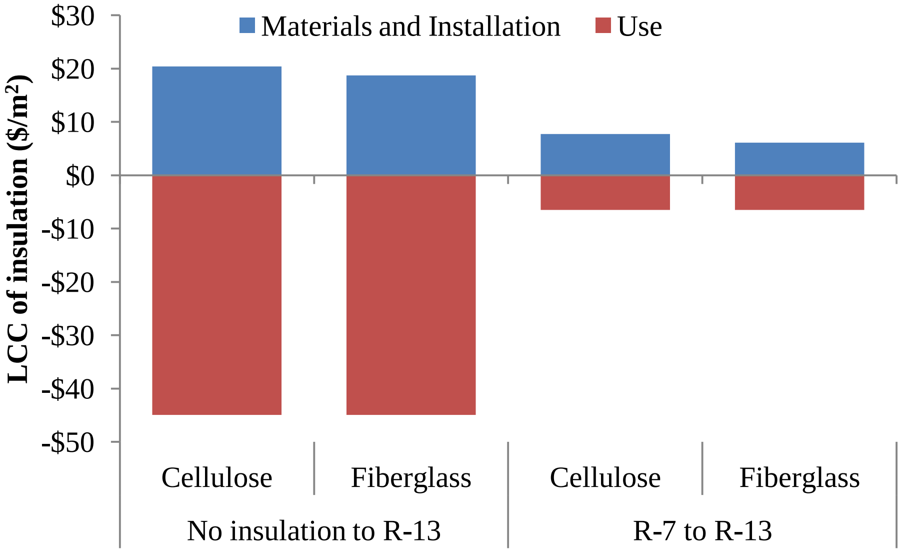

Figure 5.3: LCC of wall insulation choices for 60 year lifetime in Atlanta.

The LCC results for cities are similar to the energy cost savings trends from Section 5.3.1 on the influence of climate. These numbers differ though, as the discount rate is accounted for when considering the energy costs for the 60 year time period and the materials and installation costs are added to these figures. We can see that upgrading insulation does not always payback in the 60 year time frame. Even for retrofitting from no insulation, Honolulu, Miami, and New Orleans did not recover enough energy savings to pay for the insulation costs. All of the other cities found a return on investment for retrofitting from no insulation, with generally increasing savings from increasingly colder climates. Upgrading from R-7 to R-13 on the other hand was much less likely to return the investment and for the cities where it did, the savings were small and the payback period was long.

Table 5.4: LCC for wall insulation choices for a 60 year lifetime, in $\$/m^2$.

Cities	**No insulation to R-13**		**R-7 to R-13**	
	Cellulose	Fiberglass	Cellulose	Fiberglass
Honolulu	\$3.40	\$1.70	\$5.76	\$4.15
Miami	\$12.75	\$11.05	\$6.79	\$5.18
New Orleans	\$4.64	\$2.94	\$5.54	\$3.92
Phoenix	-\$33.34	-\$35.04	\$0.03	-\$1.59
Atlanta	-\$24.53	-\$26.23	\$1.21	-\$0.40
El Paso	-\$9.50	-\$11.20	\$3.48	\$1.86
San Francisco	-\$13.28	-\$14.98	\$2.82	\$1.21
Kansas City	-\$24.64	-\$26.34	\$1.06	-\$0.55
Albuquerque	-\$19.41	-\$21.11	\$1.99	\$0.37
Seattle	-\$26.33	-\$28.03	\$0.71	-\$0.91
Boston	-\$45.92	-\$47.62	-\$1.97	-\$3.59
Salt Lake	-\$16.95	-\$18.65	\$2.21	\$0.59
Minneapolis	-\$33.18	-\$34.88	-\$0.17	-\$1.79
Billings	-\$24.98	-\$26.68	\$1.06	-\$0.56
Duluth	-\$40.07	-\$41.77	-\$1.25	-\$2.87
Anchorage	-\$56.39	-\$58.10	-\$3.91	-\$5.53
Fairbanks	-\$73.09	-\$74.79	-\$6.47	-\$8.09

5.3.4 Single Score Results

We found in the previous sections that because the energy savings were uniform, both in kilowatt-hours and dollars, the best environmental material and the best economic material were determined solely based on which material had a lower LCA and lower cost, respectively. This meant that the most environmental option was always cellulose, and the best cost option was fiberglass. The exception to the cost analysis is that when the energy savings were not high enough, as in the three warmest cities, and for many cities upgrading from R-7 to R-13, the most economic choice was actually to do nothing and leave the home wall insulation as is. Because the cost difference was more significant than the difference in environmental performance between the insulation choices, retrofitting to R-13 fiberglass was the best overall option when these factors are weighted 50/50. There are only three exceptions to this finding and they are for the upgrading of R-7 to R-13 in Honolulu, Miami, and New Orleans.

5.4 Conclusions

In our studies of retrofitting wall insulation, we found that the best overall choice was almost universally upgrading to R-13 fiberglass. We found that our results were consistent with those from our roofing study in Chapter IV and on the same order of magnitude and following the same trends as previous studies indicated [57, 165, 166]. Insulation also has the added benefit of increasing indoor comfort and reducing acoustical transmission [169].

More work could be done on this study to understand various economic impacts, as was done in the windows study. Factors such as added resale value, the increasing cost of energy, and incentives could shorten the payback period and increase total savings for retrofitting insulation. Climate change scenarios could also be studied, though the number of degree days are expected to increase [142], which would lessen the need for high levels of insulation.

CHAPTER VI

CONCLUSIONS

6.1 Relevance of Use Phase in LCA and LCC

Throughout this dissertation we investigated how energy use impacted the environmental scores from LCA and the costs from LCC for four components of a home: flooring, windows, roofing, and wall insulation. Incorporating energy use into these analyses is often avoided for a number of reasons. Some of these reasons include issues with accounting for the diversity of homes, differences in the way homeowners use a technology, and lack of specific enough data to make direct comparisons of materials. We have tried to address these issues through sensitivity analyses, uncertainty analyses, and setting a standard home unit throughout the paper. The issues previously stated have stopped many researchers from incorporating the use phase, including energy use and maintenance into LCA analysis. However, we felt that given the use phase was often the phase with the largest environmental and cost impact, we could not ignore it in a complete analysis.

In three of the cases, we studied how climate could impact the energy use, and therefore environmental and cost impacts of a home. In Table 6.1 we can see the largest impact of energy savings for the 60 year lifetime of a home [53] for each building envelope component. Table 6.1 shows how energy savings translate into environmental impact savings and cost savings. It should be noted that the values for windows were calculated for the 60 year lifetime (twice what was considered in the windows study) and normalized by meters squared of floor space instead of by window space. For comparison, switching from carpet to linoleum could lead to an environmental savings of 18.7 Points per meter squared and a cost savings of $65 per meter squared. Roofing improvements have the largest potential environmental and cost savings in most climates, though wall insulation can lead to significant savings particularly in cold climates, and windows can lead to good savings in the extreme hot and cold climates.

Table 6.1: Highest environmental and cost saving potentials for building envelope materials.

Cities	Windows		Roofing		Wall insulation	
	Pts/m^2	\$/m^2	Pts/m^2	\$/m^2	Pts/m2	\$/m^2
Honolulu	34.76	$133	59.04	$900	4.17	$106
Miami	52.97	$38	52.33	$216	6.92	$48
New Orleans	23.91	$24	113.76	$220	39.75	$98
Phoenix	52.73	$54	161.11	$740	49.38	$334
Atlanta	22.77	$34	179.52	$488	76.34	$279
El Paso	30.61	$32	180.64	$413	68.12	$186
San Francisco	0.66	$19	158.30	$323	85.99	$209
Kansas City	38.44	$40	275.89	$504	98.58	$280
Albuquerque	30.26	$29	263.29	$527	108.29	$247
Seattle	0.69	$34	226.24	$426	106.87	$290
Boston	7.87	$54	283.66	$671	122.98	$412
Salt Lake	32.68	$33	302.10	$406	117.98	$232
Minneapolis	13.33	$43	383.07	$586	157.83	$333
Billings	15.55	$40	348.33	$464	145.98	$282
Duluth	4.84	$51	455.47	$582	196.04	$375
Anchorage	0.79	$83	495.43	$743	208.74	$477
Fairbanks	1.49	$114	641.11	$970	253.26	$580

6.2 Summary of Contributions

The work in this dissertation comprises of four detailed case studies on home components for retrofitting. LCA research has been conducted on all of these materials in the literature; however, we have contributed to the broadening view of these LCAs and have added novel approaches to understanding the sustainability of the materials. Listed below are the major contributions of this research:

- We asserted the significance of the link between the use phase of housing components, primarily from energy consumption, on the environmental and economic performance of a home.
- We investigated the importance of the time period studied in the performance metrics of a product.
- We determined the relevance of location and climate zone on the energy use results, environmental LCA results, economic LCC results, and overall sustainability performance results.
- We established a sustainability metric using environmental and economic impacts which can be utilized by developers, homeowners, and manufacturer to understand the performance of a product. The metric may be applied to other products or home components assuming a sufficient amount of inventory data.

CHAPTER VI

FUTURE STUDIES

7.1 Creation of User Interface

7.1.1 Application

In order for homeowners and builders to make sustainable housing decisions quickly and easily, it would be helpful to have an open-source tool that could compare materials based on costs and environmental effects. We propose to create an interactive app and website to assist consumers in making sustainable building and renovation decisions based on LCAs, energy and water usage, and payback periods. By making the tool open-source, manufacturers could see where they may need to improve current processes in the life cycle of their product. Contractors or builders could suggest LCAs for non-traditional materials such as reused or recycled products. Although contractors often use set blueprints for construction jobs, the goal is for consumers to have information to evaluate alternative materials so they could request changes and upgrades. In order to reach consumers, the tool needs to consider finances for the project. The product will be marketed as a tool to empower users to make informed green decisions that will lead to savings on energy, water, and material costs. It is expected that the increasing demand for sustainable products will stimulate the market for sustainable products. We will be researching the life cycle effects (from extraction of resources; to disposal or recycling) of residential construction on the environment, and how empowering consumers and manufacturers with information may reduce those impacts. Programs such as LEED version 4 and the Living Building Challenge have been pushing for more transparency, as have stakeholders, so presenting this information in an understandable way is in demand in the market.

7.1.2 Survey

We hope to present the information discovered in this research in a way which a homeowner or developer can easily access it during decision making, such as a website or preferably an app. An important part of creating an interactive communication forum is understanding human-computer interaction. Although systems we work on may become intuitive to us, we need to keep in mind who will be using the information and their capabilities. In the early development phase we want to test a few app designs with rapid prototyping. Peer critique of a few digital mock-ups will help catch major issues quickly and decide which prototypes to pursue for further development.

We plan to create an experiment to understand how the app affects decision-making for the users. In order to create the app's format quickly, we will use dummy data in these prototypes. Our group has been working with Southface, an Atlanta non-profit organization that promotes and teaches energy, water, and resource efficient building practices. Testing of the product will start with students and faculty within the sustainable education community at Georgia Tech, and later with our partners at Southface. These groups would evaluate the app based on *Nielsen's Heuristics for Expert Evaluation* [171].

Briefly these 10 evaluation criteria are:

1. Visibility of system status
2. Match between system and the real world
3. User control and freedom

4. Consistency and standards
5. Error prevention
6. Recognition rather than recall
7. Flexibility and efficiency of use
8. Aesthetic and minimalist
9. Help users recognize, diagnose, and recover from errors
10. Help and documentation

The evaluators of the app will answer a series of questions based on these heuristics, giving scores called a *Severity Rating* [171]. These ratings range from 0-4, 0 indicating there is no problem and 4 meaning the problem with the system is necessary to fix in order to continue.

After the expert groups have evaluated the app, we will bring in evaluators that would better represent our target user group. It is likely this group will find more errors and have more difficulty understanding the app than the expert groups, and fixing these problems early will save time and effort later. After these experiments have been conducted, the data collected from the evaluations will be analyzed and discussed. These results should give us intuition into whether the application is working as intended and if it is possible to release. The survey methodology is shown in Figure 7.1 below.

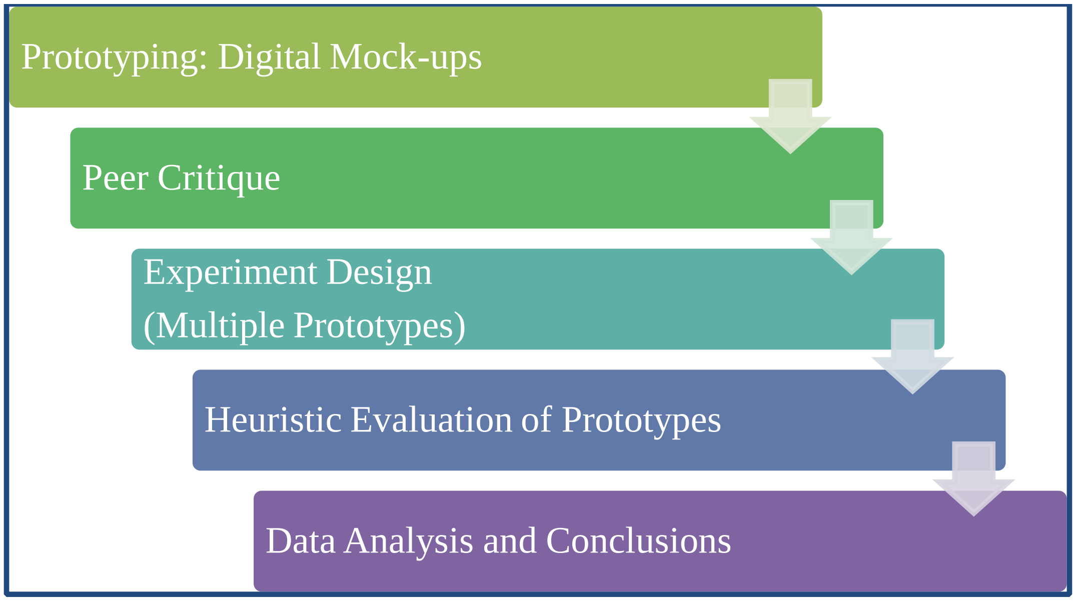

Figure 7.1: Survey methodology for testing an app.

7.1.3 Tracking impacts

After creating a user interface, there must be a way to track the results and the impact it is having on consumers and the market. We are hoping to work with Southface to teach the app to future leaders in the green construction field. These expert users could start a chain reaction in which they can teach others the tool, and so on. Once the tool is released to the general public, key metrics to track the direct impact will be the number of downloads of the app and its usage. User surveys will be sent out to see who is using the tool (e.g. consumers, manufacturers, builders, researchers) and for what purposes. Such information will indicate if we are connecting with our desired audience. Posts requesting new technologies will be pertinent in showing research impacts. Tracking some of these innovative ideas will indicate if the application has any traction in the market.

We hope to investigate the tool’s indirect impacts as well. An important measure of the app’s success is market reaction. Watching trends in product development and market shares will be important, but additionally we will follow up with surveying companies over time on their use of the app in research and development and their perception of consumer needs. We also will look for emerging companies and markets in green construction. Partnering with big box stores such as Home Depot and/or Lowes would be advantageous. They could advertise the application near environmentally-friendly products so consumers could compare alternatives in store, and we could track the changing trends in sales. Tracking the actual consumption of green construction products would show where the tool has the potential to make the greatest impacts.

7.2 Specific product studies

We believe another way to use this study is to investigate and compare specific products. This could be done internally by a company to understand how they compare to their competitors and places where they could improve in their supply chain. This also could be done for external purposes, such as for public relations or for meeting demands of sustainability building frameworks like LEED.

7.3 Policy studies on increasing adoption for technology

From the cases we studied, we noticed that there were a number of housing components which could be used that would save substantial amounts of energy, but these technologies or materials were not always adopted. We know that for the adoption of energy saving technology, the payback period in a manufacturing plant must be lower than eight years to be considered in most cases [134], and that the factors that affect adoption by homeowners are more complex than just a simple payback period [135]. Studying what incentives, education, or regulations that could advance the adoption of energy efficient technology in a home could be another way to take the information presented in this dissertation and make it pragmatic.

Additionally, the dissertation did not cover a number of variables that were outside the scope of the study, but could be very interesting. Such topics would include the advancing efficiency of our current building technology, a technology paradigm shift in how we build homes, such as factory building or 3-D printing, and the changing of the technology that comprises our energy grid. External technology factors like these could change alter the results we found in this study and lead to improvements that we cannot foresee with current technology.

APPENDIX A

Climate of US Cities

Table A.1: Climate conditions for 17 US cities.

Climate Zone	Climate	City	Heating Degree Days[172]	Cooling Degree Days[172]	Precipitation (Annual in inches)[172]
1	Very hot	Honolulu, HI	1	3954	17.87
1A	Very hot, moist	Miami, FL	105	4426	50.08
2A	Hot, moist	New Orleans, LA	1164	32.18	62.29
2B	Hot, dry	Phoenix, AZ	868	4567	8.18
3A	Warm, moist	Atlanta, GA	2880	1744	51.17
3B	Warm, dry	El Paso, TX	2473	2331	9.71
3C	Warm, marine	San Francisco, CA	2909	113	23.65
4A	Mixed, moist	Kansas City, MO	4686	1673	39.06
4B	Mixed, dry	Albuquerque, NM	4428	1035	16.30
4C	Mixed, marine	Seattle, WA	4370	188	37.72
5A	Cool, moist	Boston, MA	5681	747	43.77
5B	Cool, dry	Salt Lake City, UT	4967	1301	18.57
6A	Cold, moist	Minneapolis, MN	7614	729	30.85
6B	Cold, dry	Billings, MT	6857	537	14.77
7A	Very cold, moist	Duluth, MN	9444	205	30.96
7	Very cold	Anchorage, AK	10201	3	16.67
8	Subarctic	Fairbanks, AK	13666	61	10.81

APPENDIX B

Window compliance with building requirements

Table B.2: Window's compliance with ASHRAE **[114, 115]**, IECC **[116]**, and Energy Star **[117]** requirements based on climate.

Climate Zone	**Window 1**	**Windows 2 & 3**	**Window 4**			**Window 5**	**Window 6**			**Window 7**
			ASHRAE	IECC 2012	Energy Star		ASHRAE	IECC 2012	Energy Star	
1	Does not comply with ASHRAE, IECC, or Energy Star	Does not comply with ASHRAE, IECC, or Energy Star	No	No	No	Complies with all	No	No	No	Complies with all
2			No	No	No		No	No	No	
3			No	No	No		No	No	No	
4 (except C)			No	No	No		No	No	No	
5 & 4C			No	Yes	Yes		No	Yes	Yes	
6			No	Yes	Yes		No	Yes	Yes	
7			No	Yes	Yes		Yes	Yes	Yes	
8			No	Yes	Yes		Yes	Yes	Yes	

APPENDIX C

State electricity mixes

Table C.1: State net electricity generation sources in percent of state total **[140]**.

States	Petroleum-Fired	Natural Gas- Fired	Coal-Fired	Nuclear	Hydro-electric	Other Renewables
Alaska	13.54%	48.90%	7.45%	0%	26.90%	3.21%
Arizona	0.07%	16.26%	38.79%	36.01%	6.53%	2.34%
California	0.04%	63.73%	0.24%	11.24%	6.10%	18.64%
Florida	0.56%	64.23%	17.24%	15.35%	0.12%	2.51%
Georgia	0.37%	39.12%	27.33%	27.09%	2.60%	3.48%
Hawaii	74.28%	0%	15.22%	0%	0%	10.50%
Louisiana	0.20%	57.49%	21.37%	17.33%	0.96%	2.66%
Massachusetts	4.18%	41.40%	25.21%	18.68%	3.92%	6.62%
Minnesota	0%	6.28%	50.00%	23.11%	0.97%	19.64%
Missouri	0.13%	3.84%	82.78%	11.17%	0.59%	1.50%
Montana	0%	0%	59.23%	0%	31.44%	9.34%
New Mexico	0.24%	31.11%	62.42%	0%	0%	6.24%
Texas	0%	51.01%	30.32%	10.11%	0.18%	8.38%
Utah	0%	15.65%	80.72%	0%	1.38%	2.25%
Washington	0%	6.10%	5.21%	7.83%	76.65%	4.22%

APPENDIX D

Table D.1: Complete midpoint impacts for Atlanta from roofing study.

Impact category	R-0 As, D	R-0 As, W	R-0 Tile, D	R-0 Tile, W	R-13 As, D	R-13 As, W	R-13 Tile, D	R-13 Tile, W
Climate change (kg CO_2 eq)	8.46	57.81	38.30	280.49	-2579.58	-2566.65	-2561.93	-2502.57
Ozone depl. (kg CFC-11 eq**)**	5.88E-07	5.44E-07	7.92E-08	-7.53E-08	2.46E-07	2.32E-07	-2.57E-07	-3.06E-07
Terrestrial acidif (kg SO_2 eq**)**	0.04	0.47	0.32	2.40	-21.54	-21.43	-21.36	-20.85
Freshwater eutro. (kg P eq**)**	1.67E-03	1.49E-03	1.32E-03	6.71E-04	4.03E-04	3.45E-04	7.45E-05	-1.30E-04
Marine eutro. (kg N eq**)**	0.0111	0.0106	0.0018	0.0032	-0.1226	-0.1229	-0.1322	-0.1325
Human toxicity (kg 1,4-DB eq**)**	8.94	22.67	10.54	71.37	-438.02	-434.16	-439.24	-423.14
Photochemical oxidant formation (kg NMVOC**)**	0.04	0.04	0.06	0.14	-4.25	-4.26	-4.25	-4.25
PM formation (kg PM-10eq**)**	0.01	0.10	0.07	0.49	-4.71	-4.69	-4.68	-4.58
Terrestrial tox. (kg 1,4-DB eq**)**	6.88E-04	-9.02E-05	3.31E-03	5.99E-04	-5.37E-03	-5.62E-03	-2.65E-03	-3.52E-03
Freshwater tox. (kg 1,4-DBeq**)**	0.116	0.209	0.298	0.702	-2.712	-2.686	-2.550	-2.442
Marine ecotox. (kg 1,4-DB eq**)**	0.11	0.21	0.13	0.54	-2.81	-2.79	-2.81	-2.70
Ionising radiation (kg U_{235} eq**)**	1.25	1.19	0.79	0.55	-1.30	-1.33	-1.76	-1.84
Ag. land occup. (m^2a**)**	0.093	0.085	0.033	2.91E-03	-0.240	-0.242	-0.299	-0.3082
Urban land occup. (m^2a**)**	0.185	0.184	0.031	0.025	0.175	0.175	0.021	0.019
Natural land trans. (m^2**)**	-9.47E-04	-9.89E-04	1.15E-04	-3.13E-05	-1.71E-03	-1.72E-03	-6.38E-04	-6.85E-04
Water depl. (m^3**)**	0.062	0.060	0.008	2.54E-04	-0.005	-0.006	-0.059	-0.062
Metal depl. (kg Fe eq**)**	0.13	0.07	2.03E-03	-0.19	-0.13	-0.15	-0.25	-0.31
Fossil depl. (kg oil eq**)**	0.38	-10.62	-2.08	-40.72	-65.23	-68.72	-66.29	-78.55

Table D.1 [cont]

Impact category	R-38 As, D	R-38 As, W	R-38 Tile, D	R-38 Tile, W	R-60 As, D	R-60 As, W	R-60 Tile, D	R-60 Tile, W
Climate change (kg CO_2 eq)	-3189.77	-3183.74	-3174.15	-3153.47	-3329.74	-3325.40	-3314.86	-3300.65
Ozone depl. (kg CFC-11 eq**)**	-1.05E-07	-1.67E-08	-5.12E-07	-5.35E-07	-1.94E-07	-1.98E-07	-6.95E-07	-7.12E-07
Terrestrial acidif (kg SO_2 eq**)**	-26.62	-26.57	-26.46	-26.28	-27.77	-27.74	-27.62	-27.50
Freshwater eutro. (kg P eq)	-8.04E-04	-4.31E-04	-7.27E-04	-8.22E-04	-9.51E-04	-9.69E-04	-1.27E-03	-1.34E-03
Marine eutro. (kg N eq**)**	-0.1550	-0.1550	-0.1644	-0.1649	-0.1627	-0.1628	-0.1722	-0.1727
Human toxicity (kg 1,4-DB eq**)**	-547.04	-544.75	-548.27	-542.04	-573.64	-572.39	-575.61	-571.19
Photochemical oxidant formation (kg NMVOC**)**	-5.27	-5.27	-5.27	-5.27	-5.50	-5.50	-5.50	-5.51
PM formation (kg PM-10eq**)**	-5.83	-5.82	-5.80	-5.76	-6.08	-6.07	-6.05	-6.03
Terrestrial tox. (kg 1,4-DB eq**)**	-8.52E-03	-7.70E-03	-4.84E-03	-5.24E-03	-8.65E-03	-8.72E-03	-5.89E-03	-6.19E-03
Freshwater tox. (kg 1,4-DBeq**)**	-3.417	-3.397	-3.250	-3.208	-3.591	-3.582	-3.433	-3.403
Marine ecotox. (kg 1,4-DB eq**)**	-3.54	-3.52	-3.53	-3.49	-3.72	-3.71	-3.72	-3.69
Ionising radiation (kg U_{235} eq**)**	-5.26	-5.13	-5.57	-5.61	-8.27	-8.28	-8.73	-8.76
Ag. land occup. (m^2a**)**	-0.755	-0.737	-0.795	-0.799	-1.147	-1.148	-1.205	-1.209
Urban land occup. (m^2a**)**	0.167	0.171	0.017	0.016	0.168	0.168	0.014	0.013
Natural land trans. (m^2**)**	-0.00277	-0.00269	-0.00161	-0.00163	-0.003470	-0.003474	-0.00240	-0.00242
Water depl. (m^3**)**	-0.108	-0.103	-0.157	-0.158	-0.183	-0.183	-0.237	-0.238
Metal depl. (kg Fe eq**)**	-0.29	-0.18	-0.29	-0.32	-0.18	-0.18	-0.29	-0.31
Fossil depl. (kg oil eq**)**	-80.94	-82.44	-81.58	-87.28	-84.55	-85.62	-85.04	-89.32

REFERENCES

[1] G. R. Matos, "Use of Minerals and Materials in the United States from 1900 Through 2006," *US Geological Survey,* 2009.

[2] Energy Information Administration. (2015, June 17). *Electric Power Monthly*. Available: http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_1

[3] N. Rajagopalan, Bilec, M. M., Landis, A. E., "Residential life cycle assessment modeling: Comparative case study of insulating concrete forms and traditional building materials," *Journal of Green Building,* vol. 5, pp. 95-106, 2010.

[4] M. Wackernagel, L. Onisto, P. Bello, A. Callejas Linares, I. Susana López Falfán, J. Méndez García, *et al.*, "National natural capital accounting with the ecological footprint concept," *Ecological Economics,* vol. 29, pp. 375-390, 6// 1999.

[5] Committee on Education, "Our common future, from one earth to one world," *UN Documents: gathering a body of global aggreements,* vol. UNO, 1987.

[6] M. Xu, J. C. Crittenden, Y. Chen, V. M. Thomas, D. S. Noonan, R. Desroches, *et al.*, "Gigaton Problems Need Gigaton Solutions," *Environmental Science & Technology,* vol. 44, pp. 4037-4041, 2010/06/01 2010.

[7] M. F. Ashby, *Materials and the environment: eco-informed material choice, 2nd ed*: Elsevier, 2012.

[8] J. Elkington, *Cannibal with forks: triple bottom line for 21st century business*, 1998.

[9] K. Toepfer. (2010, One Planet Many People (Atlas Prospectus). *UNEP Press Release*. Available: http://na.unep.net/OnePlanetManyPeople/press_release.html

[10] UNEP, "World population prospects: the 2009 revision and world urbanization prospect," ed: Population division of the department of economic and social affairs of the UN Secretariat, 2009.

[11] S. Pacala and R. Socolow, "Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies," *Science,* vol. 305, pp. 968-972, August 13, 2004 2004.

[12] A. Chen. (2009) Working toward the very low energy consumption building of the future. *Lawrence Berkeley National Laboratory*.

[13] A. C. Nelson, "Toward a New Metropolis: The Opportunity to Rebuild America," *The Brookings Institution Metropolitan Policy Program,* 2004.

[14] G. A. Keoleian, S. Blanchard, and P. Reppe, "Life-Cycle Energy, Costs, and Strategies for Improving a Single-Family House," *Journal of Industrial Ecology,* vol. 4, pp. 135-156, 2000.

[15] S. Frijia, S. Guhathakurta, and E. Williams, "Functional Unit, Technological Dynamics, and Scaling Properties for the Life Cycle Energy of Residences," *Environmental Science & Technology,* vol. 46, pp. 1782-1788, 2012/02/07 2011.

[16] J. Norman, H. MacLean, and C. Kennedy, "Comparing High and Low Residential Density: Life-Cycle Analysis of Energy Use and Greenhouse Gas Emissions," *Journal of Urban Planning and Development,* vol. 132, pp. 10-21, 2006.

[17] K. Adalberth, "Energy use during the life cycle of single-unit dwellings: Examples," *Building and Environment,* vol. 32, pp. 321-329, 1997.

[18] J. Quale, M. J. Eckelman, K. W. Williams, G. Sloditskie, and J. B. Zimmerman, "Construction Matters," *Journal of Industrial Ecology,* vol. 16, pp. 243-253, 2012.

[19] Associated Press in Changsha. (2015, Chinese construction firm erects 57-sotrey skyscraper in 19 days. *The Guardian*. Available: http://www.theguardian.com/world/2015/apr/30/chinese-construction-firm-erects-57-storey-skyscraper-in-19-days

[20] (2015, The first 3Dprinted house is coming, and the construction industry will never be the same. *Business Insider*. Available: http://www.businessinsider.com/3d-printed-houses-construction-industry-neighborhoods-2015-3

[21] Lifecycle Building Center. (2013). Available: http://www.lifecyclebuildingcenter.org/about-us/

[22] Deconstruction & ReUse Network, 2013.

[23] US Green Building Council, "LEED v4," 2013.

[24] F. Pacheco-Torgal, A. Shasavandi, and S. Jalali, "Eco-Efficient Concrete Using Industrial Wastes: A Review," *Materials Science Forum,* vol. 730, p. 581, 2012.

[25] M. L. Marceau, Bushi, L., Bowick, M., "Life cycle assessment for sustainable design of precast concrete commercial buildings in Canada," presented at the 1st International Specialty Conference on Sustaining Public Infrastructure, Edmonton, Alberta, 2012.

[26] A. B. Robertson, F. C. F. Lam, and R. J. Cole, "A Comparative Cradle-to-Gate Life Cycle Assessment of Mid-Rise Office Building Construction Alternatives: Laminated Timber or Reinforced Concrete," *Buildings,* vol. 2, pp. 245-270, 2012.

[27] H. Monteiro and F. Freire, "Life-cycle assessment of a house with alternative exterior walls: Comparison of three impact assessment methods," *Energy and Buildings,* vol. 47, pp. 572-583, 2012.

[28] E. Milutienė, J. Staniškis, A. Kručius, V. Augulienė, and D. Ardickas, "Increase in buildings sustainability by using renewable materials and energy," *Clean Technologies and Environmental Policy,* vol. 14, pp. 1075-1084, 2012/12/01 2012.

[29] Modcell. (2012). *Helping you build a more sustainable future*. Available: http://www.modcell.com/

[30] R. G.-R. U. Fay, "Life-cycle energy analysis of buildings: a case study," *Building Research & Information,* vol. 28, p. 31, 2000.

[31] Cotton Armour, "Mr Insulate: Cotton Armour," 2012.

[32] N. Rajagopalan, M. Bilec, and A. Landis, "Life cycle assessment evaluation of green product labeling systems for residential construction," *The International Journal of Life Cycle Assessment,* vol. 17, pp. 753-763, 2012/07/01 2012.

[33] S. Junnila and A. Horvath, "Life-Cycle Environmental Effects of an Office Building," *Journal of Infrastructure Systems,* vol. 9, pp. 157-166, 2003.

[34] M. Buyle, Braet, J., Audenaert, A., "LCA in the construction industry: A review," *International Journal of Energy and Environment,* vol. 6, pp. 397-405, 2012.

[35] O. Ortiz, F. Castells, and G. Sonnemann, "Sustainability in the construction industry: A review of recent developments based on LCA," *Construction and Building Materials,* vol. 23, pp. 28-39, 2009.

[36] A. C. H. Skelton and J. M. Allwood, "Product Life Trade-Offs: What If Products Fail Early?," *Environmental Science & Technology,* 2013.

[37] H. C. Kim, G. A. Keoleian, D. E. Grande, and J. C. Bean, "Life Cycle Optimization of Automobile Replacement: Model and Application," *Environmental Science & Technology,* vol. 37, pp. 5407-5413, 2003/12/01 2003.

[38] Energy Information Administration, "Heating and cooling no longer majority of US home energy use," 2013.

[39] GreenWizard Inc., "GreenWizard," ed: http://www.greenwizard.com/.

[40] Athena Sustainable Materials Institute, "Athena Impact Estimator," ed: http://www.athenasmi.org/.

[41] Lippiatt B, Greig AL, and Lavappa P, "Building for Environmental and Economic Sustainability (BEES)," ed. Gaithersburg, Maryland: National Institute of Standards and Technology, 2010.

[42] Autodesk, "Green Building Studio," ed: http://usa.autodesk.com/green-building-studio/.

[43] Autodesk, "Revit," I. Autodesk, Ed., ed: http://usa.autodesk.com/revit/.

[44] Green Up DC, 2013.

[45] Envirolytics. (2013). *iViro*. Available: http://www.envirolytics.ca/index

[46] Facebook and the NRDC. *Opower*. Available: https://social.opower.com/

[47] GoodGuide. (2013). Available: http://www.goodguide.com/

[48] D. Smithwick, Park, D., Aguirre, P., Larson, K., "CityHome," ed: MIT Changing Places Labs, http://cp.media.mit.edu/research/67-cityhome.

[49] K. Larson, Smithwick, D., "Beyond the Configurator: Collecting accurate data for an architectural design recommendation engine," *Working Paper*.

[50] K. Larson, "The Home of the Future," *A+U 361*, 2000.

[51] Environmental Protection Agency, "Buildings and their impact on the environment: a statistical summary," 2009.

[52] Energy Information Administration, "Residential energy consumption survey," U. D. o. Energy, Ed., ed, 2013.

[53] Aktas CB and Bilec MM, "Impact of lifetime on US residential building LCA results," *Int J. Life Cycle Assess.*, vol. 17, pp. 337-349, 2012.

[54] W. Klöpffer, "Life cycle sustainability assessment of products (with Comments by Helias A. Udo de Haes, p. 95)," *Int J. Life Cycle Assess.*, vol. 13, pp. 89-94, 2008.

[55] R. Hoogmartens, S. Van Passel, K. Van Acker, and M. Dubois, "Bridging the gap between LCA, LCC and CBA as sustainability assessment tools," *Environ Impact Asses*, vol. 48, pp. 27-33, 2014.

[56] R. Heijungs, E. Settanni, and J. Guinée, "Toward a computational structure for life cycle sustainability analysis: unifying LCA and LCC," *Int J. Life Cycle Assess.*, vol. 18, pp. 1722-1733, 2013/11/01 2013.

[57] I. Cetiner and E. Edis, "An environmental and economic sustainability assessment method for the retrofitting of residential buildings," *Energy Build.*, vol. 74, pp. 132-140, 2014.

[58] A. Jørgensen, I. Herrmann, and A. Bjørn, "Analysis of the link between a definition of sustainability and the life cycle methodologies," *Int J. Life Cycle Assess.*, vol. 18, pp. 1440-1449, 2013.

[59] W. Klöpffer and A. Ciroth, "Is LCC relevant in a sustainability assessment?," *Int J. Life Cycle Assess.*, vol. 16, pp. 99-101, 2011.

[60] International Standards Organization, "International standard ISO 14040: environmental management-life cycle assessment- principles and framework," Geneva2006.

[61] T. E. Swarr, D. Hunkeler, W. Klöpffer, H. L. Pesonen, A. Ciroth, A. C. Brent*, et al.*, "Environmental life-cycle costing: A code of practice," *Int J. Life Cycle Assess.*, vol. 16, pp. 389-391, 2011.

[62] D. Hunkeler, K. Lichtenvort, G. Rebitzer, and A. Ciroth, *Environmental life cycle costing / edited by David Hunkeler, Kerstin Lichtenvort, and Gerald Rebitzer ; lead authors, Andreas Ciroth ... [et al.]*: Pensacola, Fla. : SETAC ; Boca Raton : CRC Press, c2008., 2008.

[63] M. Tracey. (2009, June 6). *Home fads that are falling out of style*. Available: http://styledstagedsold.blogs.realtor.org/2009/01/21/home-fads-that-are-falling-out-of-style/

[64] J. Potting and K. Blok, "Life-cycle assessment of four types of floor covering," *J. Clean. Prod.*, vol. 3, pp. 201-213, 1995.

[65] Jönsson A, Tillman A-M, and Svensson T, "Life cycle assessment of flooring materials: case study," *Build. Environ.*, vol. 32, pp. 245-255, 1997.

[66] A. Günther and H.-C. Langowski, "Life cycle assessment study on resilient floor coverings," *Int J. Life Cycle Assess.*, vol. 2, pp. 73-80, 1997/06/01 1997.

[67] J. Paulsen, "Life cycle assessment for building products: the significance of the usage phase," Dissertation, Kungliga Tekniska Högskolan, Stockholm, 2001.

[68] Å. Jönsson, "Including the use phase in LCA of floor coverings," *Int J. Life Cycle Assess.*, vol. 4, pp. 321-328, 1999/11/01 1999.

[69] J. Paulsen, "The maintenance of linoleum and PVC floor coverings in Sweden the significance of the usage phase in an LCA," *Int J. Life Cycle Assess.*, vol. 8, pp. 357-364, 2003/11/01 2003.

[70] Nebel B, Zimmer B, and Wegener G, "Life cycle assessment of wood floor coverings - a representative study for the german flooring industry," *Int J. Life Cycle Assess.*, vol. 11, pp. 172-182, 2006/05/01 2006.

[71] Homewyse. (2014, 12 Dec 2013). *Home service costs*. Available: www.homewyse.com

[72] Energy Information Administration. (2014, 23 Jan 2014). *Electric power monthly: average retail price of electricity to ultimate customers by end-use sector*. Available: http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_a

[73] ChemDry. (2014, 12 Dec 2013). Available: http://www.chemdry.com/residential

[74] Environmental Protection Agency, "Water on tap: what you need to know," 2009.

[75] Carpet and Rug Institute A. (2014, 20 Feb 2014). *About CRI*. Available: http://www.carpet-rug.org/about-cri/what-is-cri/

[76] US Census Bureau. (2007, 20 Feb 2014). *Ceramic wall and floor tile manufacturing (NAICS 327122)*. Available: http://thedataweb.rm.census.gov/TheDataWeb_HotReport2/econsnapshot/snapshot.hrml?NAICS=327122&IND=%3DCOMP%28%28C4*C4%29%2FC4%29&STATE=ALL&COUNTY=ALL

[77] Environmental Protection Agency, "Solid waste management and greenhouse gases: a life-cycle assessment of emissions and sinks," 2002.

[78] Carpet and Rug Institute B. (2014, 25 Feb 2014). *Residential vacuuming*. Available: http://www.carpet-rug.org/residential-customers/cleaning-and-maintenance/basic-cleaning/vacuuming.cfm

[79] National Wood Flooring Association. (2014, 28 Feb 2014). *Frequently asked questions: care & maintenance*. Available: http://woodfloors.org/care-maitenance.aspx

[80] Lowes. (2014, 28 Feb 2014). *Clean hardwood floors*. Available: http://www.lowes.com/cd_how+to+clean+hardwood+floors_1314379252_

[81] National Center for Healthy Housing. (2008, 12 Dec 2013). *Carpets and healthy homes*. Available: http://www.nchh.org/Portals/0/Contents/CarpetsHealthyHomes.pdf

[82] Carpet and Rug Institute C. (2014, 28 Feb 2014). *Residential deep cleaning and selecting a carpet cleaning professional*. Available: http://www.carpet-rug.org/residential-customers/cleaning-and-maintenance/deep-cleaning-and-selecting-a-carpet-cleaning-professional.cfm

[83] C. Sanz. (2012, 28 Feb 2014) Working with linoleum flooring. *This Old House*. Available: http://www.thisoldhouse.com/toh/article/0,,202857,00.html

[84] Forbo. (2008, 28 Feb 2014). *Cleaning & maintenance of marmoleum floors*. Available: http://www.forbo-flooring.com/Residential-flooring/Installation-floorcare/Floorcare/

[85] Armstrong, "Maintenance recommendations & procedures for commercial resilient, hardwood & laminate flooring," 2012.

[86] Scientific Applications International Corporation, "Life cycle assessment: Principles and practice," US Environmental Protection Agency, Reston, VA2006.

[87] M. Goedkoop, M. Oele, J. Leijiting, T. Ponsioen, and E. Meijer, "Introduction to LCA with SimaPro," *SimaPro 8 Manual*, 2013.

[88] B. Weidema, C. Bauer, R. Hischier, C. Mutel, T. Nemecek, J. Reinhard, *et al.*, "Overview and methodology: Data quality guideline for the ecoinvent database version 3," St. Gallen: The ecoinvent Centre2013.

[89] Goedkoop M, Heijungs R, Huibregts M, Schryver AD, Stuijs J, and van Zelm R, "ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level," 2012.

[90] Hofstetter P, *Perspectives in life cycle impact assessment: a structured approach to combine models of the technosphere, ecosphere and valuesphere*. Zurich: Kluwer Academic Publishers, 1998.

[91] Frischknecht R, Jungbluth N, Althaus H-J, Doka G, Dones R, Heck T, *et al.*, "The ecoinvent database: overview and methodological framework," *Int J. Life Cycle Assess.,* vol. 10, pp. 3-9, 2005.

[92] Soratana K and Marriott J, "Increasing innovation in home energy efficiency: Monte Carlo simulation of potential improvements," *Energy Build,* vol. 42, pp. 828-833, 2010.

[93] J. Woller. (1996, 18 Feb 2014). *The basics of Monte Carlo simulations*. Available: http://www.chem.unl.edu/zeng/joy/mclab/mcintro.html

[94] Fuller S and Peterson S, "Life-cycle costing manual for the federal energy management program," Gaithersburg, Maryland1996.

[95] Office of Management and Budget, "Circular A-94 Appendix C," *White House,* 2013.

[96] A. S. Rushing, J. D. Kneifel, and B. C. Lippiatt, "Energy price indices and discount factors for Life-Cycle Cost Analysis- 2013," National Institute of Standards and Technology, Gaithersburg, MD2013.

[97] Baitz M, Kreißig J, Byrne E, Makishi C, Kupfer T, Frees N, *et al.*, "Life cycle assessment of PVC and of principal competing materials," European Commission, Leinfelden-Echterdingen, Germany2004.

[98] D. L. Franke, E. C. Cole, K. E. Leese, K. K. Foarde, and M. A. Berry, "Cleaning for improved indoor air quality: an initial assessment of effectiveness," *Indoor Air,* vol. 7, pp. 41-54, 1997.

[99] National Association of Home Builders. (2014, July 28). *Housing's Contribution to Gross Domestic Product (GDP)*. Available: http://www.nahb.org/generic.aspx?genericContentID=66226

[100] Energy Information Administration, "Emissions of greenhouse gases in the United States 2009," *US Department of Energy,* p. 22, 2011.

[101] Department of Energy. (2014, July 28). *Tips: Windows*. Available: http://energy.gov/energysaver/articles/tips-windows

[102] Energy Information Administration, "Table HC10.12 average square footage of south homes, by housing characteristics, 2009," ed, 2013.

[103] S. Jaber and S. Ajib, "Thermal and economic windows design for different climate zones," *Energy Build,* vol. 43, pp. 3208-3215, 2011.

[104] N. Hester, K. Li, J. R. Schramski, and J. Crittenden, "Dynamic modeling of potentially conflicting energy reduction strategies for residential structures in semi-arid climates," *Journal of Environmental Management,* vol. 97, pp. 148-153, 2012.

[105] R. Sullivan and S. Selkowitz, "Window performance analysis in a single-family residence," Lawrence Berkeley National Laboratory, University of California, Berkeley, CA1985.

[106] J. Carmody and K. Haglund, "Measure guideline:energy-efficient window performance and selection," US Department of Energy, Springfield, VA2012.

[107] S. Widder and G. Parker, "Demonstration of the performance of highly-insulating (R-5) windows in a matched pair of homes," presented at the Thermal Performance of the Exterior Envelops of Whole Buildings XII International Conference, Clearwater Beach, FL, 2013.

[108] H. Babaizadeh, N. Haghighi, S. Asadi, R. Broun, and D. Riley, "Life cycle assessment of exterior window shadings in residential buildings in different climate zones," *Building and Environment,* vol. 90, pp. 168-177, 8// 2015.

[109] J. Salazar and T. Sowlati, "Life cycle assessment of windows for the North American residential market: Case study," *Scand J Forest Res,* vol. 23, pp. 121-132, 2008.

[110] M. Asif, A. Davidson, and T. Muneer, "Life cycle of window materials- a comparative assessment," School of Engineering, Napier University, United Kingdom, 2002.

[111] H. Babaizadeh and M. Hassan, "Life cycle assessment of nano-sized titanium dioxide coating on residential windows," *Constr Build Mater*, vol. 40, pp. 314-321, 2013.

[112] National Renewable Energy Laboratory. (2013, June 4). *National residential efficiency measures database*. Available: http://www.nrel.gov/ap/retrofits/

[113] D. Seiders, G. Ahluwalia, S. Melman, R. Quint, A. Chaluvadi, M. Liang, *et al.*, "Study of life expectancy of home components," National Association of Home Builders & Bank of America Home Equity, Washington, DC2007.

[114] ASHRAE, "Energy standard for buildings except low-rise residential buildings," in *90.1-2013*, ed. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc, 2013.

[115] ASHRAE, "Energy-efficient design of low-rise residential buildings," in *90.2-2007*, ed. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc, 2007.

[116] International Code Council, "International Energy Conservation Code," in *Residential Energy Efficiency: Section R402 Building Thermal Envelope*, ed, 2012.

[117] Energy Star, "Performance criteria," in *Windows*, ed. http://www.energystar.gov/index.cfm?c=windows_doors.pr_anat_window: Environmental Protection Agency.

[118] Morris Hershfield, "Maintenance, repair and replacement effects for building envelope materials," *ATHENA Sustainable Materials Institute*, 2002.

[119] Department of Energy. (2014, August 10). *Savings project: how to seal air leaks with caulk*. Available: http://energy.gov/energysaver/projects/savings-project-how-seal-air-leaks-caulk

[120] R. Mitchell, M. Yazdanian, and K. Haglund, "Window Selection Tool," ed. Wyoming, MN: Efficient Windows Collaborative, 2014.

[121] R. Mitchell, M. Yazdanian, L. Zhu, D. Arasteh, and J. Huang, "RESFEN 6 for calculating the heating and cooling energy use of windows in residential buildings," Lawrence Berkeley National Laboratory, Berkeley, CA2012.

[122] National Renewable Energy Laboratory. User's Manual for TMY2s [Online]. Available: http://rredc.nrel.gov/solar/pubs/tmy2/overview.html#descrip

[123] Department of Energy, "EnergyPlus," 8.3 ed, 2015.

[124] National Renewable Energy Laboratory, "BEopt," 2.3.0.2 ed, 2015.

[125] Atlanta Regional Commission, "Regional snapshot, ARC's 20-county forecasts: what the future holds," Atlanta Regional Commission, Atlanta2009.

[126] Atlanta Regional Commission, "ARC's 2014 population estimates: steady as she goes," Atlanta2014.

[127] Atlanta Regional Commission, "2009 housing variables data table," ed. Atlanta, 2009.

[128] Energy Information Administration, "Table HC2.10 structural and geographic characteristics in the south region, divisions, and states, 2009," ed, 2013.

[129] Southern Company, "Carbon disclosure report," 2014.

[130] Environmental Protection Agency, "Carbon dioxide emissions coefficients," ed, 2013.

[131] Remodeling. (2015, April 25). *2015 Cost vs value report*. Available: http://www.remodeling.hw.net/cost-vs-value/2015/www.remodeling.hw.net/cost-vs-value/2014/methodology

[132] J. J. Conti, et al, "Annual energy outlook 2015 with projections to 2040," E. I. Administration, Ed., ed: Energy Information Administration, 2015.

[133] Department of Energy. (2015, April 15). *Residential energy efficient tax credit*. Available: http://energy.gov/savings/residential-energy-efficiency-tax-credit

[134] S. T. Anderson and R. G. Newell, "Information programs for technology adoption: the case of energy-efficiency audits," *Resource and Energy Economics,* vol. 26, pp. 27-50, 3// 2004.

[135] C. Wilson and H. Dowlatabadi, "Models of Decision Making and Residential Energy Use," *Annual Review of Environment & Resources,* vol. 32, pp. 169-203, 2007.

[136] United National General Assembly, "60/1. 2005 World summit outcome: resolution adopted by the general assembly," United Nations, New York, NY2005.

[137] E. Minne and J. Crittenden, "Impact of maintenance on life cycle impact and cost assessment for residential flooring options," *The International Journal of Life Cycle Assessment,* vol. 20, pp. 36-45, 2015/01/01 2015.

[138] Energy Information Administration. (2014, May 2). *Countries: analysis*. Available: http://www.eia.gov/countries/cab.cfm?fips=ca

[139] T. Pacetti, L. Lombardi, and G. Federici, "Water-Energy Nexus: a case of biogas production from energy crops evaluated by Water Footprint and LCA methods," *Journal of Cleaner Production,* 2015.

[140] Energy Information Administration. (2015, April 2). *State net electricity generation by source: January 2015*. Available: http://www.eia.gov/state/

[141] Energy Star. (2014, 10 Oct). *Federal tax credits for consumer energy efficiency*. Available: http://www.energystar.gov/index.cfm?c=tax_credits.tx_index

[142] S. I. Seneviratne, N. Nicholls, D. Easterling, C.M. Goodess, S. Kanae, J. Kossin, Y. Luo, J. Marengo, K. McInnes, M. Rahimi, M. Reichstein, A. Sorteberg, C. Vera, X. Zhang, , *Changes in climate extremes and their impacts on the natural physical environment*. pp 109-230.: A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge, UK, and New York, NY, USA, 2012.

[143] Department of Energy, *Window selection : modern windows provide energy savings, durability, and comfort*. Washington, D.C: Building Technologies Program, Office of Energy Efficiency and Renewable Energy, U.S. Dept. of Energy, 2003.

[144] N. Petermann, "Final technical report for efficient windows collaborative: research tool dissemination to increase energy efficient fenestration product penetration," Alliance to Save Energy, Washington, DC2010.

[145] A. Thomas, E. E. Ryherd, J. Irizarry, D. Castro-Lacouture, and R. Porter, "Aircraft sound transmission in homes categorized by typical construction type," 2014, pp. 1586-1595.

[146] D&R International, "2011 Buildings energy data book," *US Department of Energy: Energy Efficiency & Renewable Energy,* pp. 1-6, 2012.

[147] K. W. Oleson, G. B. Bonan, and J. Feddema, "Effects of white roofs on urban temperature in a global climate model," *Geophysical Research Letters*, p. 37, 2010.

[148] J. R. Simpson and E. G. McPherson, "The effects of roof albedo modification on cooling loads of scale model residences in Tucson, Arizona," *Energy and Buildings,* vol. 25, pp. 127-137, // 1997.

[149] A. Synnefa, M. Santamouris, and H. Akbari, "Estimating the effect of using cool coatings on energy loads and thermal comfort in residential buildings in various climatic conditions," *Energy and Buildings,* vol. 39, pp. 1167-1174, 2007.

[150] H. Akbari, S. Bertz, D. Kurn, and J. Hanford, "Peak power and cooling energy savings of high-albedo roofs," *Energy and Buildings,* pp. 25, 117e126, 1997.

[151] H. Akbari, S. Konopacki, and M. Pomerantz, "Cooling energy savings potential of reflective roofs for residential and commercial buildings in the United States," *Energy,* vol. 24, pp. 391-407, 1999.

[152] H. Akbari and H. Taha, "The impact of trees and white surfaces on residential heating and cooling energy use in four Canadian cities," *Energy,* vol. 17, pp. 141-149, 1992.

[153] Lawrence Berkeley National Laboratory. (2015, June 6). *Cool science: cool roofs*. Available: https://heatisland.lbl.gov/coolscience/cool-science-cool-roofs

[154] Environmental Protection Agency. (2014, April 14). *Heat Island Effect*. Available: http://www.epa.gov/heatisland/

[155] E. Di Giuseppe and M. D'Orazio, "Assessment of the effectiveness of cool and green roofs for the mitigation of the Heat Island effect and for the improvement of thermal comfort in Nearly Zero Energy Building," *Architectural Science Review,* vol. 58, pp. 134-143, 2015/04/03 2014.

[156] Department of Energy. (2012, June 6). *Radiant barriers*. Available: http://energy.gov/energysaver/articles/radiant-barriers

[157] Environmental Protection Agency, "Green roofs," 2008.

[158] greenroofs.com. (2015, 2015). *The international greenroof & greenwall project database*. Available: http://www.greenroofs.com/projects/plist.php

[159] Oak Ridge National Laboratory and Southface Energy Institute. (2000, April 15). *Ceilings and attics: install insulation and provide ventilation*. Available: http://web.ornl.gov/sci/roofs+walls/insulation/fact%20sheets/attic%20floors.pdf

[160] Oak Ridge National Laboratory, "Roof Savings Calculator," ed.

[161] National Renewable Energy Laboratory, "National Solar Radiation Data Base," ed, 2008.

[162] US Census Bureau, "American Housing Survey," ed, 2013.

[163] W. Zhang, Z. Song, Y. Shi, J. Song, J. Qu, J. Qin, *et al.*, "The effects of manufacturing processes and artificial accelerated weathering on the solar reflectance and cooling effect of cool roof coatings," *Solar Energy Materials and Solar Cells,* vol. 118, pp. 61-71, 11// 2013.

[164] R. Kahhat, J. Crittenden, F. Sharif, E. Fonseca, K. Li, A. Sawhney, *et al.*, "Environmental Impacts over the Life Cycle of Residential Buildings Using

Different Exterior Wall Systems," *Journal of Infrastructure Systems,* vol. 15, pp. 211-221, 2009/09/01 2009.

[165] H. Islam, M. Jollands, S. Setunge, I. Ahmed, and N. Haque, "Life cycle assessment and life cycle cost implications of wall assemblages designs," *Energy and Buildings,* vol. 84, pp. 33-45, 12// 2014.

[166] J. Carreras, D. Boer, G. Guillén-Gosálbez, L. F. Cabeza, M. Medrano, and L. Jiménez, "Multi-objective optimization of thermal modelled cubicles considering the total cost and life cycle environmental impact," *Energy and Buildings,* vol. 88, pp. 335-346, 2/1/ 2015.

[167] N. Pargana, M. D. Pinheiro, J. D. Silvestre, and J. de Brito, "Comparative environmental life cycle assessment of thermal insulation materials of buildings," *Energy and Buildings,* vol. 82, pp. 466-481, 10// 2014.

[168] R. D. Schlanbusch, B. P. Jelle, L. I. Christie Sandberg, S. M. Fufa, and T. Gao, "Integration of life cycle assessment in the design of hollow silica nanospheres for thermal insulation applications," *Building and Environment,* vol. 80, pp. 115-124, 10// 2014.

[169] P. Ricciardi, E. Belloni, and F. Cotana, "Innovative panels with recycled materials: Thermal and acoustic performance and Life Cycle Assessment," *Applied Energy,* vol. 134, pp. 150-162, 12/1/ 2014.

[170] National Association of Home Builders: Research Center, "Review of structural materials and methods for home building in the United States: 1900-2000," ed. US Department of Housing and Urban Development, 2001.

[171] J. Irizarry, Gheusari, M., Walker, B.N., , "Usability assessment of drone technology as safety inspection tools," *Journal of Information Technology in Construction,* vol. 17, pp. 194-212, 2012.

[172] National Oceanic and Atmospheric Administration, "1981-2010 U.S. Climate Normals," ed, 2011.