The Next Generation of Residential Construction:
Adoption of Green Building Programs, Environmentally Certified Wood Products and the Transparency of Environmental Friendliness

Charles Tait Bowers

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Reading Committee:

Ivan Eastin, Chair

Indroneil Ganguly, Co-Chair

B. Bruce Bare

Program Authorized to Offer Degree:

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University of Washington

Abstract

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Charles Tait Bowers

Chairs of Supervisory Committee:
Professor Ivan Eastin
Associate Professor Indroneil Ganguly
School of Environmental and Forest Sciences

The downturn in the housing market, in 2006, created a need to analyze the strengths and weaknesses of the residential construction industry to learn what drivers will influence the next generation of homebuilding. As the housing market continues its recovery, we must seek to understand the real and perceived weaknesses and strengths of the home building industry. Architects, as the visionaries in home design, have played an important role in the industry as innovators of new concepts and designs. They typically stipulate building materials and strongly influence energy efficiency and quality of construction.

Green building programs were designed to bridge the gap between traditional construction methods and innovative building techniques and materials. Adopting a green building framework will allow architects to design homes that meet energy efficiency requirements and air quality standards, utilize renewable and recyclable materials, reuse existing structures or foundations, and minimize water use to produce environmentally friendly homes and buildings. By meeting specific criteria within green building programs (i.e., United States Green Building Council LEED (Leadership in Energy and Environmental Design) for Homes and the National Home Builders Association's National Green Building Standard (NGBS)), homes can be certified as meeting current environmental standards for "green construction." While these green building initiatives are relatively new, having gained prominence in the last two decades, new updates are published every few years. The most recent update for both programs occurred in 2018, and the latest version of the LEED for Homes program (version 4.1) is currently under review. Updates usually require more rigorous methods of auditing a building's performance or authorize new materials and methods for certification.

Wood and wood-based materials (e.g., plywood, oriented strand board) are common in residential construction, with most wood products used in the United States coming from domestic forests. Reacting to the recent push for sustainable forest management, forest certification standards such as the Forest Stewardship Council (FSC) and the Sustainable Forestry Initiative (SFI) allow for third-party audits of forest lands to determine if sustainable forest management and regeneration methods are being met. The FSC and SFI also allow for the logs and wood products taken from certified forests to be labeled and marketed as environmentally certified. Environmentally certified wood products (ECWPs) are eligible to

receive green building points when used in a certified home if they meet the requirements of the green building program.

This research adopts a multi-level approach to identify the factors that influence architects' specification of ECWPs. In particular, this research explores if there are unique demographic or psychographic characteristics that promote architects' adoption and use of ECWPs as well as their participation in residential green building programs (GBPs). This research is based on a survey of 385 U.S. architects who participated in residential construction projects, and who were asked questions related to their awareness and use of GBPs and ECWPs. An analysis of the survey data found that there are regional differences between architects who utilize GBPs and ECWPs. Additionally, the results suggest that many architects who use GBPs and ECWPs have an inherent environmental orientation when specifying building materials for a residential project. The most significant factors influencing architects' use of ECWPs was whether or not they had previously participated in a green building program or had used other green building products and technologies.

To help determine the environmental friendliness of wood-based building materials, comparisons were made with similar products made from steel and concrete through a life cycle analysis (LCA). By comparing the results of products' LCA's, we can assess whether renewable materials (e.g., wood) have lower environmental impacts relative to non-renewable materials (e.g., steel and concrete). A functional unit comparative LCA analysis was conducted for structural beams made from wood, steel, and concrete utilizing a "cradle-to-installed" methodology. Based on the results of the comparative analyses, wooden glue-laminated beams required 139% and 357% less primary energy during their manufacture than steel and concrete beams, respectively.

This research will help identify innovative architects who are more likely to stipulate innovative home design methods and environmentally sustainable building materials. This research also helps to provide vital LCA data that can help wood product manufacturers demonstrate the environmental performance of wood building materials through the development of environmental product declaration information based on life cycle assessment (LCA) protocols.

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1.1 Introduction

Building materials and home design continue to evolve as both fuel costs and demand for energy and water-efficient residences increase. The development of green building programs in the late 1990s began the implementation of energy-efficient design guidelines and eco-friendly, renewable building materials designed to minimize buildings' environmental impact (USGBC, 2019b). These programs also established certification programs and award eco-labels for buildings that meet certain design standards as having been built or "designed for the environment." Only in the last ten years have green building programs (GBPs) been developed for single and multi-family residential housing so that consumers can enjoy energy and water savings with nominal to moderate increases in initial home costs (NAHB, 2019b; USGBC, 2019b). Most GBPs try to integrate eco-friendly materials into the design and construction of the home, including environmentally certified wood products (ECWPs) harvested from sustainably managed forests. The impact of GBP's on ECWPs specification and use would be appealing to the forest products industry as an additional avenue to market their products. However, integrating ECWPs is not necessary nor sufficient for the home to achieve third-party certification as a "green" home (Ganguly, Bowers, Eastin, & Cantrell, 2013).

Most timber harvested from certified forests was initially used to manufacture value-added wood products like cabinetry, moldings, and other appearance-specific products. However, the development of residential GBPs created a market for certified structural wood materials (e.g., dimension lumber and wood-based panels) (Bowers, Ganguly, & Eastin, 2014; Ganguly et al., 2013). These materials constitute the majority of the wood used in home construction and therefore represent a large percentage of a home's environmental footprint. We can determine a product's total impact on the environment—from the procurement of raw materials, manufacturing, transportation along the supply chain, installation in a building, and its ultimate disposal or reuse—using the quantitative measures of life cycle analysis.

Architects generally specify materials used in residential home construction, and their choice of eco-friendly (e.g., energy efficient) materials influences the home's carbon footprint. Architects' differing perceptions of these materials determine whether individual materials are specified in the homes they design (Damery & Fisette, 2001; Knowles, Theodoropoulos, Griffin, & Allen, 2011). Their perceptions could stem from their history using a product, information provided about a product, or through their interactions with builders or customers.

The focus of this research is to determine what material attributes and green building characteristics influence architects' decisions to specify ECWPs in the homes they design. Additionally, this research examines if an architect's prior participation in a residential GBP predicts their use of ECWPs. Subsequently, the survey data will be used to determine if architects' preferences for wood-based building materials are attributable to their perception of that material's environmental friendliness or "life cycle impact." These types of environmental quantitative comparisons (including environmental product declarations or EPDs) indicate design decisions architects will make in the future to reduce the environmental footprint of residential homes. If differences exist between groups of architects and their material choices, marketing efforts could be targeted towards specific groups of architects (e.g., innovators). Understanding adopter segments within a market could allow organizations to reduce marketing expenses while increasing the success of a new product launch (Fell, Hansen, & Becker, 2003). Furthermore, concentrating marketing efforts towards the right market segment could increase efficiency in the distribution of information materials and programs, and projected increases in green home construction could create opportunities in the marketplace for specific ECWPs (Estep, DeVallance, & Grushecky, 2013). As architects become more aware of the environmental footprint of the buildings they design, they may be more willing to specify ECWPs to improve the environmental performance and rating of their homes within residential GBPs.

1.2 Background

1.2.1 U.S. Residential Construction Market

The U.S. housing sector is still recovering from the housing bubble of 2004-2008. The bubble developed predominantly as a result of a loosely monitored home loan industry, which allowed homebuyers to obtain a larger mortgage than they could afford. As a result, credit markets are now more restrictive, increasing the amount of time it takes for first time home buyers to save enough money to purchase an entry level home. These restrictions, along with the collapse of the speculative housing market, led to the lowest rate of home building and the weakest demand for wood products since the Great Depression (Keegan, Sorenson, Morgan, Hayes, & Daniels, 2011). After the consolidation of the home building sector, it was the fiscally prudent homebuilder and/or architect who was able to survive. Many fly-by night homebuilders, contractors and “house flippers” went bankrupt as a result of their financial risks.

There were 1.25 million housing starts in 2018, a decrease from the pre-bubble construction average of 1.49 million starts from 1990-2004 (U.S. Bureau of Census, 2018). An analysis of housing starts over the last 30 years (Figure 1-1) reveals a drastic drop in U.S. home construction between 2006 and 2009. Since then, current 2018 housing starts have recovered 74% relative to the pre-bubble average, with a 57.1% recovery in single-unit homes and recovery surpassing the average in multi-unit homes (144.3%). Multi-unit buildings tend to stay on the market for shorter periods of time, which expedites the recovery of construction costs (NAHB, 2019a), and have rebounded quickly to meet housing needs of those unable to obtain a mortgage. This is especially apparent in urban areas where the need is the greatest. The 2017 tax law limited the amount of deductible mortgage interest available to homeowners, further slowing the recovery of housing starts.

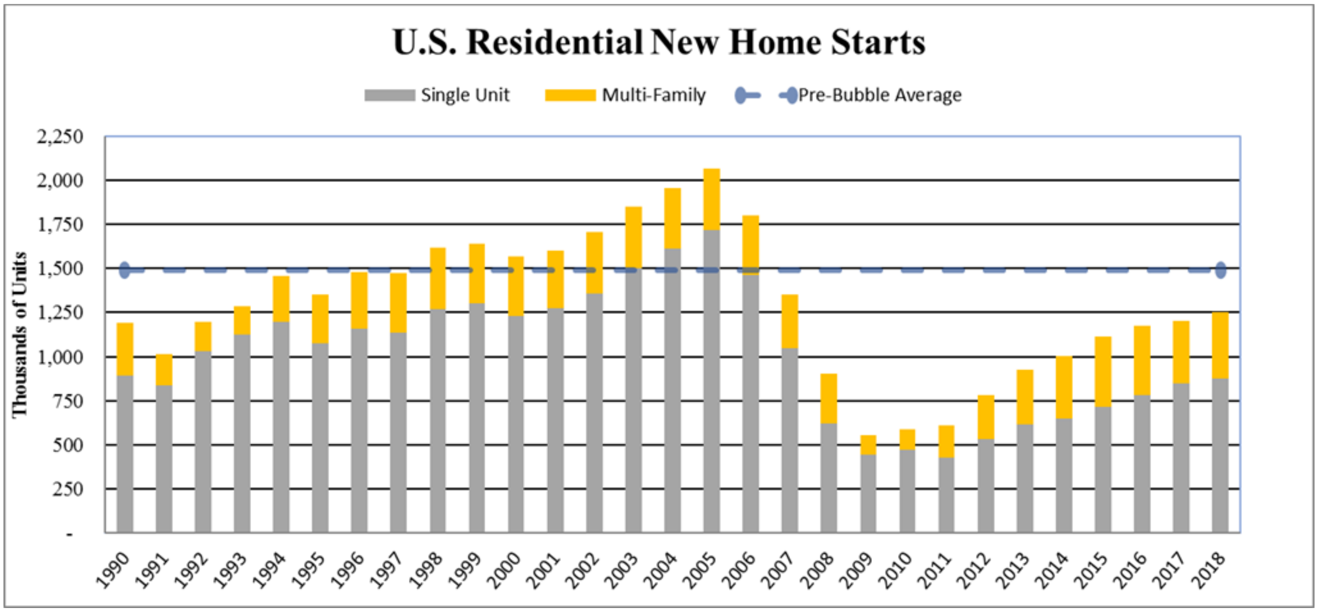

Figure 1-1 U.S. Residential Home Starts in Thousands of Units (U.S. Census, 2019)

Housing starts remain below their pre-bubble levels across all four main U.S. geographic regions (Figure 1-2) (U.S. Bureau of Census, 2018). The South, the largest home building region in the U.S., sustained the largest drop in housing starts with 388,000 less starts than the pre-bubble average (666,000/year). Comparing 2018 housing starts to their pre-bubble average, the housing market has recovered well in the South (91%) and West (87%). The Northeast has recovered moderately (61%), but the Midwest has been sluggish to respond (35%). While housing starts in the South and West should eventually recover to pre-bubble averages, the process for the other two regions may take longer. Housing starts will probably not recover to peak levels due to an increase in renters and multi-unit housing complexes, but this is greatly dependent on future U.S. population growth.

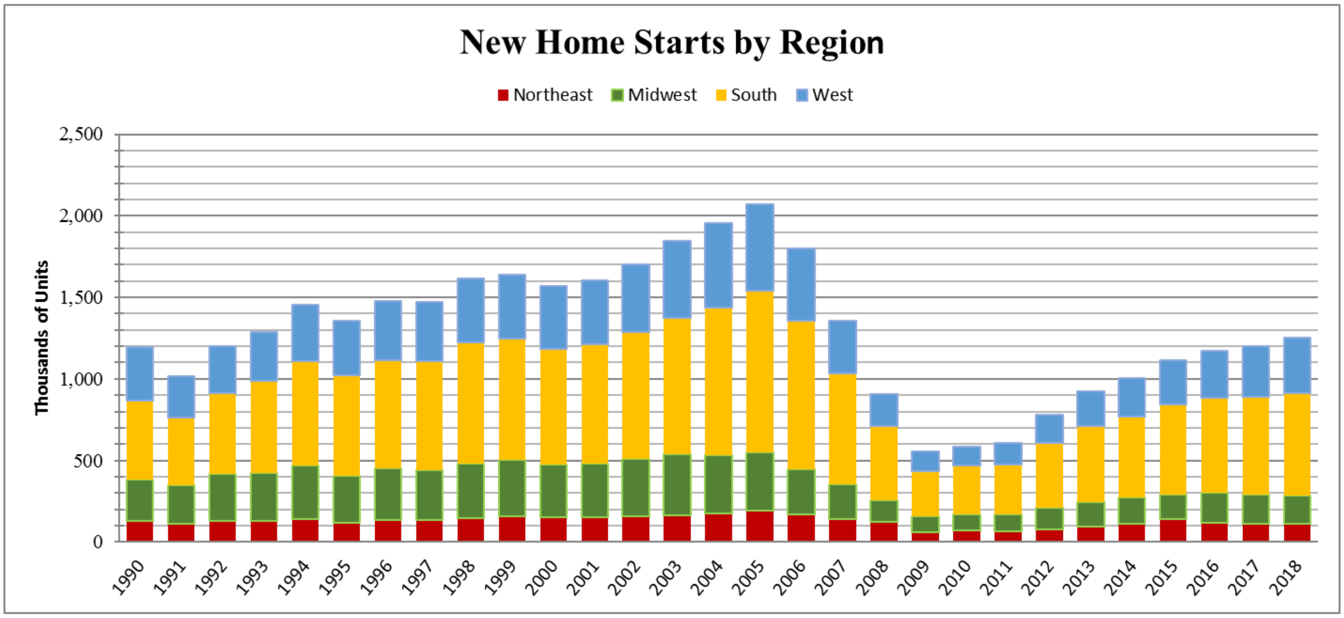

Figure 1-2 U.S. Regional Residential Home Starts in Thousands of Units (U.S. Census, 2019)

As first-time homebuyers reenter the marketplace, there continues to be a lack of affordable housing inventory. Many large cities have housing shortages as eligible buyers struggle to find a “starter home.” Some homebuilders have focused on building higher-end homes and custom homes, which tend to be more profitable, as opposed to starter homes, which have smaller profit margins. While many first-time buyers would prefer to purchase a new home (Sasatani, 2013), there is a discrepancy between new home buyers and the availability of new homes on the market (Figure 1-3). The supply of existing homes for sale is also declining in many metropolitan and suburban areas, resulting in higher home prices as well as rental rates, which stagnates sales for both new and existing homes. Without the construction of new homes priced for first-time buyers, the dream of purchasing that “first home” is delayed until new buyers accumulate savings for a down payment.

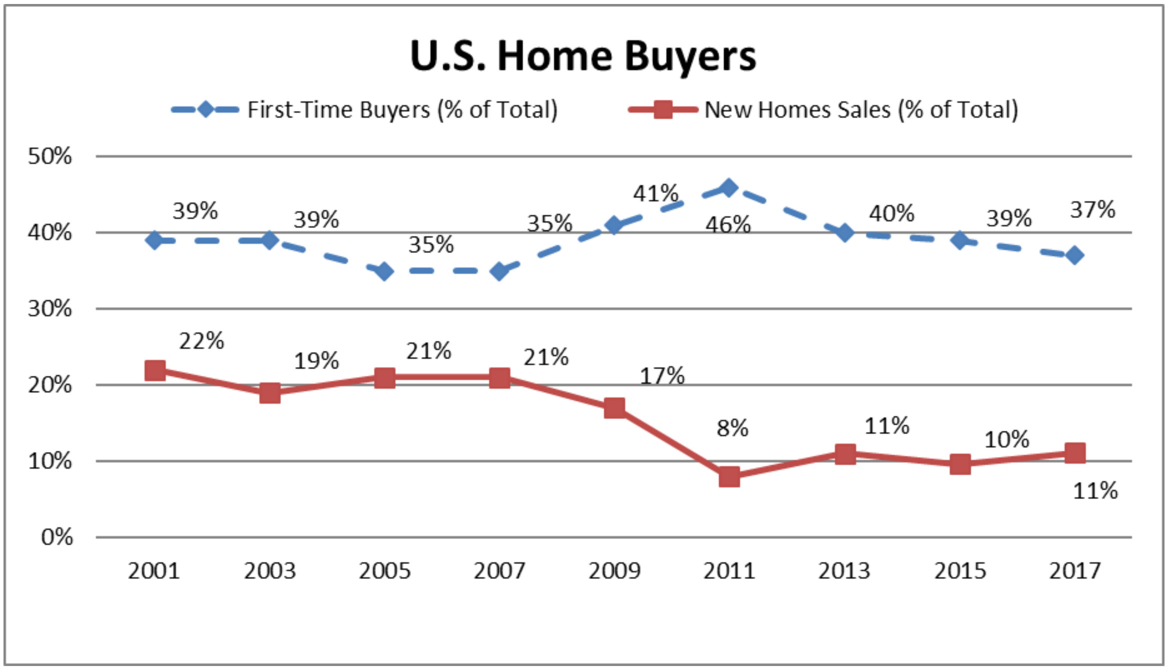

Figure 1-3 First Time Home Buyer versus Availability of New Homes (NAHB, 2017)

The residential construction sector, which consists of both new home construction and repair and remodel activity, is the largest consumer of wood in the U.S., having used more than two-thirds of the softwood lumber in 2016 (Figure 1-4) (WWPA, 2017). The Western U.S. has historically supplied approximately half of the softwood lumber produced in the U.S., and has been a major source of structural panels and other wood based materials (WWPA, 2017). As the prominent market, this sector greatly impacts the local forest products industry and disrupts the entire wood procurement supply chain.

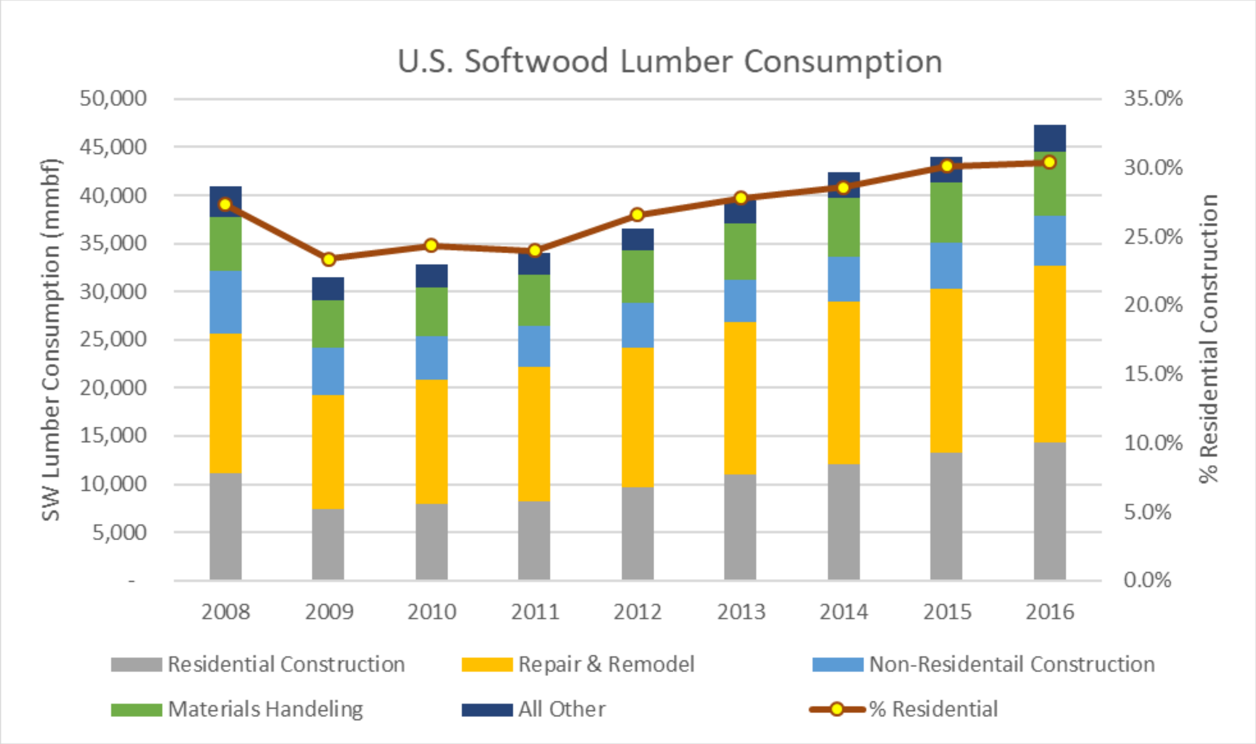

Figure 1-4 U.S. Consumption of Softwood Lumber (WWPA, 2016)

Wood is generally perceived to be a more eco-friendly and sustainable building material relative to steel and concrete, based on a number of environmental criteria. However, Wagner and Hansen (2004a) suggest that many architects may not share this perception. When given the option, some architects specify steel studs instead of wood because of steel's perceived strength and durability, while others perceive that steel is more environmentally friendly than wood (Wagner & Hansen, 2004a). These perceptions could stem from steel's scrap value and the incentive of potential reuse after a building's end-of-life. In the past, wood from demolished homes has been taken to the local land fill to decompose; now wood is carefully removed from deconstructed homes and reused or recycled.

The environmental impacts of substituting wood for steel and concrete have been studied, particularly in regard to the impact that each construction material has on the carbon footprint of a home. A study by Lippke and Edmonds (2006) evaluated components and subassemblies of a residential home with wood, steel, and concrete materials, finding that energy use and potential contribution to global warming were significantly lower with wood-based components. They also discussed how environmental impacts vary by region and available energy sources. Another study by Upton et al. (2008) compared wood-based wall systems to thermally-comparable steel or concrete building systems; their results indicated that wood-based wall systems produced a 15-16% reduction in total energy for non-heating/cooling purposes and 20-50% lower net greenhouse gas emissions than steel and concrete systems. Despite these studies, a lack of information about reducing the environmental impacts of structural building materials persists, particularly in regard to non-residential structures. McKeever and Adair (1998) found that 50% of non-residential structures in the U.S. could have been built with wood within existing national building codes. However, local building codes, design difficulty, local fire codes, and concerns about durability most likely discouraged its use (Kozak & Cohen, 1999). Oster and Quigley's (1977) study on innovations in the construction industry confirmed that building codes were indeed a hindrance to the adoption of new technologies and design. Multiple studies revealed that the embodied energy and sequestered CO_2 in wood-framed wall systems and wooden buildings is lower than comparable structures or systems that use concrete and/or steel (Athena Sustainable Materials Institute, 2004; Lippke, Wilson, Meil, & Taylor, 2010; Puettmann & Wilson, 2005; Upton et al., 2008). Thormark (2006) showed that material choice alone can reduce the amount of embodied energy by 17% when wood is substituted for steel or concrete.

The forest products industry is heavily reliant on the residential construction market. The downturn in the housing market spurred U.S. wood and timber manufacturers to find new methods to add value to their products and maintain their market share in an increasingly competitive building product marketplace. To demonstrate the environmental sustainability of wood products, an increasing number of forest owners and lumber manufacturers are obtaining third-party certification or are sourcing timber from certified forestlands. Environmental certification can help to reduce external pressure from environmental non-government organizations (ENGOs), local governments, wood remanufacturers and the general public while allowing manufacturers to market their sustainable forestry practices.

Certified (or green) products need to provide an inherent benefit to obtain a price premium in the market. Many green products offer benefits such as cost effectiveness, health and safety, increased performance, symbolism, status, and convenience (Thompson, Anderson, Hansen, & Kahle, 2010). Yet with low awareness among potential end users of ECWPs, unreliable availability, and premium pricing, there have been few monetary or functional incentives for architects to specify ECWPs (Ganguly, Eastin, & Rabotyagov, 2008; Irland, 2007). Residential GBPs offer an incentive for architects and builders to specify ECWPs by awarding green building points for their use in construction projects.

1.2.2 Certified Wood Programs

There are three prominent forest certification standards in the U.S.: the Forest Stewardship Council (FSC), the Sustainable Forestry Initiative (SFI), and the American Tree Farm System (AFTS). Whereas FSC is a global certification program, SFI is focused on North American forests while ATFS was developed for small, non-industrial private forests. SFI is one of many national certification programs that are embraced under a global umbrella certification program known as the Program for the Endorsement of Forest Certification (PEFC). At the beginning of 2019, 65.9 million hectares of North American forests were certified under the FSC program, while 165.4 million hectares were certified under the PEFC program (FSC, 2019;

PEFC, 2019b). For PEFC, this represents 132 million hectares of forestland in Canada[1] and 33.4 million in the U.S.[2] These totals represent 33% of global FSC-certified areas and 54% of global PEFC-certified areas. As of 2019, PEFC has endorsed 44 national certifications in 49 countries worldwide with over 300 million hectares of certified forest land, while FSC is represented in 84 countries with almost 200 million hectares (FSC, 2019; PEFC, 2019b). Portions of these lands are certified by both the FSC and PEFC; 8.8 million hectares in the U.S. and 23.1 million hectares in Canada have dual certification as of 2018 (PEFC, 2019a). Certified wood is a substantial and rapidly growing source of wood used in residential construction since an increasing area of forestland in the U.S. is being voluntarily certified.

ENGOs introduced forest certification as a way for forest landowners and the forest products industry to assure customers that their products come from forests that are managed to the highest economic, social, and environmental standards (Cashore, Auld, & Newsom, 2003) Forest certification provided a framework for forest owners and governments to receive independent third-party oversight of their operations. Introduced in 1993, the Forest Stewardship Council (FSC) was the first international certification program. ENGOs have typically favored FSC certification over SFI because of the degree of stakeholder involvement (Gullison, 2003). Another important distinction for FSC is its global focus and adaptability to many forest types, whereas SFI is used only in the U.S and Canada (SFI, 2015) and thus focused on forests types and stakeholders in these regions.

Both FSC and SFI have two types of certifications within their programs. The first is forest management certification, which pertains to the responsible management of natural and planted forests. This certification also considers local wildlife, indigenous people, land rights,

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[1] Sustainable Forestry Initiative = 98.5 million hectares, Canadian Standards Association = 33.5 million hectares

[2] Sustainable Forestry Initiative = 26.0 million hectares, American Tree Farm System = 7.4 million hectares

and the protection of areas with high levels of conservation value (FSC, 2019; SFI, 2017). The second type is Chain of Custody (CoC) certification, which verifies how materials move through a wood-product manufacturers supply chain while maintaining identifiable markings that prove the material has been sourced from sustainably managed forests. The CoC certification assures customers of the origin of the materials they use, while also providing an ecolabel that indicates that certified materials are compliant with green building programs.

Chain of Custody certification can apply to an organization or a project. Organizations that process or sell forest products can choose to have their business and facilities certified to demonstrate compliance with public and private procurement policies (i.e. GBPs), thus demonstrating that their materials were sustainably sourced. Projects can have buildings or objects that are partially or completely made from sustainably certified materials (FSC, 2017; SFI 2017). Under CoC, forest product manufacturers can choose the type of label they place on their products depending on whether the product is made entirely from sustainably certified wood or contains a combination of certified and non-certified materials. These non-certified materials must be obtained from a "controlled source" (i.e. a managed forest with legally sourced materials).

The benefits of ECWPs go beyond contributing to the responsible management of forestlands and the environment. Increasing the use of wood in homes also provides aesthetic benefits, while utilizing a renewable and recyclable material that can improve energy efficiency and promote energy savings. Since wood is one of the primary materials used in residential home construction, builders should be more conscious of its use by sourcing it from sustainably managed forests. However, research indicates multiple impediments to increased use of ECWPs, such as price; Vlosky and Ozanne (1998) showed that most customers are not willing to pay the price premium associated with ECWPs. Certain non-market-based incentives (e.g., GBPs) may provide a bridge to the increased utilization of ECWPs and help offset their higher cost.

1.2.3 Green Building Programs

Green building programs in the U.S. were developed to increase the energy and water efficiency of buildings while reducing waste from daily operations. The United States Green Building Council (USGBC) created the Leadership in Energy and Environmental Design (LEED) program in 1998 to provide a method of rating buildings based on a set of measurable design criteria. LEED was implemented in reaction to the fact that the majority of natural resources and energy in the U.S. was used to construct and operate buildings, both residential and nonresidential. The USGBC estimates that 13% of potable water and 72% of electricity consumption is from building operations, which constitutes 39% of total CO_2 emissions (USGBC, 2017).

LEED for Homes is a sub-category of LEED that focuses on residential construction projects. There are certain prerequisites that every building needs to meet to achieve a specific certification level (e.g., Certified, Silver, Gold, and Platinum); LEED for Homes, like many of the other LEED programs, is comprised of six major credit categories: Location and Transportation, Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality, plus additional points for Innovation and Design and Regional Priority Credits.

The National Association of Home Builders has also developed a residential GBP called the National Green Building Standard (NGBS), which generates credits at the levels of Bronze, Silver, Gold, and Emerald. Several significant differences exist between LEED for Homes and NGBS in regard to the number of points allowed for meeting requirements, especially the use of

ECWPs. While NGBS accepts the use of ECWPs that have been certified under all third-party certified forest product programs, LEED for Homes only recognizes wood products certified under the FSC program[3]. Under v4.1 of the LEED certification program, an alternate compliance path allows a point to be awarded for wood certified under other standards (e.g., SFI) if the wood complies with strict criteria (SFI, 2016), though this is a pilot project and has not been adopted into standard practice. The exclusion of non-FSC programs has contributed to the constrained supply of certified wood that has limited the adoption and utilization of certified wood in green buildings (Irland, 2007). The constrained supply of FSC-certified wood and long lead times could continue to limit the use of certified wood by architects and green builders (Germain & Penfield, 2010).

Many home developers have noted that certification helps attract buyers and renters because of a growing interest in sustainable lifestyles (McCormick, 2008). A 2009 study by McGraw Hill reported that certified homes generated 3.5% higher occupancy rates and 3% higher rental rates than conventional structures and generated a 6.6% higher return on investment. Since builders that survived the downturn in the housing market focused on building multi-family and custom homes, current builders could try to differentiate themselves by implementing green building materials and design methods for these particular housing segments. Additionally, architects who design with a “green” focus may receive additional market opportunities due to more informed, environmentally aware home buyers and market expectations for the next generation of new homes. Despite the continuing slowdown in residential construction, a movement toward green construction techniques and materials

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[3] This is being revised for the newest version of the LEED for Homes (v4.1) program to allow the use of forest products under other certification standards but requires additional auditing by the USGBC to be an approved equivalent. It is not clearly stated that SFI or others standards are distinctly approved programs (USGBC, 2019b).

persists, even if buildings are not directly seeking certification. One incentive is increased energy savings for homeowners who implement green construction in their current homes or in new homes. The increase in green construction can be attributed to a number of factors including the public's growing awareness of green practices, an increase in government interventions, and recognition of bottom line cost advantages (R. Vlosky, Gazo, Cassens, & Perera, 2009).

1.3 Theoretical Constructs

There are overarching themes throughout this research that are utilized as particular theoretical constructs. These constructs have been well developed in marketing research and provide insight into forest product markets. The three main theoretical constructs that will be discussed at length in the following chapters are:

1. Market Orientation
2. Adoption of New Products and Technologies
3. Willingness to Pay

These theoretical constructs provide insight into an architect's decision to use or not use green building programs and environmentally certified wood products. With respect to market orientation, are there inherent psychographic orientations that influence architects' perceptions of materials and therefore influence the types of materials they specify? Do environmentally oriented architects allow that focus to influence their material specification decisions? Based on these orientations, can we identify groups of architects who are more likely to use GBPs and ECWPs? With respect to willingness to pay, it may be as simple as a financial perception (e.g., the perceived costs) of ECWPs that outweighs their environmental benefits. Finally, can analyzing the adoption process for GBPs and ECWPs reveal which factors seem to influence their use (i.e. demographics, material preferences and attributes, and willingness to pay)?

1.4 Research Objectives

The purpose of this study is to comprehensively analyze a survey of architects in the United States to examine their perceptions and use of residential GBPs and ECWPs. These exploratory findings are discussed in Chapter 2 and are the foundation for further hypotheses testing.

The following chapters address three main research objectives as discussed in Chapters 3 and 4 along with the three theoretical constructs to gather a focused assessment of architects and their relationship with environmentally aimed programs and products. The research objectives of this dissertation are:

1. To discover if differences exist between architects that use programs and products that are “green,” and to determine if architects have particular market orientations and thus can be segmented into groups that are more likely to participate in GBPs and specify ECWPs.

2. To develop a prediction model of architects who use GBPs and ECWPs based on various demographic and psychographic attributes or economic barriers.

3. To identify architects’ environmental perceptions of building material attributes in the context of a home’s structural components (wood, steel, and concrete). If their perceptions do differ, then supporting evidence derived from a quantitative life cycle assessment is necessary. A comparison of materials used in typical residential construction (e.g., wooden glued laminated beams (glulam), steel beams, and reinforced concrete beams) is an example of a functional unit analysis that impacts the environment via extraction, manufacture, transportation, and installation.

1.5 Research Questions

The following research questions are discussed in detail in the appropriate chapters based on a comprehensive analysis of the survey data (Chapter 2). Chapter 3 uses survey findings to address particular questions regarding architects' market orientations, segmentation, and their participation in residential GBPs and specification of ECWPs.

- Do architects have particular market orientations in regard to their selection of building materials (economic, social, or environmental)?
- Do architects have differing perceptions of building materials based on specific environmental attributes (e.g., energy efficiency, recyclability, or energy use during manufacturing)?
- Do architects have preferences for innovative building products that influence their adoption of GBPs and ECWPs?
- What factors influence architects' adoption of GBPs and ECWPs?
- Are there factors that limit the use of ECWPs and residential GBPs?
- Are there associations between the use of residential GBPs and the use of ECWPs?
- Are there similarities within groups of architects with varying levels of ECWPs use?

Chapter 4 explores architects' environmental perceptions of specific building materials and then determines if those perceptions are valid based on a comparative life cycle assessment of three common building materials.

- What are architects' environmental perceptions of different building materials and do similarities exist between architects with comparable material perceptions?
- Do the environmental impacts of building materials made from wood, steel, and concrete differ when they perform identical functions within a residential home?

The following hypotheses will be tested within each chapter to reach conclusions on the main research questions of this study.

1.6 Hypotheses Development

A unique opportunity exists to compare factors that influence architects to adopt residential GBPs and ECWPs. Architects could have varying market orientations based on the material attributes they prefer in their selection of building products. A previous study by Koebel, Papadakis, Hudson, and Cavell (2004) identified possible reasons for adopting innovative products in the construction industry stemming from their technical and economic attributes. Architects that specify environmentally friendly materials and are aware of the importance of energy-saving and low-carbon-emission materials are already meeting some of the requirements of a green building. Environmentally oriented architects should be more inclined to participate in GBPs if they are already implementing products that would qualify toward a home certification. There is a belief that architects are environmentally conscious when specifying construction materials (Wagner & Hansen, 2004b) and therefore could be incentivized to use GBPs and/or ECWPs. The adoption or implementation of GBPs should be easier for these types of architects. Chapter 3 analyses these factors and establishes if different types of market orientations exist for architects.

H1: Different market segments of architects exist who are more likely to utilize GBPs

H2: Different market segments of architects exist who are more likely to utilize ECWPs

Chapter 3 will also model the adoption behavior of architects to determine which variables influence the use of GBPs and certified wood. Thompson et al. (2010) have shown that psychographic and demographic variables are connected to environmentally conscious consumer behavior. By utilizing both types of variables from the survey, a model can be developed to identify the factors that significantly influence architects who are more likely to use residential GBPs and ECWPs.

Firm size influences the adoption and diffusion of innovations within the construction sector. Many empirical studies have found that firm size has a positive effect on the likelihood of environmental actions (Ganguly, Koebel, & Cantrell, 2010; Nishitani, 2010). A study by Hassell et.al. (2003) described the advantages that large homebuilders have in the adoption of innovations based on the capital, talent, and market advantages of the firm, but Koebel et.al. (2006) argued that large builders can be constrained by shareholders and the need to minimize their risks. Slaughter (1993) revealed that smaller firms were a source of innovation with the homebuilding industry, while a different study showed that large builders' access to capital allowed them to be more innovative in their buildings (Eastin, Shook, & Fleishman, 2001). Another study showed that small homebuilders make smaller incremental changes with the products they specify, but are more likely to listen to their customers' needs and assess their attitudes and willingness to pay for environmentally friendly homes (Koebel, Papadakis, Hudson, & Cavell, 2004).

There are many independent architects who design only a few custom homes a year, while some architects work for large firms and design many similar or specified homes. In trying to relate firm size to architects in this study, those who work for a firm or a larger organization (e.g., homebuilder) were labeled as "firm" versus architects who work for themselves as "independent." For client type, architects that work directly with homeowners are likely working on homes that are heavily customized compared to an architect that works with homebuilders and there may be more constraints on the home design. Measuring architect firm size could show similar results to studies of homebuilders.

H3a: Independent architects are more likely to utilize GBPs

H3b: Architects who work with directly with customers are more likely to utilize GBPs

More experienced firms have extensive social and professional networks, consisting of other competitors, suppliers, architects, and government officials, which may increase their awareness of and willingness to use residential GBPs and/or ECWPs. However, the general belief is that younger individuals care more about environmental issues. There are numerous theories that support this belief; the most common is that those who joined the profession when environmental concerns were a salient issue are more likely to be sensitive to these issues (Straughan & Roberts, 1999).

Though age studies are far from conclusive, there is reason to believe that firm experience is a relevant a factor, since greater years in business give a firm a higher likelihood of participating in a green building project or specifying ECWPs. Experience could also be linked to continuing education via additional training and seminars, but this variable was not a focus of this research.

H3c: Architects who have been in business longer are more likely to utilize GBPs

Area of residence correlates with architects' concern about the environment (Hounshell & Liggett, 1973; Samdahl & Robertson, 1989; Zimmer, Stafford, & Stafford, 1994). With the exception of Hounshell and Liggett, these studies show a positive correlation between architects practicing in urban/suburban areas—rather than small cities or rural areas—and their likelihood to have environmental concerns.

H3d: Architects who conduct business in urban/suburban areas are more likely to utilize GBPs

McGraw Hill (2012) reports that opportunities for green home construction vary based on region, with the highest in the Pacific (AK, CA, HI, WA, OR) and West North Central (IA, KS, MN, MO, NE, SD, ND) regions. Materials and construction styles vary by region (Emrath, 2010; Indroneil Ganguly & Eastin, 2007; Shook & Eastin, 2001), which could indicate areas of the country with higher likelihoods of using residential GBPs. For example, Ganguly and Eastin (2007) found builder awareness of certified wood was significantly higher on the West Coast.

H3e: Regional differences exist between architects who are more likely to utilize GBPs

An architect's participation in a residential GBP could indicate their future participation in additional residential GBPs. This initial experience could have a positive effect because they have been through the process before, or a negative effect if that experience was burdensome or time consuming.

H3f: Architects who have participated in other green building programs are more likely to utilize GBPs

Similar hypotheses to those related to GBPs will be tested to determine the variables in architects' decisions to use ECWPs.

H4a: Independent architects are more likely to utilize ECWPs

H4b: Architects who work directly with homeowners are more likely to utilize ECWPs

H4c: Architects who have been in business longer are more likely to utilize ECWPs

H4d: Architects who conduct business in urban/suburban areas are more likely to utilize ECWPs

H4e: Regional differences exist between architects who are more likely to utilize ECWPs

H4f: Architects who have participated in other green building programs are more likely utilize ECWPs

Architects that have participated in a residential GBP will have already decided whether to utilize ECWPs to obtain green building points toward a home's certification. Determining if a link between GBPs and ECWPs exists will help develop the adoption model in this chapter.

H5: Architects who have participated in a residential GBP are more likely to specify ECWPs

While not required to get a building certified as green, homes that use ECWPs might be specified by environmentally oriented architects that realize their environmental benefits and the market value of their eco-label with minimal or no difference in cost. In addition, a preference for other environmentally conscious building products (i.e. solar water heating, solar electricity generation, etc.) could indicate an architect who is more progressive in their selection of certified building materials. Architects who rate the environmental attributes of wood-based building materials higher than steel or concrete could be more likely to specify ECWPs since they already understand the benefits of designing with wood.

H6a: Environmentally oriented architects are more likely to utilize GBPs

H6b: Innovative, technologically oriented architects are more likely to utilize GBPs

H7a: Environmentally oriented architects are more likely to utilize ECWPs

H7b: Innovative, technologically oriented architects are more likely to utilize ECWPs

H7c: Architects who rate the environmental attributes of wood highly are more likely to utilize ECWPs

Even though specific price premiums for ECWPs have not been shown, other influences, such as restricted supply, could make ECWPs more difficult to acquire (Gullison, 2003). Willingness to pay (WTP) studies show that consumers have historically been unwilling to pay price premiums for certified products (Cai & Aguilar, 2013; Ozanne & Vlosky, 2003), but architects who have a greater understanding of certification labels may differ. More recent research has argued that substantial premiums do not exist on certified wood and therefore should not factor into their use (Tuppura, Toppinen, & Puumalainen, 2016). Architects may vary in what they are willing to pay for ECWPs to achieve the few subsequent green building points and may feel the need to pay a small premium to differentiate their firm as environmentally responsible.

H8: Architects are less likely to specify ECWPs because of their higher prices

Similarities may exist between frequent users and occasional users of ECWPs; the variables that determine these similarities could provide insight into drivers that control group membership. Following these analyses will be an objective comparison of the differences between users of SFI and FSC ECWPs, as well as differences between users of LEED for Homes and the National Green Building Standard.

H9: Similarities exist within groups of heavy users and light users of ECWPs

Chapter 4 will discuss architects' underlying environmental perceptions of the three primary building materials utilized in home construction (wood, steel, and concrete). It will be determined if architects have differing perceptions when only accounting for these materials' environmental attributes and if similarities exist within these different groups of architects.

H10: Similarities exist within the group of architects who rate wood-based materials as having lower environmental impact than steel and concrete

Architects' perceptions of these materials may vary, yet quantifiable data of these differences was not available until recently. By conducting life cycle analyses, we can determine the environmental impacts of the production, transport, use, and ultimate end-of-life scenario of various building materials. The environmental footprints of the three primary building materials will be compared from cradle-to-installed in a life cycle assessment based on a functional unit analysis for each material. For this research, a wooden glulam beam will be compared with steel and concrete beams. Evidence from these analyses will help determine whether differences exist between the three materials when compared on a functional unit basis.

H11: The environmental burdens of the production and transportation of wood, steel, and concrete beams vary based on functional unit design scenarios.

1.7 Dissertation Outline

The results of this research are presented in Chapters 2-4, each of which has or will be submitted for publication in academic journals. Chapter 2 provides an exploratory overview of survey results and a summary of important findings. A portion of this chapter was published in *The Forestry Chronicle* (Bowers et al., 2014). A more comprehensive analysis of the overall survey will be published in a future CINTRAFOR working paper. These works identify links between users of residential GBPs and ECWPs and significant demographic factors that contribute to their awareness and use.

Sections of Chapters 3 are informed by the preliminary findings presented in Chapter 2. This chapter develops a model of demographic and psychographic endogenous variables that determine use of GBPs and ECWPs to test hypotheses (***H1***) through (***H9***). The model predicts users and non-users of residential GBPs and ECWPs and assesses similarities within these user groups. An article describing this analysis is being prepared for submission to the *Forest Products Journal*.

The results from the LCI update on glued-laminated timber (glulam) was recently published in the *Forest Products Journal* (Bowers, Puettmann, Ganguly, & Eastin, 2018). These results will be utilized in Chapter 4 for further analyses in a comparative LCA. As the next generation of residential GBPs requires transparency regarding the environmental impacts of individual building materials, a life-cycle impact assessment will provide necessary data to assert a product's environmental friendliness (***H10 & H11***). In this case, the functional unit utilizing the recently published LCI data of a glulam beam will be compared with a steel beam and precast concrete beam in an identical use scenario.

2. Architects' Use of Residential Green Building Programs and Environmentally Certified Wood Products

Submission Information

A portion of this chapter has been published in *The Forestry Chronicle*, a peer-reviewed journal focusing on forestry, management, and forest products. It provides forest practitioners in Canada and around the world a means to communicate with their peers in the professional community.

Overall survey results will be presented as a CINTRAFOR working paper and distributed as a resource for the forest products community and others looking for further information on this subject.

2.1 Forest Certification Programs

Throughout history, humans have utilized readily available forest materials to provide protection from animals and the weather. As technology and innovation advanced towards modern tools, the processing of wood became easier and more efficient. The use of timber and poles allowed for stable, long-lasting structures and for interior spaces to grow in size. Basic forest harvesting practices also evolved as the integration of mechanization progressed, yet these practices also damaged forest ecosystems and disrupted flora and fauna. Past management of forest ecosystems in heavily forested areas like western Washington and Oregon, and other regions of the country that relied on forest products for their livelihood, helped create the need to implement forest management standards that considered the non-timber elements of the forest. Forest certification standards were therefore developed by various stakeholders, implemented by forest managers, and verified by independent third-party agents to encourage sustainable forest management practices. These practices were originally developed to address concerns about biodiversity loss and tropical deforestation (Rametsteiner & Simula, 2003), but have since been adapted to other types of forest biomes.

Lingering concerns from the continued deforestation of the tropical rainforests led to a global discussion of ways to protect diminishing ecosystems. The Tropical Forest Action Plan developed by the FAO (Food and Agriculture Organization, 1985) reported the dangers and long-lasting damage of deforestation to the fragile ecosystem of tropical rainforest and proposed a plan to protect these forests, which were disappearing at an alarming rate (Perera & Vlosky, 2006). During the 1992 Conference of Environment and Development (UNCED), the United Nations discussed the possibility of a global forest agreement (Humphreys, 1996). While the discussed principles were non-binding, there was little consensus on how to balance conservation and use of the forests (Humphreys, 1996), thus certifying sustainably managed forests became an alternative. Under certification standards, ENGOs would be able to establish the criteria for conserving forestlands, while allowing protocols for the sustainable use of forests (Nussbaum & Simula, 2013). The certification programs needed to be established with the input of numerous stakeholders to get an overarching system of guidelines. While other previous policies, such as log export restrictions, did little to address the issue of deforestation, certifying forests as sustainably managed was envisioned to be more effective in reducing deforestation rates, without being a barrier to trade (Sasatani, Ganguly, Eastin, Chen, & Bowers, 2015).

Currently, there are over 50 certification programs around the world that address various types of forests in specific regions. In the United States, there are three prominent forest certification standards: the Forest Stewardship Council (FSC), the Sustainable Forestry Initiative (SFI), and the American Tree Farm System (AFTS). Whereas FSC is a global certification program, SFI is focused on North American forests while ATFS was developed for small, non-industrial private forests. Most North American forests are certified under one of the programs listed in Table 2-1. Globally, the Programme for the Endorsement of Forest Certification (PEFC) has the largest amount of forest lands certified under its umbrella because it recognizes pre-existing national and regional programs that are currently active in North America like SFI, AFTS and the Canadian Standards Association (CSA), whereas FSC chooses to remain an independent entity with no reciprocity with other forest certification programs.

Table 2-1 Major Certification Programs Used in North America

Abbreviation	Full Name	Founded	Location	US	Canada	Land Certified (Hectares)
FSC	Forest Stewardship Council	1993	Denmark	Yes	Yes	65.9 million
SFI	Sustainable Forestry Initiative	1994	US/Canada	Yes	Yes	124.5 million
ATFS	American Tree Farm System	1941	US	Yes	No	7.4 million
CSA SFM	Canadian Standards Association	1996	Canada	No	Yes	33.5 million
PEFC	Programme for the Endorsement of Forest Certification	1999	Switzerland	Yes	Yes	165.4 million

Instituted in 1993, the Forest Stewardship Council (FSC) was the first international certification program to provide a framework for establishing the criteria for certifying sustainable forest management (FSC, 2019). Prompted by environmental NGOs, different stakeholders such as suppliers, manufacturers, landowners, retailers, and environmental organizations assembled to create the original framework of the FSC program (Klooster, 2005). The participants represented a wide variety of social, environmental, and economic interests with the goal of achieving an equal balance of voting rights from each sector (Auld, Gulbrandsen, & McDermott, 2008). This framework provided the processes and training of agents that would allow FSC to be an oversight body (Scrase, 1995). The FSC program follows ten broad principles that allow for compliance to local laws, application of sustainable forest management practices with biodiversity protections, involving indigenous communities and culture within management plans, and support for local workers (FSC, 2018).

In contrast, the Sustainable Forestry Initiative (SFI) was an industry-backed program developed by the American Forest and Paper Association in 1994. SFI is one of many localized certification schemes embraced by a global umbrella certification known as the Programme for the Endorsement of Forest Certification (PEFC). SFI was endorsed by the PEFC in 2005 and became an independent non-profit organization in 2007. PEFC, founded in 1999, endorses national and regional certification systems like SFI that comply with its guidelines. National forest certification programs that hope to be recognized by PEFC need to meet the standards of ISO/IEC Guide 59:1994 Code of Good Practice (PEFC), 2018). As mentioned in Chapter 1, mutual recognition between PEFC and FSC wood products has not been achieved because FSC distinguishes between plantations, semi-natural forests, and natural forests and applies different standards and protocols to each. Perhaps more importantly, FSC is highly critical of the forest industry’s involvement in the SFI organization.

PEFC does not directly certify forest lands in North America, but instead relies on local or national certifications. In the United States, PEFC-US consists of two certifications, SFI and the American Tree Farm System (ATFS) (PEFC, 2018). SFI promotes management principles that value social, economic, and environmental entities, which make up the constituency of its board of members. Most of the certified structural wood products harvested from U.S. forest lands are certified by SFI, making it the largest program in the country. The other, older U.S.-based certification program is the American Tree Farm System (ATFS), a family forest certification program that focuses on small, non-industrial private forests. Established in 1941, ATFS differentiates itself from the other certification programs by implementing forest management plans that are specific to the size and silviculture intensity of each particular tract of privately-owned timberland (American Tree Farm System, 2018).

Mandatory regulations imposed by governments and international associations regarding forest management may not incentivize producers and manufacturers to abide by the rules, whereas environmental certifications of wood products encourage sustainable forest management with market-based incentives. A voluntary market-based system like FSC or SFI assumes there is a market preference for environmentally friendly products certified by independent commissions that are providing a framework to protect forest environments (Upton & Bass, 1996). Van Kooten et al. (2004) suggested that forest certification sought to address the improper use or exploitation of the forests through regulations enforced by the market by either a premium for certified products or threat of consumer boycotts. The effectiveness of a particular certification system is based on consumer trust, system monitoring of sustainable management, and the provided advantages of market access for suppliers (van Kooten, Nelson, & Vertinsky, 2005). Third party certification of sustainable forest management practices assumes that customers are willing to pay a premium for wood products from sustainably managed forests, even though research does not indicate discernable price premiums in the marketplace (Marx & Cuypers, 2010; Tuppura et al., 2016; van Kooten et al., 2005). Even though most certification programs are widely accepted, there is still some question of their effectiveness in achieving sustainable forest management (Auld et al., 2008; Clark & Kozar, 2011).

2.2 Environmentally Certified Wood Products

Environmentally certified wood products (ECWPs) come from sustainably managed forests under any of the officially recognized programs. U.S. wood typically comes from either

FSC, SFI, or ATFS certified forests; wood is also occasionally designated or labeled as being certified by the PEFC, but this material has adhered to the principles of one of the regional certification standards. FSC has two types of certifications that it oversees: a forest management certification, which pertains to the responsible management of forests and forest plantations and considers local wildlife, indigenous people, land rights, and the protection of forests of high conservation value (FSC, 2019); and a Chain of Custody (CoC) certification, which verifies materials' progress through a wood product manufacturer's supply chain while maintaining identifiable markings that prove the material has been sourced from sustainably managed forests. The CoC assures customers of the origin of the materials they use while also providing an ecolabel that qualifies the material as compliant with a green building program.

CoC can apply to an organization (business, etc.) or a project. Organizations that process or sell forest products can choose to have their business and facilities CoC certified to demonstrate compliance with public and private sector procurement policies (i.e. GBPs), thus advertising that their materials were sustainably sourced. Projects can have buildings or objects that are completely or partially made from FSC-certified materials (FSC, 2017). Under CoC, forest product manufacturers can choose the type of label they place on their products depending on whether the product is either entirely from FSC-certified forests or contains a combination of certified and non-certified materials. These non-certified materials must be obtained from a "controlled source" (i.e. a managed forest with legally sourced materials).

The FSC 100% label signifies that the wood used in a product consists entirely of FSC-certified material. The FSC Mix label is a hybrid product that contains a combination of certified and non-certified materials; the non-certified forest material must be from a "controlled" source. The FSC Mix label was initially developed in reaction to an insufficient supply of wood from certified sources in tropical forests to meet production demands (FSC, 2017). The mix of FSC-certified wood and “controlled wood” must meet two requirements. The first is that material cannot be from one of five “unacceptable” categories: 1. Illegally harvested wood 2. Wood harvested in violation of traditional and human rights 3. Wood from forests with high conservation values (HCVs) that are worthy of protection 4. Wood from forests being converted to plantations or non-forest use 5. Wood from genetically modified trees (FSC, 2017). The second requirement is that the forest management enterprise that oversees the procurement of the forest product during harvest and processing can prove the material is from acceptable sources. This can be done with proper documentation referencing the product description, quantity, name of buyer, date of invoice, shipping information, and a specific certification code from an FSC-certified organization (e.g., PEFC). This allows for the controlled wood to be tracked through the supply chain like typical FSC-certified materials. Approximately two-thirds of FSC-certified wood is used in remanufactured or value-added products, like flooring or millwork, but some is also utilized for dimension lumber and structural panels.

SFI also has two main certification types. The first is the forest management standard, which is similar to the FSC standard that promotes sustainable forest management with specific conservation requirements. It also has the CoC certification that tracks forest products through the many stages of the supply chain. SFI uses three methods to track certified wood and communicate forest fiber content: physical separation, average percentage, and the volume credit method (SFI, 2017). These methods allow for consumer assurance that raw materials follow the proper channels to verify that they are derived from certified sources. Beyond the physical separation method, companies can streamline the process by

1. Using an average percentage method which allows manufacturers to label all their products as “SFI-Certified Chain of Custody” as long as at least 70% of the wood/material is composed of certified forest content. If it does not meet this threshold, the material must be labeled without the “Promoting Sustainable Forestry” verbiage and disclose the actual percentage of certified content.
2. Under the volume credit method, an organization can only claim or use the SFI label on the amount of certified forest content that is processed through their system. Then they can make claims or label that percentage of their output.

The physical separation and volume credit methods are consistent with all global supply chain standards and can be documented as such. Both FSC and SFI standards must be verified through independent third-party certification protocols before presenting labels or claims to the purchasing body or end customer. This documentation and labeling allows ECWPs to receive points in various green building programs.

2.3 Residential Green Building Programs

Building with respect for the environment is an ancient concept centered around using renewable materials from nature and incorporating natural light and fresh air. As durability and longevity became crucial to construction methods, man-made materials and designs suppressed the amount of air, light, and water entering a structure, leading to cold, damp buildings with ineffective airflow that negatively affected human health. More recently, “green” building methods have utilized resources like water and electricity more efficiently and allowed for higher quality indoor environments with fresh air and ample sunlight. The implementation of these features starts with design and continues throughout construction, daily operation and maintenance, renovation, and eventually demolition.

The United States Green Building Council (USGBC) created the Leadership in Energy and Environmental Design (LEED) in 1998 to provide a method of rating buildings based on measurable design criteria. It was implemented in reaction to the fact that the majority of natural resources consumed in the U.S. were from daily building operations. The USGBC says 13% of potable water and 72% of electricity consumption are from building operations, which constitute 39% of the total CO_2 emissions (USGBC, 2017). Launched in 2008, LEED for Homes is one of the sub-categories of LEED that focuses on residential construction projects; the program certifies single-family and low-rise, multi-story/family structures. If a structure is six stories or more, it must adhere to the larger scale LEED Building Design and Construction Guidelines (BD+C). There are different building certification levels with varying requirements: Certified, Silver, Gold, and Platinum. LEED for Homes, like many of the other LEED programs, is comprised of six major credit categories: Location and Transportation, Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, and Indoor Environmental Quality, plus additional points for Innovation and Design and Regional Priority Credits (USGBC, 2017). LEED for Homes also requires that all residential projects meet the Energy Star standard and performance criteria. Ongoing audits must be performed to verify that a building is operating to the design requirements of its certification level through third party utility reporting, particularly for energy and water consumption (USGBC, 2017).

The National Association of Home Builders (NAHB) also has a nationwide residential green building program called the National Green Building Standard (NGBS). In 2007, a partnership between the NAHB and the International Code Council (ICC) developed a green building standard that was accepted and accredited by the American National Standards Institute (ANSI) for all residential construction projects, given the code ICC-700. The standard encompasses not only multi-family and single family construction, but also remodeling and land development certifications (NAHB, 2019b). The NGBS certification includes high- and low-rise apartments and condominiums and residential units in mixed-use buildings (commercial and residential). Like LEED for Homes, certification is tiered. NGBS has four levels of certification: Bronze, Silver, Gold, and Emerald, with Emerald being the highest achievement. In addition to mandatory measures, points are accrued through six main categories: lot design and development, water efficiency, energy efficiency, resource efficiency, indoor environmental quality, and homeowner education. NGBS is a general code of green building practices that municipalities can use to develop their own local green building program. An online scoring tool and guidelines for having third-party verification facilitate compliance with the NGBS program. Performance testing is generally optional but is required if the homeowner is looking to acquire Energy Star certification to qualify for other subsidy programs.

Several significant differences exist between LEED for Homes and NGBS in terms of how points are awarded in the different categories, especially regarding the use of ECWPs. NGBS accepts the use of ECWPs that are certified under all third-party certified forest product programs, including SFI, ATFS, CSA SFM, FSC, and PEFC, and makes the provision of accepting other certified wood products under “other such credible programs as they are developed and implemented.” In contrast, LEED for Homes does not accept ECWPs unless they have been certified by the FSC program, with the caveat of “another USGBC approved equivalent” (for which there is none at this time) (USGBC, 2019). Hence, under the LEED certification program, no points are awarded for homes built using ECWPs certified under most of the sustainable forest management programs used in North America[4]. V4.1 of the LEED certification program offers an alternative compliance path which allows a point to be awarded for wood certified under other standards if the wood complies with strict criteria (SFI, 2016): 100% of forest products from legal sources, 70% from responsible sources, and the remainder must be CoC certified (SFI, 2016), but this is not standard practice. Past exclusion of non-FSC programs was largely responsible for the constrained supply of certified wood that limited the adoption and diffusion of certified wood in green buildings. Availability issues continue today due to long lead times (Irland, 2007), and the constrained supply of FSC-certified wood could continue to limit the use of certified wood by green builders (Germain & Penfield, 2010) in the future. Knowles et al. (2011) noted that architects had problems designing large wood-framed buildings because of difficulties sourcing adequate supplies of FSC-certified wood. The FSC has tried to address this ongoing issue by providing new mixed-source labels for lumber that contains a mix of FSC and non-FSC woods. As of mid-2011 (the time of this study), there were more than 12,000 (single and multifamily) housing units certified by LEED for Homes and approximately 6,000 (single and multifamily) housing units certified by NAHB. The current number of units certified under each program include 18,020 single-family homes and 123,206 multifamily units under LEED for Homes, and 14,980 single-family homes and 147,983 multi-family units (from 4,280 buildings) under NGBS (Home Innovation Research Labs, 2019; USGBC, 2019a). These numbers include high rise apartments and condominiums under NGBS; structures over six stories do not use LEED for Homes and instead abide by regular Building Design and

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[4] This is being revised for the newest version of the LEED for Homes (v4.1) program to use forest products under other certification standards but requires additional auditing by the USGBC to be an approved equivalent. It is not clearly stated that SFI or others standards are distinctly approved programs (USGBC, 2019). .

Construction guidelines. If high-rise residential units under LEED were added to this total, it is estimated the total number of certified units would be well over 300,000 (USGBC, 2018).

The use of ECWPs is optional in both of these green building programs, and the total number of points available for the use of certified wood is specified within LEED for Homes's materials and resources chapter, and in NGBS's resource efficiency chapter (USGBC 2017; NAHB 2019). The various ways points are attained by using environmentally certified wood products differ within each building standard. LEED for Homes gives points for compliant building components (roof, floor, walls, etc.) that are made from 90% FSC-certified materials by weight or volume. Homes can receive 0.5 points per item for a maximum of 4 points for single-family homes and 5 for multifamily (mid-rise). Additional credits toward this maximum can be gained for components that are extracted, processed, and manufactured locally (within 100 miles), yet this is worth just 0.5 points per component and only available to those regions of the country where structural lumber is produced. Wood that is tropical of origin is required to be FSC-certified or reclaimed. To meet each certification threshold there needs to be prerequisites met in the six main LEED categories. ECWPs maximum of 4 points can help a single-family home to achieve the minimum thresholds for each certification level: 40 points for a rating of Certified (10% possible from ECWPs), 50 points for Silver (8%), 60 points for Gold (6.7%), and 80 points for Platinum (5%).

As part of the ANSI/ICC-700 2012 (with 2015 revisions)-recognized National Green Building Standard, ECWPs can earn green building points in two ways: the first is under Section 606.2(1), in which a minimum of two certified wood-based products are used for non-structural elements of a building (such as the trim, cabinetry, or millwork); the second is under Section 606.2(2), in which structural wood-based products are used in at least two major elements (roof, floor, etc.) of the project. These products can be certified by ATFS, CSA, FSC, PEFC, SFI, the National Wood Flooring Association's Responsible Procurement Program (RPP), other programs endorsed and recognized by PEFC, and NGBS-certified products (GCP) that adhere to the requirements of any of the approved forest certification programs. Up to 7 points can be gained from using ECWPs under NGBS, with additional points (up to 3) available as one of the bio-based materials in a structure's total building material costs. While not specific to ECWPs, further points can be gained within the resource efficiency category when materials under 606.3—which are manufactured with 33% energy from renewable sources, combustible waste sources, and/or renewable energy credits (RECs)—are used for the major components of the building. This is common with structural wood products since most lumber processing facilities reuse scrap and waste wood for heat and steam energy in a boiler. Submitting a Products Declaration—which entails the environmental impact of a product compared to another product intended for the same use—can also earn further points. This declaration can be achieved through life cycle assessment protocols and combined with other building materials or products to achieve additional points for practice Section 611.4.

Each category in NGBS must meet the minimum points for certification for a building to achieve an overall certification level (e.g., a Bronze-certified home achieves points at the Bronze level for every category), thus ECWPs' impact on points is relevant only to the category in which they are housed. For the resource and efficiency category (Chapter 6), the range of points available for ECWPs (7 to 10) is dependent on its percent of a project's total material costs (0.5% of cost =1.5 points, 1% of cost = 3 points); the caveat is that another bio-based material (e.g., engineered wood) needs to be at those percentages of total material costs to receive all potential points under Section 606.1. ECWPs' percentage of points relative to points required for each level of certification are: 43 points for a rating of Bronze (16.3-23.3% possible from ECWPs), 59 points for Silver (11.9-16.9%), 89 points for Gold (7.9-11.2%), and 119 points for Emerald (5.9-8.4%). After meeting prerequisite point totals in each category, the hierarchy of certification levels in NGBS for an entire project are: a minimum of 231 points for Bronze, 334 for Silver, 489 for Gold, and 611 for Emerald (NAHB, 2019b). Though there is not a significant number of points attributed to certified wood under either program (relative to the total number of points required to achieve each certification level), the use of ECWPs can provide a home with an additional eco-label for using certified wood. The ecolabel can be featured while marketing the home and therefore provide additional value to environmentally focused customers, and perhaps offer a price premium in environmentally sensitive markets.

The NGBS standard undergoes rigorous public review and meets the requirements of a true consensus standard as required by ANSI. NGBS fees are more affordable for builders since they are charged based on the number of lots, whereas LEED for Homes has a base application fee with additional charges based on acreage (community size), which can increase costs for larger home builders. NGBS requires more points to be earned in all categories (energy efficiency, water efficiency, resource efficiency, indoor environmental quality, site design, and homeowner education) to advance to a higher level or rating (e.g., a Silver NGBS home is better in every category than a Bronze). In LEED for Homes, additional points do not have to be achieved in all categories to reach a higher level of certification. A Gold-rated home can be achieved with only the minimum requirements for energy efficiency (which is the certified level) while the additional points needed can be acquired in other categories (NAHB, 2019b; USGBC, 2017).

While LEED for Homes and NGBS are the two most prominent residential green building programs in the U.S., other programs are used both nationwide and regionally. These other green building programs and codes have been implemented and accepted by builders and architects also looking to increase the environmental and health performance of buildings, sites, and structures, but follow criteria that may differ from the more widely known programs. Green Globes, a system administered by the Green Building Initiative, has a rating and certification program that mainly focuses on commercial and multi-family residential structures with an emphasis on water and energy savings and achieving a high level of recycling (Green Building Initiative, 2018). The International Living Future Institute's "Living Building Challenge" implements a certification system but does not rate structures. It advocates the design, operation, and construction of a building with the goal of improving its environmental and health performance. It also goes a step further by focusing on structures that are "restorative, regenerative, and an integral component of the local ecology and structure" (International Living Future Institute, 2018). The Living Building Challenge identifies 20 requirements to achieve full certification by an independent auditor, evaluating a structure's performance for twelve months to verify sustainable metrics. An extension of this is the recent Zero Energy Building (ZEB) program, which allows a project to demonstrate zero energy performance by harnessing energy from the sun, wind, and/or earth to meet its net energy demand (International Living Future Institute, 2018). The Passive House Institute has the voluntary Passive House (PHIUS+) program that measures the performance of a structure through an audit process. This program does not require but does emphasize the energy efficiency performance of windows, doors, and skylights relative to their impact on interior surface temperatures and thermal comfort (Passive House Institute US, 2018).

Beyond large national programs, there are regional and local green building programs that states and cities use to certify buildings. These programs differ in scope and purpose but many focus on the nuances of residential construction. Table 2-2 details some of the larger state-level home certification programs but is not a comprehensive list of all available programs in the U.S. Participation in other building programs could be a precursor for involvement with one of the two larger programs; this potential linkage will be investigated later.

Table 2-2 Major National Green Building Programs in the U.S.

Name	Agency	Region
Green Point Rated	Build It Green	California
Earth Advantage Certification	Earth Advantage	Portland, OR
Built Green	Built Green Washington	Bellevue, WA
EarthCraft	Southface	Atlanta, GA – covers southeast
Florida Green Home Certification Standard	Florida Green Building Council	Orlando, FL
Green Built Home	Wisconsin Environmental Initiative	Madison, WI
Green Built Homes	Green Built Alliance	Asheville, NC

Source: National League of Cities 2013

2.4 Research Methods

An online field study survey is the most cost-effective way to perform a nationwide sampling of practicing architects regarding their knowledge of green building programs and environmentally certified wood products. This study which was distributed for responses in 2011 employed multiple-choice, ranked lists, and preference queries to help answer research questions. Participants were asked to answer the survey completely to generate full responses for advanced quantitative analyses. The survey was designed to discover how architects rated the importance of different building material attributes, since these attributes could ultimately influence design decisions. Other questions in the survey assess architects' attitudes and preferences to specific energy-saving and environmentally friendly building materials typically found in residential green building programs. The scope of this research mainly focuses on the awareness and use of wood-based materials and residential green building programs, but additional questions provide further knowledge to help discern interesting phenomena in the adoption of "green" products.

There are inherent difficulties to getting completed surveys. Trying to collect responses from participants in certain industries is challenging since it is not always clear if the contact point is the correct person to be filling out the survey. Also, depending on the length of the survey, fatigue could result in incomplete surveys. It has been shown that it is hard to obtain a representative sample of builders/contractors; response rates have usually been around 10% (Eastin et al., 2001; Fell et al., 2003). Because of this dilemma, oversampling of respondents is necessary to achieve the required sample size for a study.

A 2011 online survey was utilized to collect information for this study, which allowed for a quick and cost-effective way to reach our target population. A web-based survey provides logically sequenced questions and permits respondents to only answer relevant questions. For example, if a respondent reports they have used a green building program, they would then be asked to rate the top three reasons for using it, whereas the survey program would automatically skip this follow-up question for a respondent who had not used a green building program. The survey also allows respondents to take a pause from the survey and resume where they left off, thereby helping to reduce survey fatigue. The survey was powered by Qualtrics (Qualtrics, 2011), a web-based survey software tool that records completed responses into a database as they are submitted.

2.4.1 Sample Subjects

Architects are one of the main material-specifying groups in the home construction process. Their designs help determine the materials specified from their blueprints. Architects are especially prominent in projects where there is intent to differentiate, like high-end condos, corporate headquarters, show rooms, etc. (Wagner & Hansen, 2004a). Kozak and Cohen (1999) found similarities between architects and civil engineers; both specify materials and designs and have similar job responsibilities in home construction. Builders are the next link in the chain and are responsible for procuring materials and constructing the building. This is the point when variables that determine material use differ (e.g., material availability) (Ganguly, Bowers, Eastin, & Cantrell, 2013).

Research has shown that architects are perceived to be environmentally conscious specifiers of construction materials (Wagner & Hansen, 2004b), and may be the customer group that considers a material’s environmental impact when making material selection decisions (Von Hippel, 1986). For structural products, Wagner and Hansen (2004b) saw that material availability and uniform quality were of the greatest importance to architects, with durability and environmental sustainability the next tier of importance. Architects differ regionally in regard to specifying environmentally sustainable structural products; the West Coast differed from the other three main geographical regions in the U.S. with a preference for more environmentally focused products (Wagner & Hansen, 2004a).

Damery and Fisette (2001) surveyed architects, contractors, and homeowners on their preferences for home siding product, comparing the reasons respondents selected a particular building material. The results were weighted toward appearance and performance as opposed to cost and personal recommendations. Wagner and Hansen (2004a) found that architects separate the wood products they specify in their designs into three different groups: structural, appearance, and engineered wood. Structural wood is classified as dimension lumber that is used to frame a home. Appearance grade wood is typically used for trim and moldings visible on the inside of a home and contain minimal knots and defects. Engineered wood is usually machine graded for its bending strength. Architects looking to utilize wood in multi-story and multi-family structures have the option of using Cross-Laminated Timber (CLT), but there is still a considerable amount of uncertainty regarding this product in the marketplace given its low level of awareness among architects (Mallo & Espinoza, 2015).

Turning to green building programs and the use of certified wood, architects have struggled with the lack of explicitly rewarding material reduction strategies with respect to structural systems (Knowles et al., 2011). Material reduction strategies can reduce the environmental footprint of a home by decreasing the embodied energy of the structure. While measuring the carbon footprint of a structure has gained popularity among designers and architects, there is a lack of accurate information on whole building environmental building declarations. However, Life Cycle Assessments (LCA) will help provide that crucial information for the next generation of building programs (Bowers, Puettmann, Ganguly, & Eastin, 2018). Most of the currently available information is inconsistent, particularly for materials like steel that have become more globalized due to large imports from China. Also, there are few, if any, comparable benchmarks to verify if a material is environmentally preferable to other available construction materials. This issue will be addressed in the next generation of GBPs as the transparency of a material’s environmental impacts will be available through environmental product declarations (EPDs). Properly conducted LCAs of various products’ impacts on the environment (global warming potential, eco-toxicity, acidification, etc.) will allow for accurate comparisons of construction materials for an entire building’s carbon footprint. Additionally, a building’s performance standards will be audited after its first year (USGBC, 2017).

Knowles et al. (2011) found that for architects, picking a structural system and then making it green are separate conversations. Knowles noted that architects had difficulty making large wood-framed buildings environmentally friendly because they were unable to procure enough certified materials. There were timing discrepancies between the availability of material during project planning and when the material was actually needed, and lag times of up to 24 months to order certified wood (Knowles et al., 2011). Architects are more aware of FSC-certified wood in the marketplace (Bowers, Ganguly, & Eastin, 2014), and have shown a preference for FSC-certified wood because the certification system was created by stakeholders, while SFI was created by the industry and still allowed for practices like clear-cutting (Knowles et al., 2011).

Other studies have looked at innovative products and strategies as they pertain to homebuilders who are a part of the same supply chain. Koebel and Cavell (2006) looked at builder characteristics and determined that larger nationwide builders were more likely to adopt innovative products or strategies. Looking at builder size, Eastin et al. (2001) argued that small builders tend to adopt modifications and materials that fit into existing systems, while larger builders introduced more innovations. These various factors and demographics could be important when looking at architects and their material preferences. A premium value proposition is key to competitive advantage in the context of innovative building materials (Smith & Wolcott, 2006). McGraw Hill found that two-thirds of builders indicated that government incentives, changes in building codes, ordinances, and regulations were the initial triggers to start implementing green practices. However, builders actually building green homes indicated other customer and/or social demands (McGraw Hill Construction, 2009). Architects' and builders' perceptions of certified wood products are potentially different from each other because of their roles in home construction. Architects' reasons for building green and utilizing certified wood products could provide a different set of parameters or barriers that factor into utilizing particular green building standards.

Predicting whether certain architects will be more or less likely to use ECWPs is a helpful tool in defining market segments and could help describe architects who are more likely to participate in or adopt green building programs (GBPs). This study is unique in that the product that is being used to gauge architect preference is a commodity type product (lumber) that is typically purchased for performance and structural use rather than appearance. Thus, there is no discernible difference between wood coming from various certification schemes since all programs require wood to meet typical wood grading and quality standards.

2.5 Sampling Design

2.5.1 Target Population

This study's survey was designed to analyze and estimate the characteristics of architects in the U.S. residential construction industry, focusing on those who had participated in residential green building programs. There are approximately 105,000 architects in the U.S., with only a small percentage working in the residential housing sector. The nationwide averages of firm revenues derived from residential housing are only 8% from multi-family residences and 6% from single family residences (American Institute of Architects, 2017). There are no data regarding how many architects participate in residential construction; a conservative estimate is that 25% of architects are involved with some type of single- or multi-family construction project. During the time of this research, 3% to 7% of total housing starts were LEED or NGBS certified, with many of these starts coming from multi-family units to scale down certification costs. As of 2014, approximately 4% of single-family homes were certified, whereas 12% to 15% of multi-family projects were certified (USGBC, 2017). From these totals, the number of architects participating in green building is estimated to be 5,280 (5%) as of 2010.

2.5.2 Minimum Required Sample Size

The survey utilized the American Institute of Architects (AIA) database for a simple random sample of registered architects; architects were eligible to complete the survey if they had participated in at least two residential home building projects in 2010. The sample size was calculated based on the study's variable of interest: architects that were aware of residential green building programs (Bartlett, Kotrlik, & Higgins, 2001; Cochran, 1977). The following equation was used to generate the proper sample size (Krejcie & Morgan, 1970):

$$n = \frac{\chi^2 NP(1-P)}{d^2(N-1) + \chi^2 P(1-P)} \qquad \text{(eq. 1)}$$

Where:

n = required sample size; N = target population size; P = estimated value for the proportion of a sample who are aware of GBPs; d = acceptable margin of error for the estimated value of P; χ^2 = table value of chi square for one degree of freedom relative to the desired level of confidence (1-d).

There are an assumed 105,000 architects (N) in the U.S., including both residential and non-residential types (American Institute of Architects, 2017); 2,000 were randomly selected to receive the survey with a target completion rate of 400/2000 (20%). The sample size of 400 was based on the following assumptions: there are varied levels of awareness among architects regarding Green Building Programs, so a value of 0.5 (50%) is used for P since this will determine the largest required sample size for our desired accuracy level of (d) = 5% (Cochran, 1977). Based on the previous assumptions, the corresponding χ^2 value for one degree of freedom was calculated to be 3.84. Using equation 2 and the pre-stated assumptions, the minimum sample size was calculated to be 379. The sample size for this segment of the population then was set at a minimum of 400 respondents for convenience. After the initial email distribution of the survey, the response was so large that it was closed after approximately 500 responses since we did not want to exceed the originally designed sample size. If a survey response is too large, it is often far too simple to find results that are statistically significant. 509 architects responded to the survey; some respondents did not answer every question so the number of responses to the questions differ. This survey unfortunately did not implement a forced response to the questions, but this helped minimize survey fatigue and reduce non-rational answering, such as selecting 1 for every question for quicker completion.

The main advantages of using a panel-based internet survey are greater speed and lower cost of implementation (Dillman, 2000; Duffy, Smith, Terhanian, & Bremer, 2005). There is also a reduced time lag with this type of data collection as opposed to more traditional methods (Schonlau, van Soest, Kapteyn, & Couper, 2009). A web-based survey allows for flexibility by ordering the questions logically. Logically sequenced questions allowed the researcher to ask questions based on previous responses by progressively profiling the respondents. For example, if a respondent reported they have used a green building program, they would then be asked the top three reasons for using it. Similarly, if a respondent was aware of green building programs but had not yet used them, they would be asked the top three reasons why they had not used a green building program. Employing this methodology should minimize the variance by reducing respondents' guessing.

A copy of the architects' survey is attached in Appendix A. The survey was powered by Qualtrics (Qualtrics Labs, Inc., version 2011) web-based survey software and pre-tested by AIA members for clarity and validity (Figure 2-1). Upon completion, the relevant data was imported into SPSS and R to conduct the necessary statistical analysis.

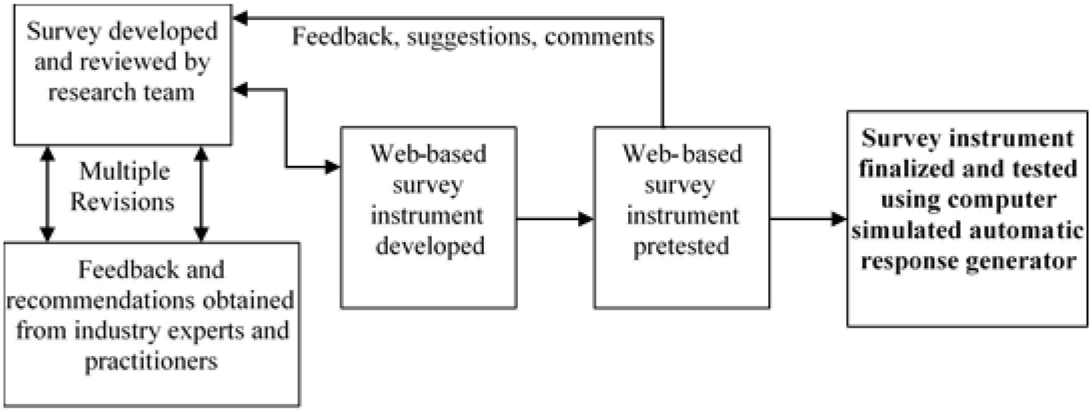

Figure 2-1 Survey Instrument Development and Design Process

2.6 Data Collection

To achieve representative data from architects active in the residential construction market, the survey started with two questions to determine if an architect was qualified to continue the survey. The first asked if the participant is an architect, engineer, or designer. If they were a builder, contractor, or other, they were not allowed to complete the survey. This ensures valid data by only allowing the population of interest to complete the survey. The second question requested the number of projects an architect had designed during 2010. This question provided a sample of architects that were currently active in the residential construction sector. Architects needed to have participated in a minimum of 2 homes or projects; it was determined that 1 project could be considered not active because the respondent could be participating only in that single project and not working full time. Accounting for part-time or semi-active architects could significantly left skew the data regarding the number of completed homes. If the answer was less than 2, the respondent was thanked and exited from the survey. The reliability of these measures and survey content was verified by AIA; the questions are similar to those asked by the AIA when generating demographic overviews of the architects and engineers that are members of their organizations. At the end of the survey, the respondent provided their individual or firm demographics, such as zip code and state, and was anonymously coded for reference purposes.

2.6.1 Biases

Non-response bias was addressed through a procedure suggested by Armstrong and Overton (1977), in which the characteristics of late respondents who are thought to be similar to non-respondents are compared to first or early respondents. T-tests of the means of respondents in both groups were compared to ensure there was not a significant difference between respondents. With an acceptable $p\text{-value} < 0.05$, if one out of twenty questions exhibited a difference from the mean the groups could still be considered similar.

Non-sampling error is more complicated and harder to control because it is composed of two factors: non-response errors—when sample members do not respond—and response errors—when subjects purposely misreport their answers. Response error is difficult to isolate from non-sampling error because there is no way to predict how a subject will respond. Responses can change based on the subject’s mood, time constraints, or even dislike of taking surveys. Response bias is often used to measure the relative size of a response error’s contribution to the non-sampling error (Assael & Keon, 1982).

Non-coverage bias can occur when there is under coverage in the sample frame. This is when the observed responses deviate from the population parameters because of the difference between respondents and non-respondents. A past problem was emailing a survey to a sample group in which many builders or architects did not have email addresses. This should not be a problem in this study since it utilized a database that includes email addresses for registered builders and architects. Additionally, this survey had a rapid response from initial distribution to meeting the sample size threshold; since we used only one email distribution, it was not reasonable to try to distinguish non-respondents. To test the randomness of the sample, the respondents were divided equally into groups, which were compared against each other. The results did not indicate any significant differences between the groups.

2.7 Results and Discussion

2.7.1 Response Rate

509 surveys were received, 450 of which were valid (completed by an architect, designer, or engineer). Out of these 450 responses, 429 responded beyond the general qualified response questions and provided answers to demographic questions of interest to the research questions. Survey fatigue for some respondents was apparent as response rates dropped along the duration of the survey. Response rates for questions close to the end of the survey were lowest. 385 surveys responded to the pertinent questions containing potential impact variables, which met the required survey sample size for this research. The survey sample size consisted mostly of architects (98.2%), with a few responses from designers (1.7%) and an engineer (0.2%). Some of the respondents added that they were also involved in the building of homes, but this was out of the context of the research questions.

2.8 General Demographics of U.S. Architects

The following demographic questions provide a general overview of U.S. architects that work within the residential construction sector. These results attempt to provide a snapshot of what would be expected if this survey was distributed to the entire population of U.S. architects that participate in residential home design.

2.8.1 Employment and Client Type

Employment structure and type of client could provide details about an architecture firm's decision structure and responsibilities regarding reporting and managing their various projects. In this survey, architects were asked about their employment type: whether they work directly for home builders, for architectural firms, or are independent. As shown in Figure 2-2, most architects worked for architectural firms (57.8%), whereas a reasonable number considered themselves independent consultants (35.2%). Respondents that answered "other" declared themselves owners of architecture firms, independent/sole-proprietor architects, and/or design/builders. If a respondent answered 'other' and indicated they were an architect or sole proprietor, it was assumed they were an independent consultant and they were reclassified as such.

The primary client type is the entity for whom the architect designs a project. The architect is responsible for communicating with the client and providing detailed plans and specifications for the project in question. Figure 2-3 reveals that most residential architects work directly with homeowners (64.3%), while a small percentage (10.8%) work for small- to medium-sized home builders. Respondents that selected other (16.7%) worked for various government entities, multi-family housing developers, and commercial developers (i.e. hotels that have units available for purchase, etc.).

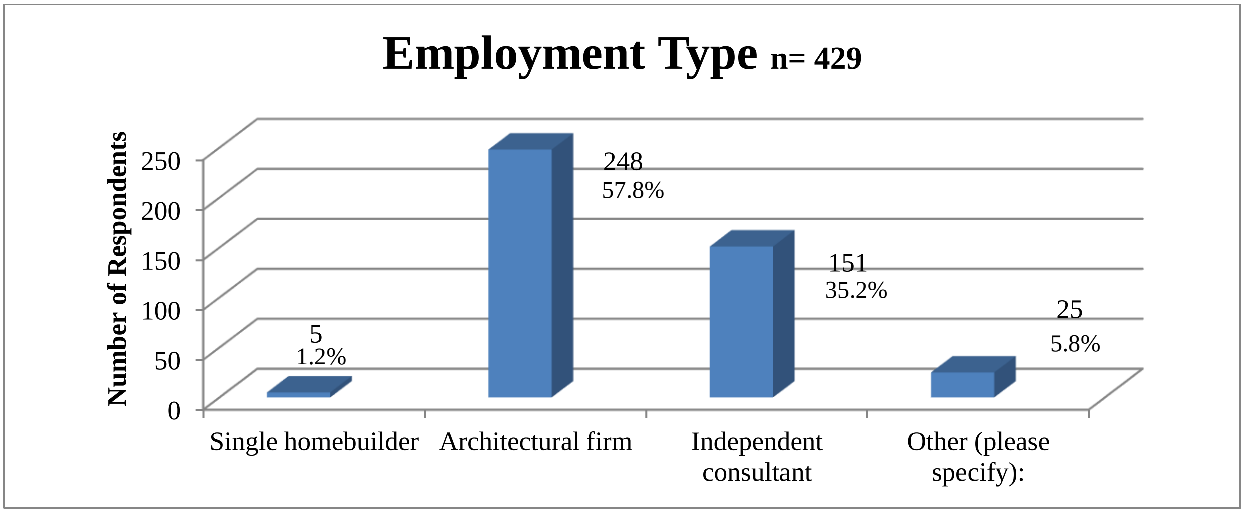

Figure 2-2 Employment Type of Survey Respondents

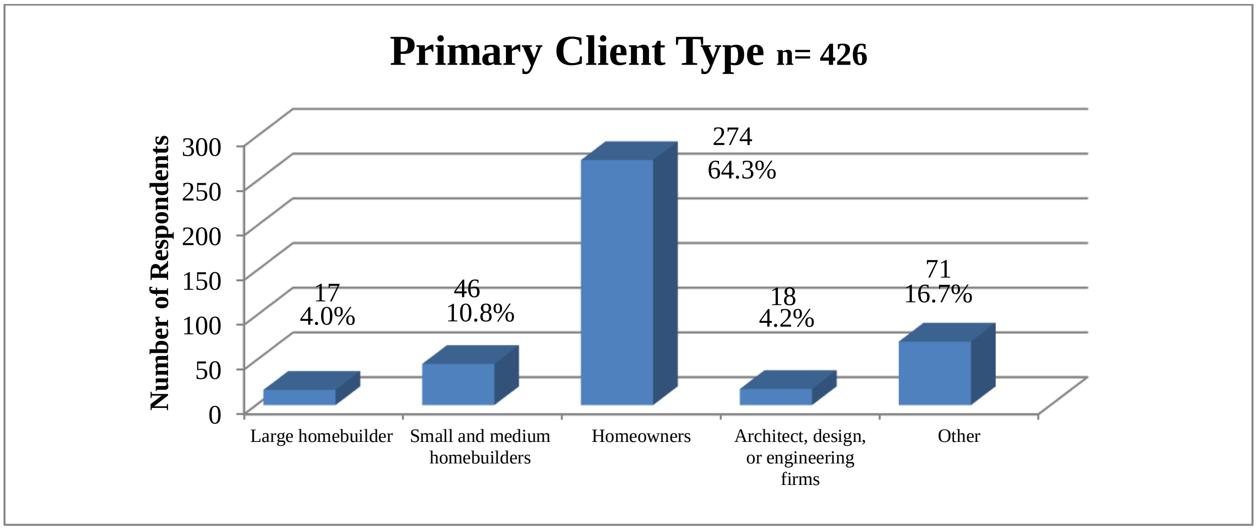

Figure 2-3 Primary Client Type of Survey Respondent

2.8.2 Location

Location can determine construction practices and the specific materials utilized in homes. Material use varies by region (Ganguly & Eastin, 2007), and different regions could show a preference for adopting environmentally friendly materials at a higher rate (Ganguly, Bowers, Eastin, & Cantrell, 2013). Table 2-3 and Figure 2-4 provide a breakdown by region and state for the respondents of this survey. Respondents represented 45 states and covered all four census regions. The highest number of respondents lived in the South (32.7%), followed by the West (25.7%), Northeast (22.4%), and the Midwest (19.2%). California, Texas, Illinois, New York, New Jersey, and Florida were highly represented.

Table 2-3 The Distribution of the Respondents by Census Region

Northeast		Midwest		South		West	
State	**Architects**	**State**	**Architects**	**State**	**Architects**	**State**	**Architects**
Maine	0	**Ohio**	3	**Delaware**	1	**Alaska**	2
N. Hampshire	3	**Michigan**	9	**Maryland**	16	**Washington**	18
Vermont	1	**Indiana**	4	**Virginia**	12	**Oregon**	6
Massachusetts	11	**Illinois**	31	**W. Virginia**	1	**California**	47
Rhode Island	3	**Wisconsin**	9	**N. Carolina**	14	**Hawaii**	2
Connecticut	12	**Minnesota**	9	**S. Carolina**	7	**Idaho**	0
New York	25	**Iowa**	5	**Georgia**	13	**Montana**	0
New Jersey	20	**Missouri**	5	**Florida**	20	**Wyoming**	2
Pennsylvania	18	**Kansas**	2	**Alabama**	3	**Colorado**	14
		Nebraska	2	**Mississippi**	2	**Utah**	4
		S. Dakota	0	**Tennessee**	5	**Nevada**	1
		N. Dakota	1	**Kentucky**	5	**Arizona**	6
				Louisiana	4	**New Mexico**	5
				Arkansas	2		
				Texas	31		
				Oklahoma	0		
Total NE	**93**	**Total MW**	**80**	**Total South**	**136**	**Total West**	**107**
NE %	**22.40%**	**MW %**	**19.20%**	**South %**	**32.70%**	**West %**	**25.70%**

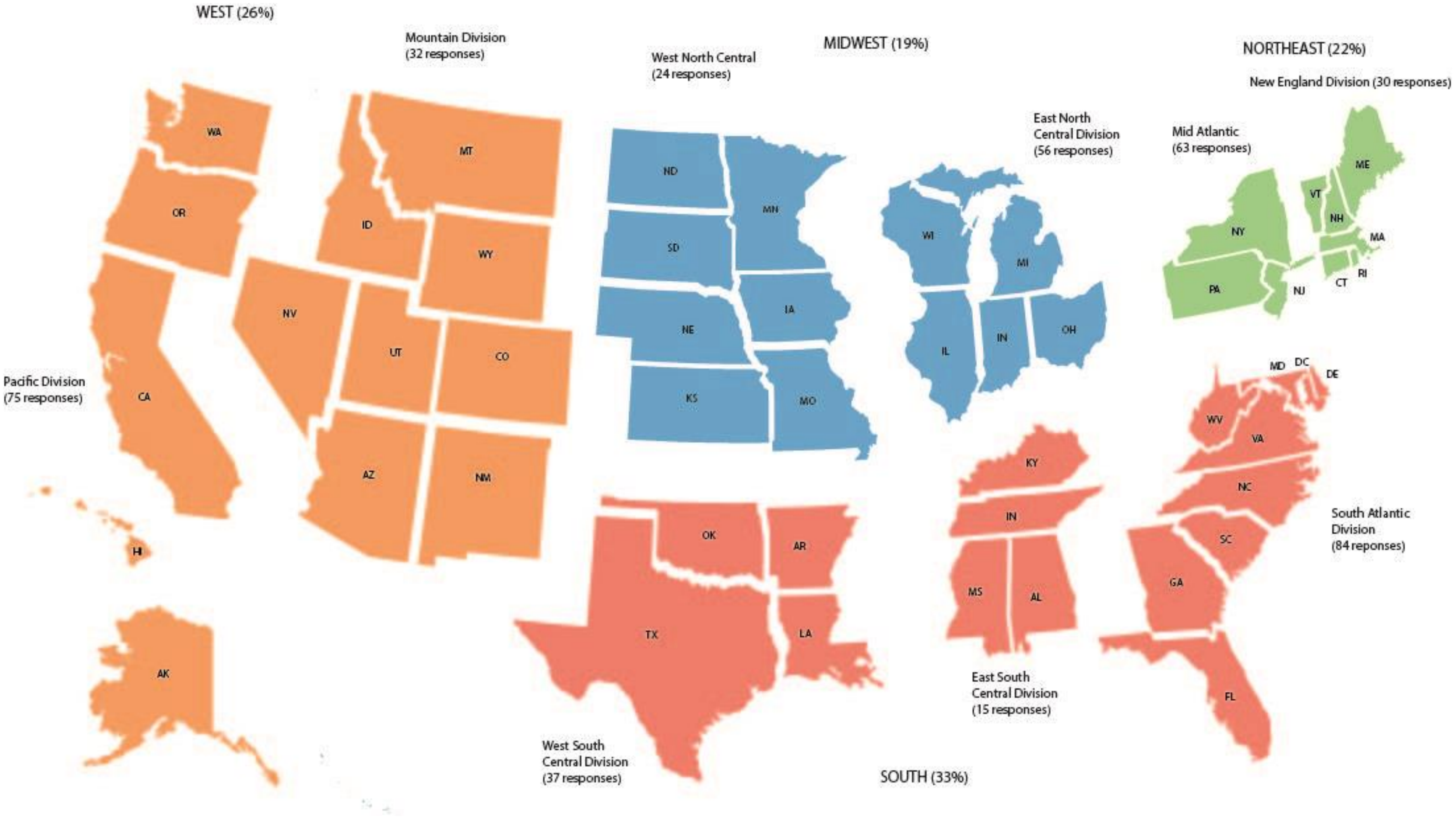

Figure 2-4 Breakdown of Respondents Based on U.S. Census Regions

Information about a location's population density can also provide insight into possible differences in construction practices and material use. Urban locations tend to have a higher propensity for multistory multi-family residences versus more remote rural locations. Respondents were asked in which of the three main community structures they conducted most of their business: rural, small town, or urban/suburban, each of which was defined within the survey.[5] As shown by Figure 2-5, an overwhelming majority of architects worked in urban/suburban areas (78.8%), with the remaining working in small towns (16.1%) and only a few in rural areas (5.1%).

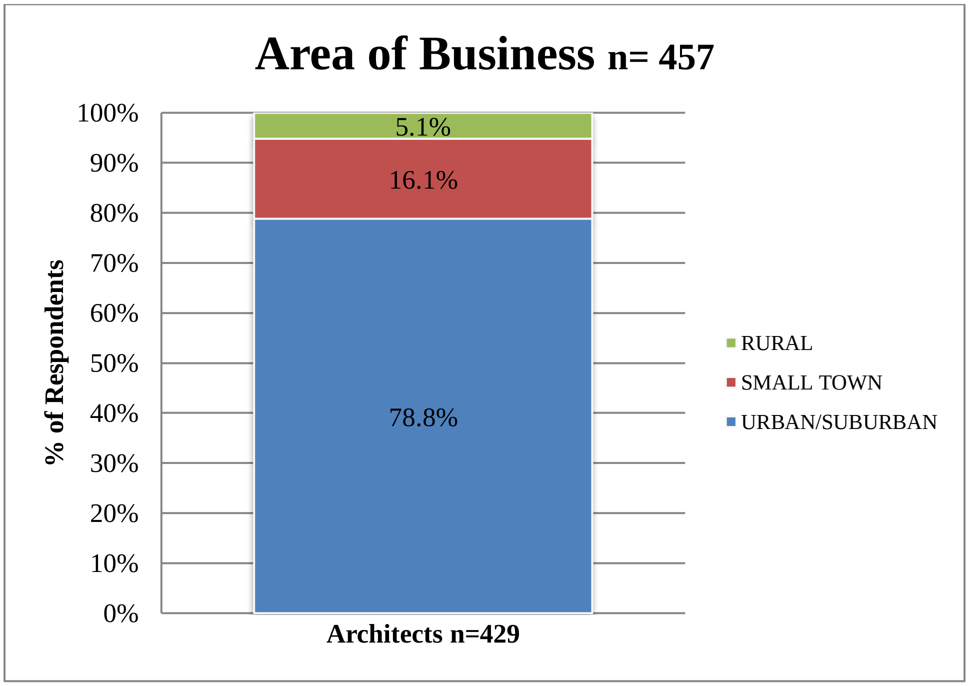

Figure 2-5 Area Survey Respondent Conducts Business

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[5] Urban/Suburban area= city or group of contiguous communities with a population greater than 50,000, small town = city or group of contiguous communities with a population less than 50,000, rural area = low density population scattered over a wide area.

2.8.3 Size of Firms

Respondents were asked how many homes or projects they had participated in in the previous year to gauge the volume or size of the architect’s firm or client base. There was a minimum threshold of 2 projects to participate. The survey did not record the number of projects with which a respondent was involved, therefore employment and client type were used to determine size of the firm. Since architects are not typically involved with the sale of the home, they were not asked about annual revenue. Questions regarding source of revenue or type of construction projects did not provide meaningful results because they were only answered by three respondents.

2.8.4 Years in Business

To gauge their experience in the industry, respondents were asked to specify the number of years that they or their organization had been in business. Figure 2-6 shows the distribution of the responses in 10-year segments. The mean was 24.4 years, the median 25 years, and the standard deviation 11.4 years. Some architects/firms had been in business for an extensive period, with 2.1% reporting they had been in business for 50-60 years. 60 years was the highest recorded; 3 respondents reported they had just started (0 years).

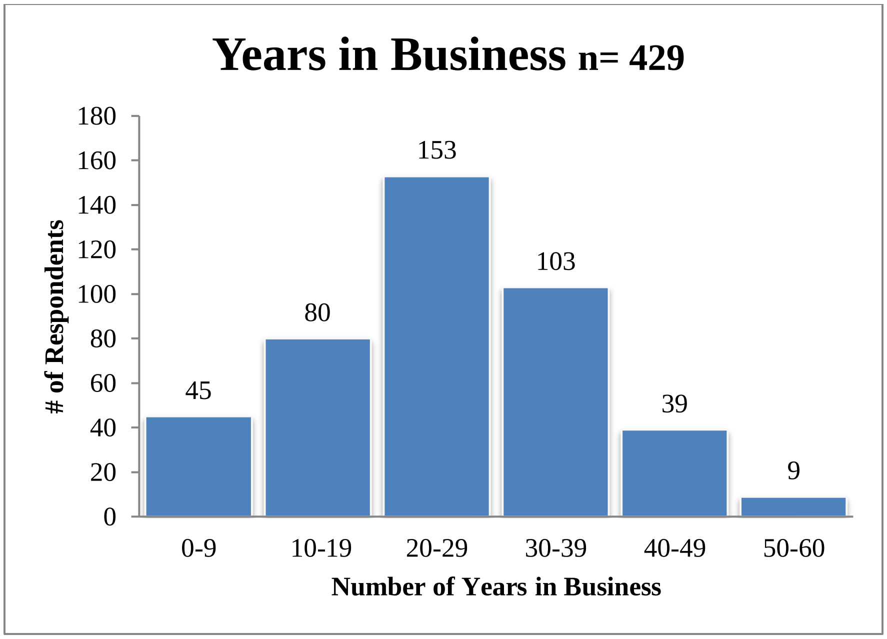


Figure 2-6 Architects' Years in Business

2.9 Awareness and Use of Residential Green Building Programs (GBPs)

One of the objectives of this study was to evaluate architects' awareness and use of residential green building programs (GBPs). Architects were asked to indicate their level of awareness and use of the two green building programs designed to certify residential structures in the U.S., LEED for Homes and NGBS. Architects could select from four options:

1. Not aware of the program,
2. Aware of the program, but have not used it,
3. Aware of the program and planning to use it in the future, and
4. Have used the program

The results are sorted into three categories of respondents: non-aware, aware non-users, and users. Figure 2-7 details how familiar each respondent was with the programs. There was a higher percentage of architects who had used LEED for Home (23.4%) compared to NGBS (6.9%), coinciding with less familiarity with NGBS (16.7%) while less than 1% of architects reported they had not heard of LEED for Homes. To categorize these results further into "users" versus "non-users," respondents were separated into two groups: one that had used one or both of the programs, and another that had used neither of the programs (even if they were planning to use it in the future). Table 2-4 shows that 3.9% of architects had used both programs; the number of architects who had only used LEED for Homes (19.5%) was six times higher than those that had only used NGBS (3.1%). Overall, 26.5% of respondents had participated in one of the primary GBPs. The large percentage of architects that have not used either program indicates that there is considerable room for potential growth in this sector.

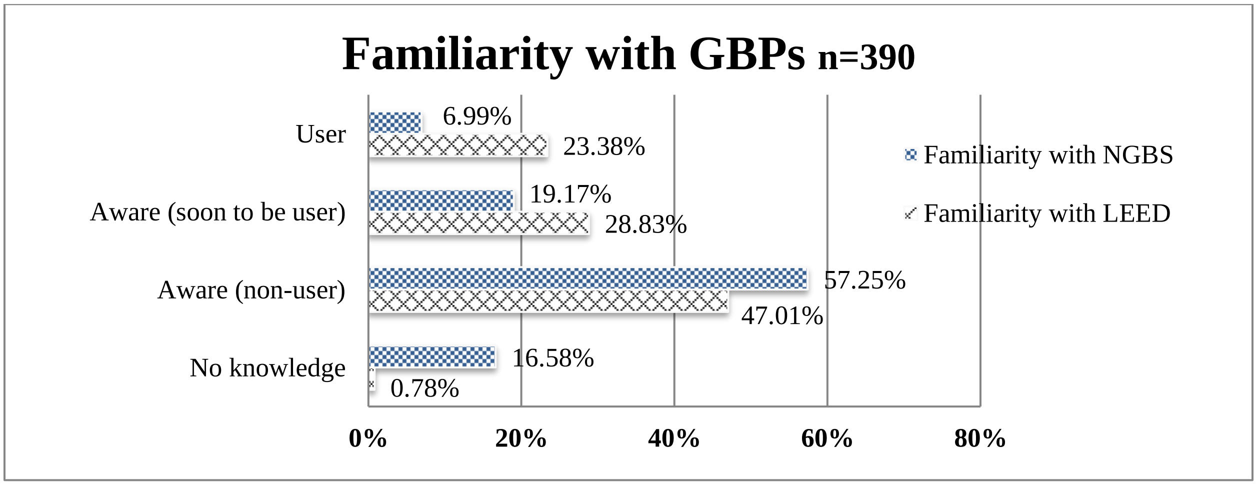


Figure 2-7 Familiarity and Use of LEED for Homes and the National Green Building Standard

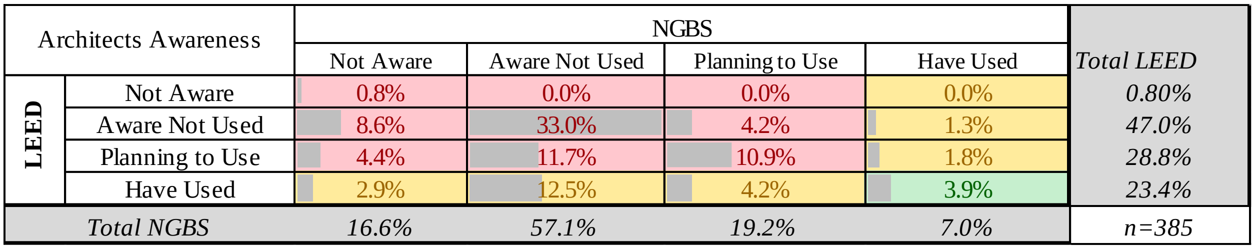
Table 2-4 Use of LEED for Homes and National Green Building Standard

Architects	n=385
Use Neither	73.51%
LEED Only	19.48%
NGBS Only	3.12%
Users of Both	3.90%
	100.00%

Table 2-5 provides a more detailed comparison of both GBP programs with a cross tabulation of the awareness and use of both. The gray shading within the cells represents the relative number of respondents for that cell with respect to the cell with the highest frequency.

The cells designated red are respondents that have not used, while yellow and green signify that either one or both programs have been used, respectively. Of the respondents that had used LEED for Homes, only 4.2% were planning to use NGBS, while of the respondents that had only used NGBS, just 1.8% were planning to use LEED for Homes. This could be a result of customers or homebuilders requesting LEED for Homes since homebuilders are also more aware of this program (Sasatani et al., 2015). One-third of respondents were aware of both programs but had not used and were not planning to use either program. The reasons why these respondents have chosen not to participate is discussed later in this section.

Table 2-5 Awareness and Use of LEED for Homes and National Green Building Standard



Architects Awareness		NGBS				
		Not Aware	Aware Not Used	Planning to Use	Have Used	*Total LEED*
LEED	Not Aware	0.8%	0.0%	0.0%	0.0%	*0.80%*
	Aware Not Used	8.6%	33.0%	4.2%	1.3%	*47.0%*
	Planning to Use	4.4%	11.7%	10.9%	1.8%	*28.8%*
	Have Used	2.9%	12.5%	4.2%	3.9%	*23.4%*
Total NGBS		*16.6%*	*57.1%*	*19.2%*	*7.0%*	*n=385*

As detailed earlier, there are other local and national green building programs that architects could utilize. Table 2-6 shows that 27.1% of all respondents used another regional building program. Of the respondents who had used only one of the two major GBPs, 43.5% of those who had used LEED for Homes and 22.2% of those who had used NGBS had also used a different regional green building program. Additionally, 21.0% of respondents that had not used either program reported that they had used another regional green building program, such as Built Green, Living Building Challenge, Earth Advantage, Green Built, and Energy Star.

Table 2-6 Use of Regional Green Building Programs

	Use of other Regional GBPs			
	Yes		No	
	Counts	%	Count	%
Total Respondents	82	27.1%	221	72.9%
Breakdown by Residential Green Building Program Participation				
Have Used Neither	46	21.0%	173	79.0%
LEED for Homes	27	43.5%	35	56.5%
NGBS	2	22.2%	7	77.8%
Have Used Both	7	53.8%	6	46.2%

Table 2-7 shows the number of certified projects completed using LEED for Homes or NGBS, as well as the awarded level of certification. Many architects design structures that, either during the project or its audit, do not reach their intended certification levels. They were asked the number of projects they had finished in the previous two years because of the lengthy duration from initial design to a complete and certified home. The respondents reported that they had completed homes from all category levels, though the lowest level of certification was most common for both LEED for Homes and NGBS: 60 of the 177 projects using LEED for Homes achieved the Certified award, and 10 out of 22 NGBS-certified homes achieved the Bronze level. Overall, architects were more familiar with and have utilized the LEED for Homes program at a higher frequency, but this question was underreported with many non-responses. The lack of NGBS certifications could be because it was developed by the National Association of Home Builders and focuses on homebuilders rather than architects and designers.

Table 2-7 Number of Certified Homes Achieved at Each Level by Survey Respondents

	LEED		NGBS
Platinum	28	Emerald	3
Gold	39	Gold	4
Silver	35	Silver	5
Bronze	15	Bronze	10
Certified	60		
Total	177		22

Architects who reported that they were aware of LEED for Homes or NGBS but had never used either were asked the top three reasons for this choice. Figure 2-8 shows that for LEED for Homes, *homebuyer not willing to pay premium for certification* and *no demand* were the both ranked 1st an equal number of times (44), with *homebuyer not willing to pay* (70.1%), *documentation difficult* (69.5%), and *too expensive* (61.7%) the top three reasons for both programs. It is interesting that *no market demand* (58.1%) was ranked 1st as many times as *homebuyer not willing to pay* yet was not in the top three overall reasons. Respondents that selected *other* (13.2%) mentioned reasons such as “does not guarantee a truly green building,” “green building products are overrated,” and “requires 3rd party certification” for why they had not used the program.

As shown in Figure 2-9, *no market demand* (41.6%) was selected as the main reason (1st) for not using NGBS. The top three reasons for not using the program were: *no market demand* (84.8%), *homebuyer not willing to pay* (65.2%), and *do not have the necessary training* (46.1%). While there was a higher response of *no market demand* for NGBS compared to LEED for Homes, the majority of respondents did not think NGBS was *too expensive* (36.0%). Lack of training was an issue with NGBS, but documentation (36.5%) was not as much of a deterrent as it was for LEED for Homes (69.5%). *Other* (26.4%) reasons mentioned were: “they did not know much about it,” “LEED is more recognizable,” and “lacks credibility.”

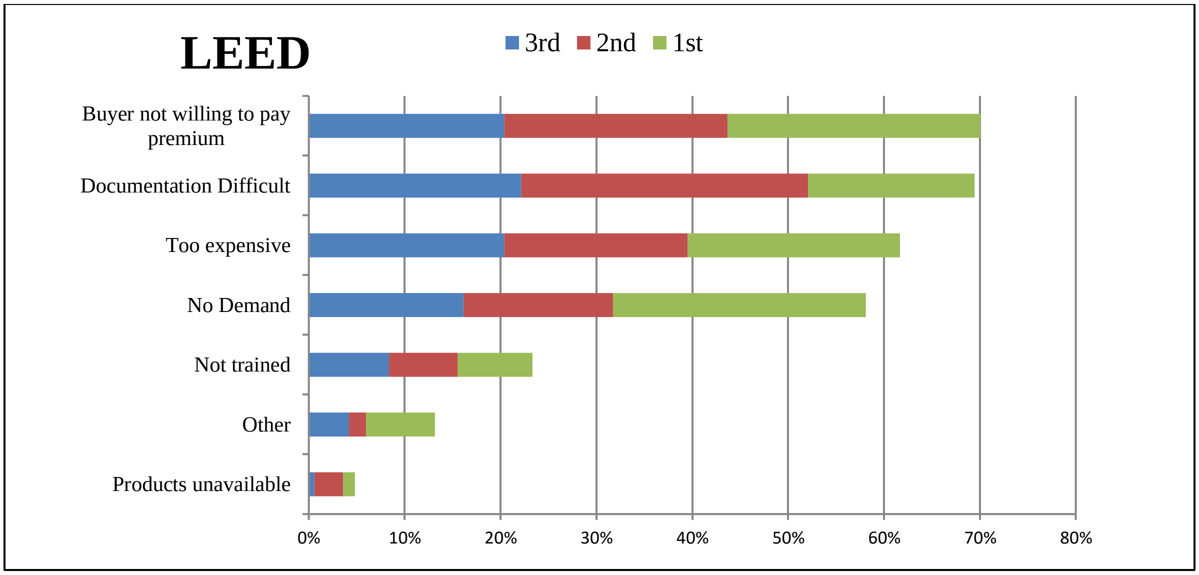


Figure 2-8 Reasons Architects Have Not Used LEED for Homes

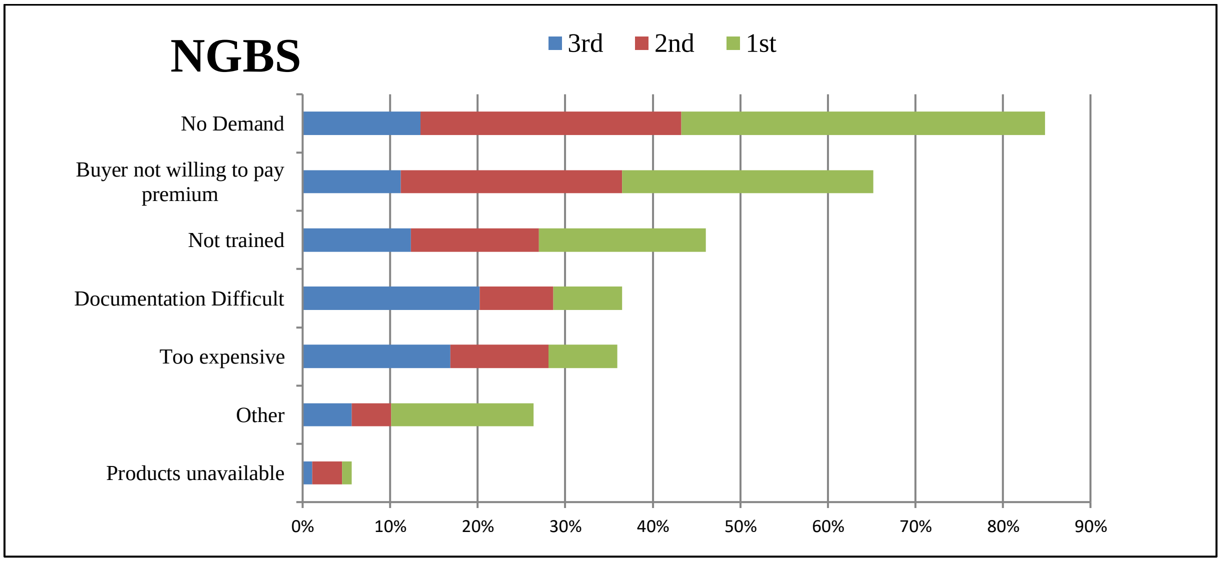


Figure 2-9 Reasons Architects Have Not Used the National Green Building Standard

Architects that reported using either the LEED for Homes or NGBS programs or were aware of them and planned to use them in the future were asked their top reasons for these choices. Figures 2-10 and 2-11 show that the primary reason was *homeowner specified* (34.6%) for LEED for Homes and *differentiate my homes* (38.6%) for NGBS. The top three reasons overall for using or considering LEED for Homes were: *differentiate my homes* (84.0%), *homeowner specified* (72.8%), and *strong demand for green homes* (64.2%). Reasons cited when *other* was selected were: “to verify if the house performs as designed,” “tax incentives,” and “code requirements.” The top three reasons overall for using or considering NGBS were: *differentiate my homes* (83.1%), *strong demand for green homes* (57.8%), and *documentation process is straightforward* (56.6%). These results suggest that architects realized the marketability of green-certified homes and sensed enough demand in the marketplace to justify the certification process. Architects noted that homeowners were more likely to specify LEED for Homes (72.8%) relative to NGBS (42.5%), yet architects that had used or were contemplating using NGBS reported that the *builder specified the program* more frequently (32.5%) than LEED for Homes (24.1%). There was also a strong perception that the documentation process was easier for NGBS (56.6%) than for LEED for Homes (19.8%). Architects did not consider either certification program profitable; only 13.0% of respondents for NGBS and 12.0% for LEED for Homes listed this as a top reason.

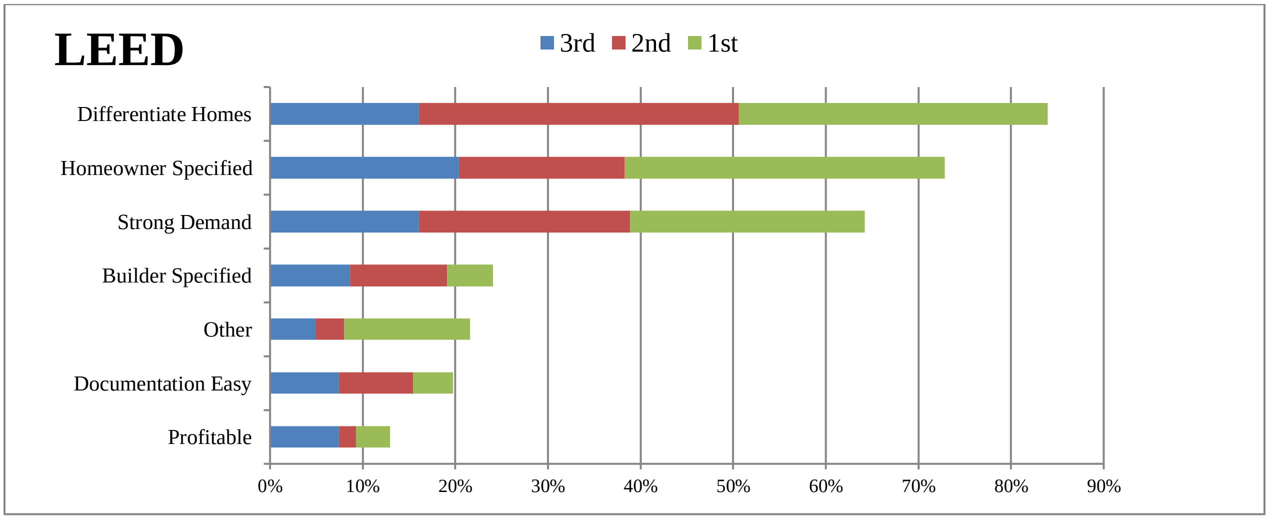


Figure 2-10 Reasons Architects Have Used LEED for Homes

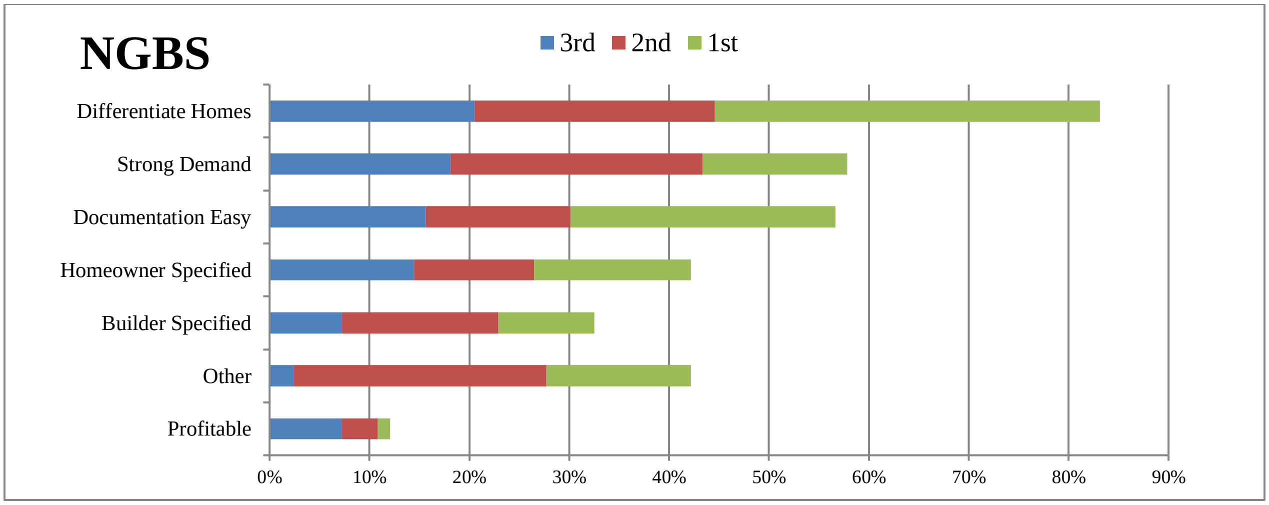


Figure 2-11 Reasons Architects Have Used National Green Building Standard

Respondents that were aware of or had used both GBPs were asked their perceptions of the programs, comparing them with respect to seven different attributes (Figure 2-12). Figure 2-12 shows these results in a bar chart with 0% as the baseline for how each category was rated for both programs. To help visualize these results, the "neutral" and "I don't know" responses have been removed. The range of responses for "neutral" was 10.9% for *brand recognition* to 27.3% for *environmental footprint.* The range of respondents that did not know or had no opinion ranged from 34.1% for *brand recognition* to 50.8% for both *willingness to pay* and *documentation required*.

Responses to the comparative rating of the two programs ranged from 55.0% to 22.2%. The highest response was for *brand recognition*, which significantly favored LEED for Homes; *influence on sales* and *environmental footprint* also favored LEED for Homes. More respondents thought that NGBS was preferable regarding *documentation requirements, easier rules* and *lower costs of certification*. *Willingness to pay* was equal; it also had the highest number of "I don't know" responses.

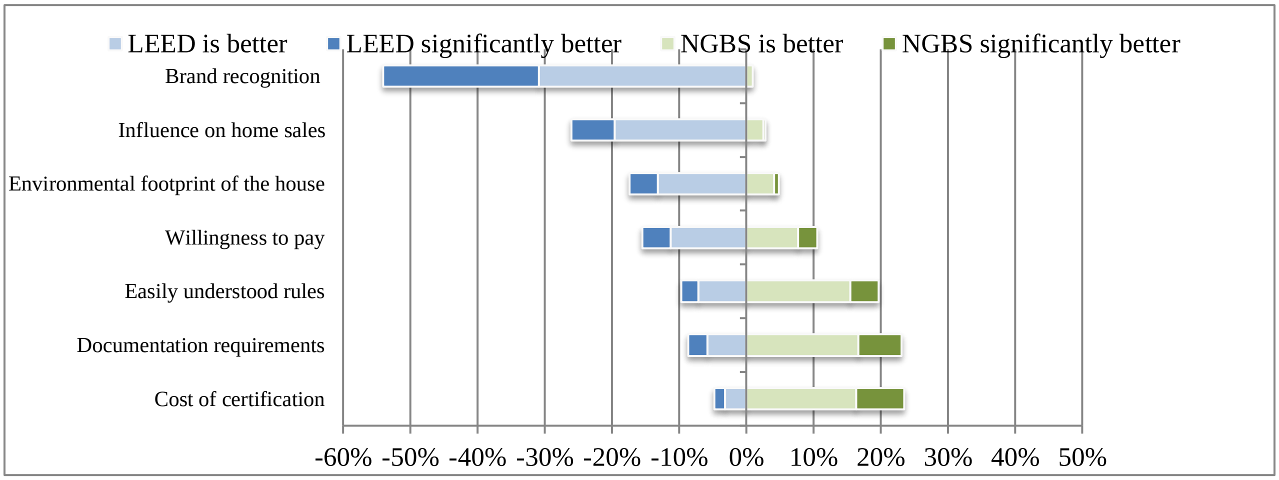


Figure 2-12 Comparison of Perceptions of LEED for Homes versus National Green Building Standard

The last question respondents were asked measured the top three reasons they had used any type of green building program. The responses in Figure 2-13 show that the top-ranked reason (1st) was being *good for the environment* (46.4%), which also received the highest overall combined response (70.5%). Respondents also noted that *lower energy costs* were important (51.2%), followed by *customer demand* (33.3%) and the ability to *differentiate their homes* (31.4%). *Law requirement in the future* was rated 3rd overall (40.6%); since all respondent architects were members of the AIA, they were probably aware of the changes in building codes and subsidies that are moving in favor of green building practices. As noted previously, very few architects felt that green building was profitable (3.9%).

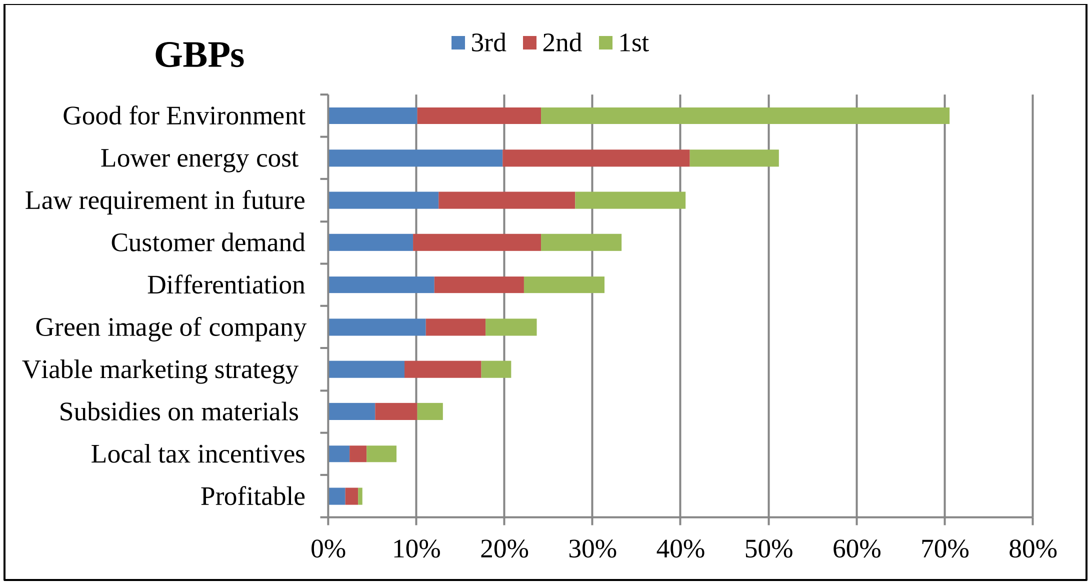


Figure 2-13 Reasons Why Architects Have Used a Green Building Program

2.10 Awareness and Use of Environmentally Certified Wood Products (ECWPs)

The main objective of this survey was to obtain a better understanding of both architects' awareness and use of environmentally certified wood products (ECWPs) and their perceptions of the two major forest certification standards in North America, the FSC and SFI programs. Respondents were asked to indicate their familiarity with certified wood from either of the two programs, selecting from four responses:

1. Haven't heard about it ("not aware"),
2. Aware of certified wood program, but never used it ("aware non-user"),
3. Occasionally required or specified it ("light-user"), and
4. Frequently specify it ("heavy-user")

Figure 2-14 shows the responses regarding architects' awareness and use of SFI and FSC-certified wood. The survey results show that a higher percentage of architects had used FSC-certified wood (54.1%) compared to SFI-certified wood (25.8%). Respondents were also less familiar with SFI-certified wood: 23.3% had no knowledge of it compared to 13% of respondents who had no knowledge of FSC-certified wood. To summarize the results into "users" versus "non-users," respondents were separated into two groups: one that had used one or both of the programs, and another that had used neither even if they were aware of certified wood programs. Table 2-8 shows these groups' use of ECWPs: 25.0% of architects had used both programs; 29.0% had only used FSC-certified wood, significantly more than those who had only used SFI-certified wood (0.75%). These results indicate that architects have more experience using FSC wood than SFI-certified wood, a potential result of the points awarded for FSC-certified wood under the LEED for Homes program. Almost half of the respondents (45.3%) had not used ECWPs.

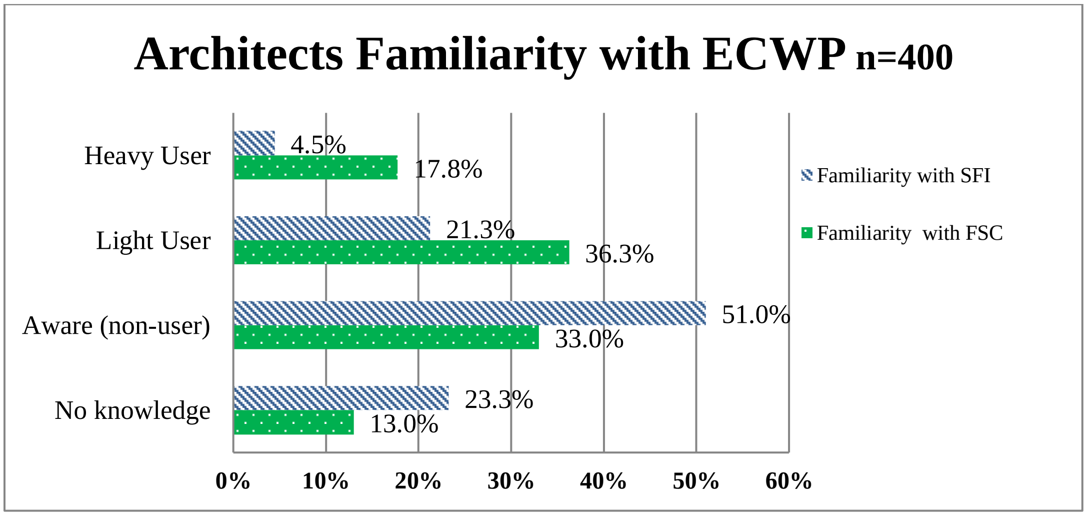


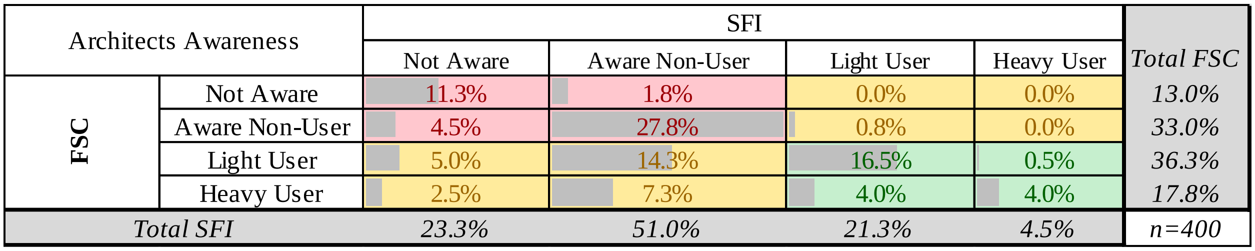
Figure 2-14 Architects Familiarity with Environmentally Certified Wood Products

Table 2-8 Respondents' Use of FSC and SFI Wood

Architects	**n=400**
Don't Use Certified Wood	45.25%
SFI Only	0.75%
FSC Only	29.00%
Users of Both	25.00%
	100.00%

Table 2-9 provides more detailed information on the survey respondents with the cross tabulation of the awareness and use of ECWPs. The gray shading within the cells represents the relative number of respondents for that cell with respect to the cell with the highest frequency. Of the respondents that had used FSC (54.1%), only 46.2% reported using SFI. Again, one of the drivers for this discrepancy could be their preference for or familiarity with the LEED for Homes program. The group of architects that were unaware of FSC ECWPs were largely unaware of both programs. The largest group of respondents was architects who were aware of both programs, but non-users of any ECWPs (27.8%). This provides support for the continued distribution and promotion of information about ECWPs and reveals that there is room for growth in the marketplace for ECWPs. With these needs to increase market awareness and use of these programs, it is crucial that the industry promotes ECWP’s benefits, such as improving the environmental performance of a building and reducing its carbon footprint. These environmental aspects of ECWPs are more complex than a simple focus on the number of points awarded by their use within a GBP.

Table 2-9 Awareness and Use of FSC and SFI Wood



Architects Awareness		SFI				*Total FSC*
		Not Aware	Aware Non-User	Light User	Heavy User	
FSC	Not Aware	11.3%	1.8%	0.0%	0.0%	*13.0%*
	Aware Non-User	4.5%	27.8%	0.8%	0.0%	*33.0%*
	Light User	5.0%	14.3%	16.5%	0.5%	*36.3%*
	Heavy User	2.5%	7.3%	4.0%	4.0%	*17.8%*
Total SFI		*23.3%*	*51.0%*	*21.3%*	*4.5%*	*n=400*

Figure 2-15 provides the percentage of homes architects designed with ECWPs. The majority of respondents (87.3%) indicated that ECWPs were specified in 50% or less of their homes. The remaining architects (13.7%) designed with ECWPs in greater than 50% of their homes. This contingent of architects is less than the 18.3% who reported being heavy users of ECWPs (Table 2-9). This discrepancy is likely a result of architects who reported being heavy users yet selected the 31-50% category for percentage of homes designed with ECWPs.

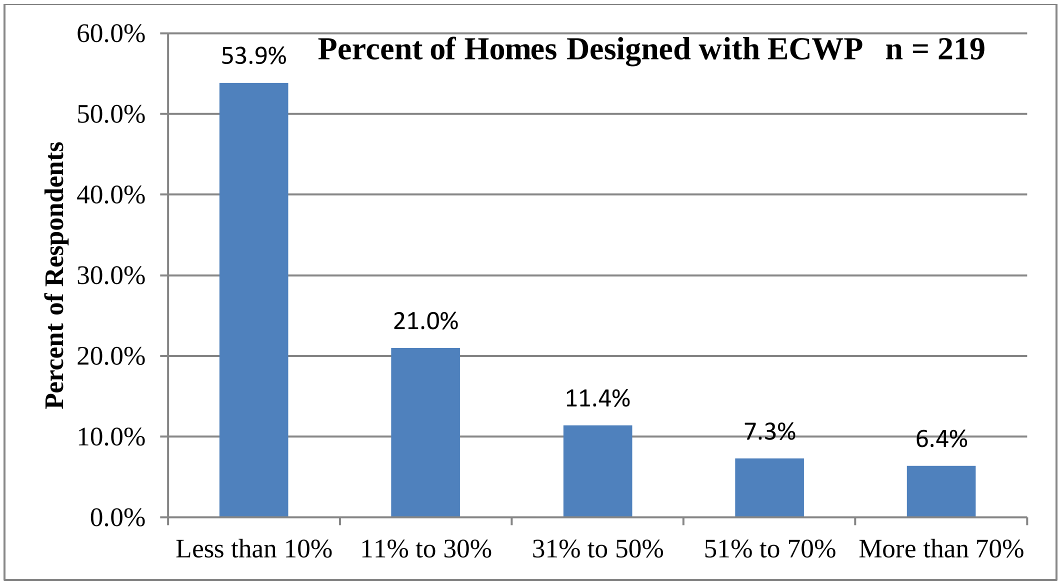


Figure 2-15 Percent of Homes Utilizing ECWP by Architects

Environmentally certified wood products have historically been sold at a price premium in many markets. While this is true for many value-added or secondary products, it is not always the case for commodity products (e.g., dimension lumber), since certified lumber is often mixed with uncertified lumber. Because of this, it was important to confirm if respondents thought ECWPs were priced higher and approximate the price premium. The survey revealed that most architects who have used certified wood believed there was approximately a 5 to 10% price premium on FSC (45.4%) and SFI (46.3%) certified wood (Figure 2-16). The distribution of responses for each price premium level was similar for both FSC and SFI ECWPs. Less than 5% of respondents felt there was no price premium for certified wood products sold under either program.

Table 2-10 shows the price premium architects believed to exist on wood from SFI and FSC-certified forests, and whether they believe one of the programs has a higher premium. The cross tabulated results are from architects who were aware of or had used wood from either certification program. The gray shading within the cells represents the relative number of respondents for that cell with respect to the cell with the highest frequency. Based on the tabulated results, most architects (38.7%) believed there was a 5 to 10% premium on ECWPs regardless of certification program. The cross-tabulation provides a visual indicator of whether architects perceive FSC or SFI as having a higher premium. The red highlighted cells to the lower left are respondents (12.1%) that perceived FSC as having a higher premium, whereas the blue highlighted cells to the upper right were respondents (6.3%) that perceived SFI as having the higher premium. A majority of architects (81.7%), did not discern a difference in price premiums between programs.

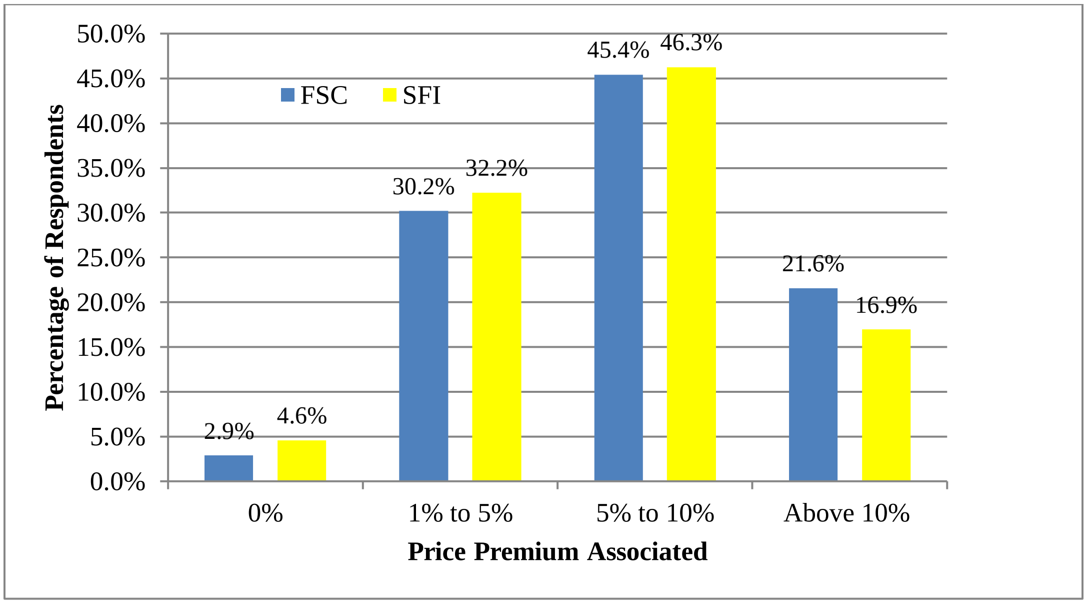


Figure 2-16 Price Premiums of FSC- and SFI-Certified Wood

Table 2-10 Price Premiums of FSC and SFI Wood

Architects Aware of or Used ECWPs		**SFI Premium**				
		0%	1% - 5%	5% - 10%	10% +	*FSC Total*
FSC Premium	0%	1.7%	1.0%	0.0%	0.0%	*2.7%*
	1% - 5%	1.7%	26.3%	3.0%	0.0%	*31.0%*
	5% - 10%	0.7%	2.0%	38.7%	2.3%	*43.7%*
	10% +	0.7%	2.7%	4.3%	15.0%	*22.7%*
SFI Total		*4.7%*	*32.0%*	*46.0%*	*17.3%*	*n =300*

FSC and SFI wood users were then asked if their use had decreased, stayed the same, or increased over the last two years. Figure 2-17 shows that a majority of architects' use of FSC (70.2%) and SFI (81.6%) remained the same. While very few had decreased their use, a significant number had increased their use of FSC (25.6%), with a slightly lower number increasing their use of SFI (17.5%). Respondents who were users or aware of FSC and SFI wood were then asked how they anticipated their use to change over the following two years. Figure 2-16 shows that 98% of current users expected their use of certified wood to either increase or stay the same. Many respondents who had not used ECWPs thought they would continue to not use them for both FSC (72.0%) and SFI (73.9%), while 23.5% of non-users planned to begin using FSC and 20.7% to begin using SFI over the next two years.

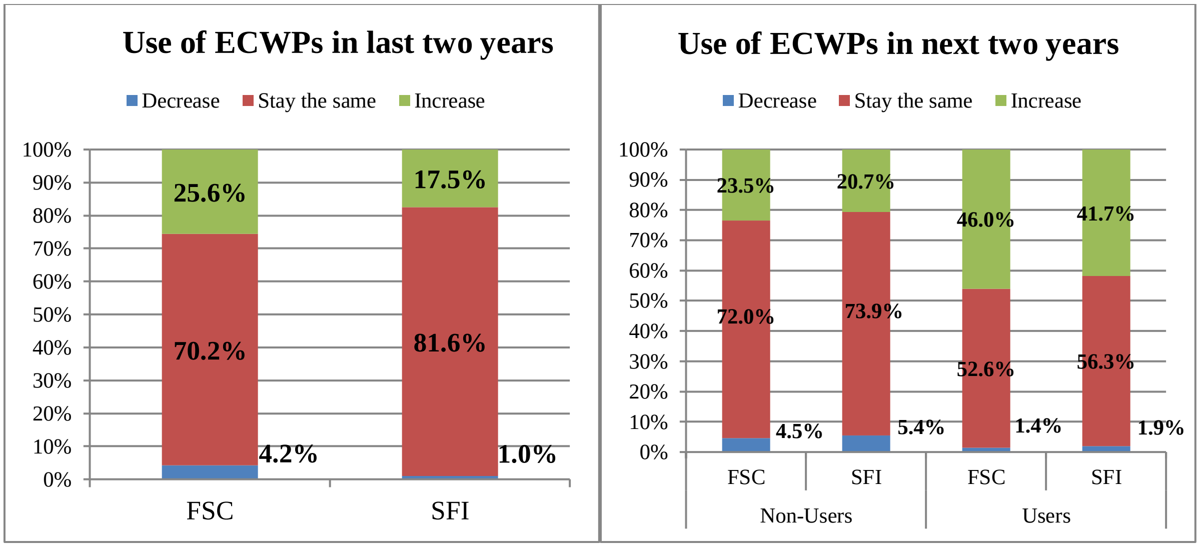


Figure 2-17 Changes in ECWP Use in the Last Two Years and in the Next Two Year

To gather additional information regarding respondents' perceptions and knowledge of both certification programs, the FSC-certified wood program was compared to the SFI certification program along several criteria. Architects who had used or were aware of both programs were asked to compare the programs using a set of five different attributes (Figure 2-18). Respondents were also given the option to respond "I don't know" if they were uncertain about how the programs compared; to help simplify the results, the "neutral" and "I don't know" responses have been removed from the analysis. The percentage of responses in the neutral category ranged from 32.4% for *sustainable forest management* and *availability* to 38.5% for *homeowner awareness*. The percentage of respondents that did not know or who had no opinion ranged from 36.8% for *homebuilder awareness* to 41.2% for *availability*.

For those who expressed an opinion regarding the five categories, the response rate ranged from 30.4% for *homebuilder awareness* to 21.3% for *homeowner awareness*. When analyzing the data by category, FSC-certified wood was rated significantly better in all five categories; *homebuilder awareness* (24.3%) was the highest overall response favoring FSC and *sustainable forest management* (8.1%) was the highest response of "FSC significantly better." Respondents who preferred SFI rated *sustainable forest management* (9.4%) highest overall (about 50% less than FSC); the categories most frequently rated as "SFI significantly better" were *sustainable forest management* (2.0%) and *availability* (2.0%). The category *better for the environment* was the least-rated category for FSC; *homeowner awareness* was the least-rated category for SFI.

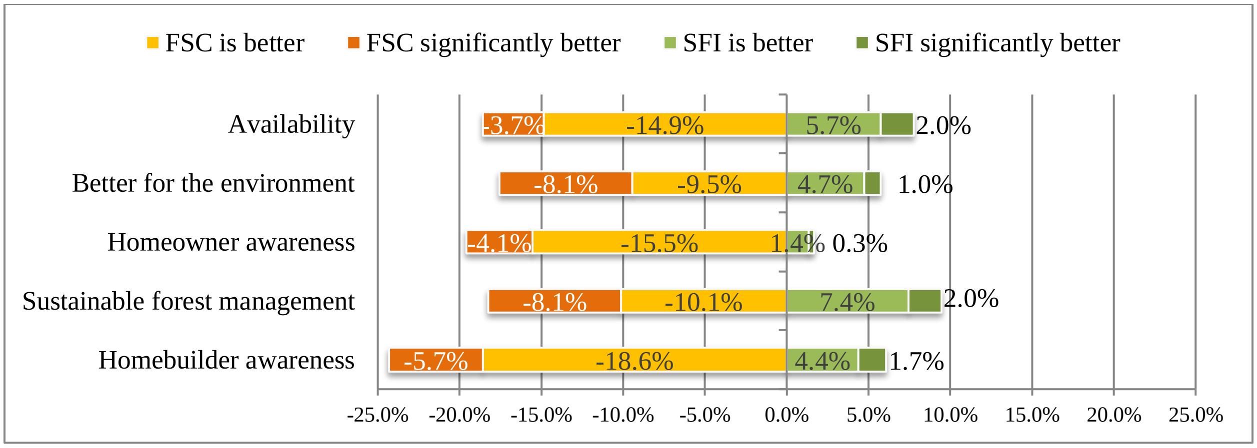


Figure 2-18 Comparison of Perceptions of FSC versus SFI Wood

Architects who had heard of FSC- and SFI-certified wood but had never used certified wood were asked to specify the top three reasons they had not used them (Figures 2-19 and 2-20). For FSC-certified wood, *no customer demand* was ranked most important 55.1% of the time, with *no customer demand* (92.1%), *high cost* (60.2%), and *never felt the need* (44.1%) ranked as the top three reasons why they had not used the program. The response *not readily available* (42.4%) was ranked 1st as many times as *never felt the need* and was almost in the top three. Availability of FSC-certified wood has not always been reliable in all regions and could be a factor preventing its use. Respondents who selected *other* mentioned reasons such as "do not know enough about it," "not a high priority," "political nonsense," and "I try to use locally sourced wood" as reasons they had not used FSC-certified wood.

For SFI-certified wood (Figure 2-19), *no customer demand* (44.0%) was the greatest deterrent. The top three reasons for not using the program were *no customer demand* (86.3%), *high cost* (52.0%), and *not readily available* (44.6%). While there was a slightly lower response for *no customer demand* regarding SFI compared to FSC, *high cost* was not as problematic as it was only selected 1st by 12.6% of the respondents. The response *not readily available* was slightly higher than *never felt the need* for SFI-certified wood, revealing that availability of certified wood is problematic for both certification programs. More respondents selected *will use soon* regarding FSC (20.3%) than SFI (13.1%). Reasons mentioned as *other* for the SFI program included “did not know much about it,” “FSC is the LEED for Homes standard,” “government issues,” “more harmful,” and “cannot secure enough for multifamily project.”

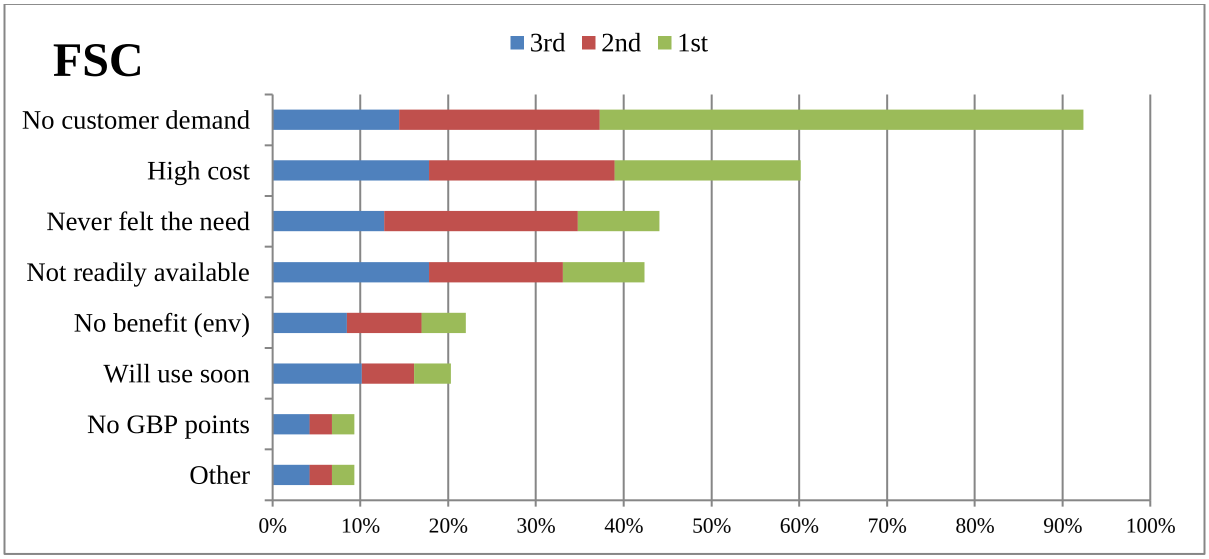


Figure 2-19 Reasons Architects Had Not Used FSC Wood

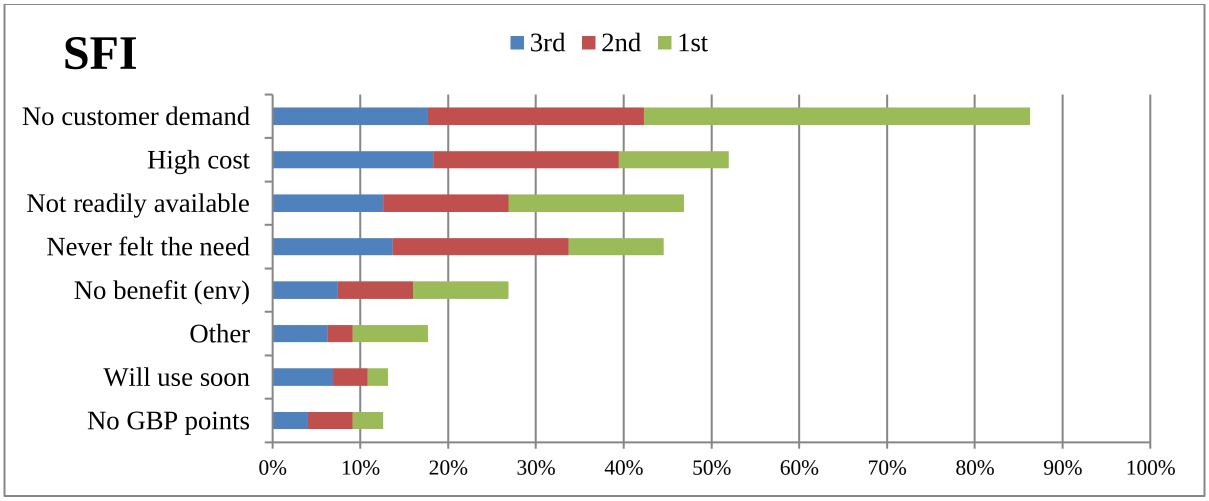


Figure 2-20 Reasons Architects Had Not Used SFI Wood

Architects who had used FSC- or SFI-certified wood were asked for the top reasons they used certified wood from either program (Figures 2-21 and 2-22). The reason ranked 1st for both programs was *good for the environment* with 39.6% for FSC and 33.3% for SFI. The top three reasons for using FSC were *good for the environment* (78.6%), *green building points* (47.4%), and *customer demand* (41.7%). Reasons cited for *other* included “LEED accepts it,” “developer guideline,” and “program has integrity.” The top three reasons for using SFI were *good for the environment* (80.0%), *green building points* (48.9%), and *part of my practice* (47.8%). Architects rated *green image of my company* highly for both programs with a 37.0% response for FSC and 40.0% for SFI. Respondents for both FSC and SFI ranked *profitability* last with 1.6% for FSC and 1.1% for SFI. Architects realized that the additional cost for materials does not necessarily allow them to raise the cost of a home, but rather using ECWPs is a case of environmental ethics (although using ECWPs may lead to a more profitable certified home). *Differentiation of home* was rated low since many homeowners do not know that ECWPs were used in their home. Reasons cited when *other* was selected for SFI users were “builder request,” “industry expectation,” and “competes with FSC.”

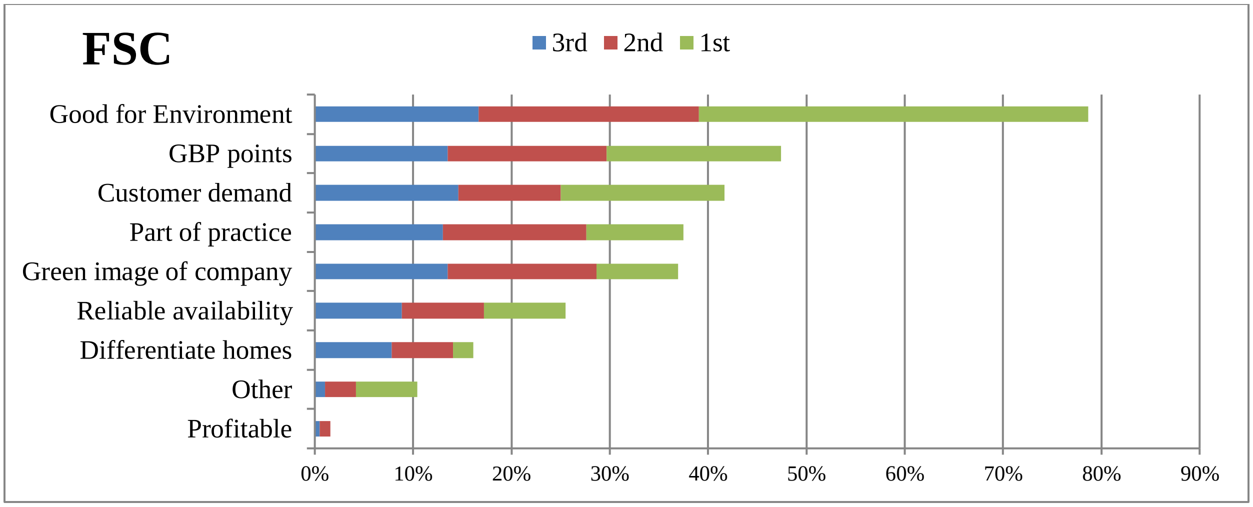


Figure 2-21 Reasons Architects Have Used FSC Wood

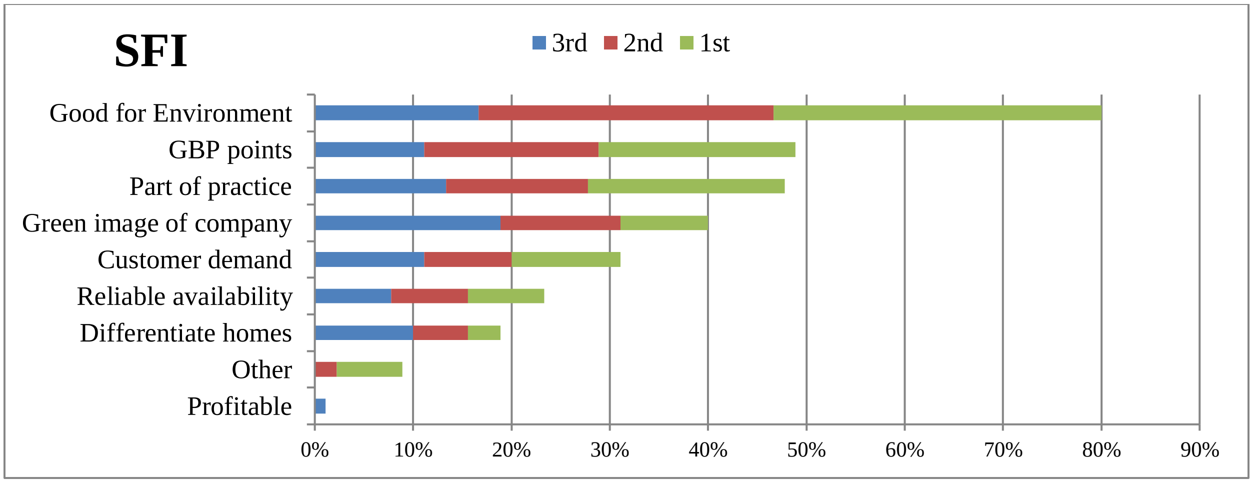


Figure 2-22 Reasons Architects Have Used SFI Wood

2.11 Wood, Steel, and Concrete

There are three main materials used for a building's structural materials: wood, steel, and concrete. The survey sought to gain more insight into architects' perceptions of these different materials with respect to their environmental impact and performance during material production, building use, and end of life. Respondents rated six different attributes of these materials on a five-point scale, with the choices: "strongly disagree," "disagree," "neutral," "agree," "strongly agree." The attributes were *recyclability*, *durability*, *renewability of the materials*, *energy efficiency within the home*, *low* CO_2 *emissions during manufacturing*, and *low* *energy use during manufacturing*. A composite score was calculated for each material along each attribute where a "strongly agree" response scored +2, "agree" +1, "neutral" 0, "disagree" -1, and "strongly disagree" -2. Figure 2-23 shows the responses; the red on the left indicates negative responses (not having that attribute) and the green to the right positive responses (material having that attribute) for each building material. Wood was rated highly for each environmental attribute and was the highest scoring material for *highly renewable*, *energy efficiency in a home*, *low* CO_2 *emissions during manufacturing*, and *low energy use during manufacturing*. Steel and concrete were rated negatively for these four same attributes, with the exception of steel's positive rating in the *highly renewable* category. For *long life* and *recyclability*, wood was rated third and second respectively, although all materials received highly positive ratings in this category with some negative response to concrete's recyclability. It is apparent that architects perceive wood as an environmentally friendly material. Based on this simple comparison architects believe that wood has a better environmental profile than steel and concrete.

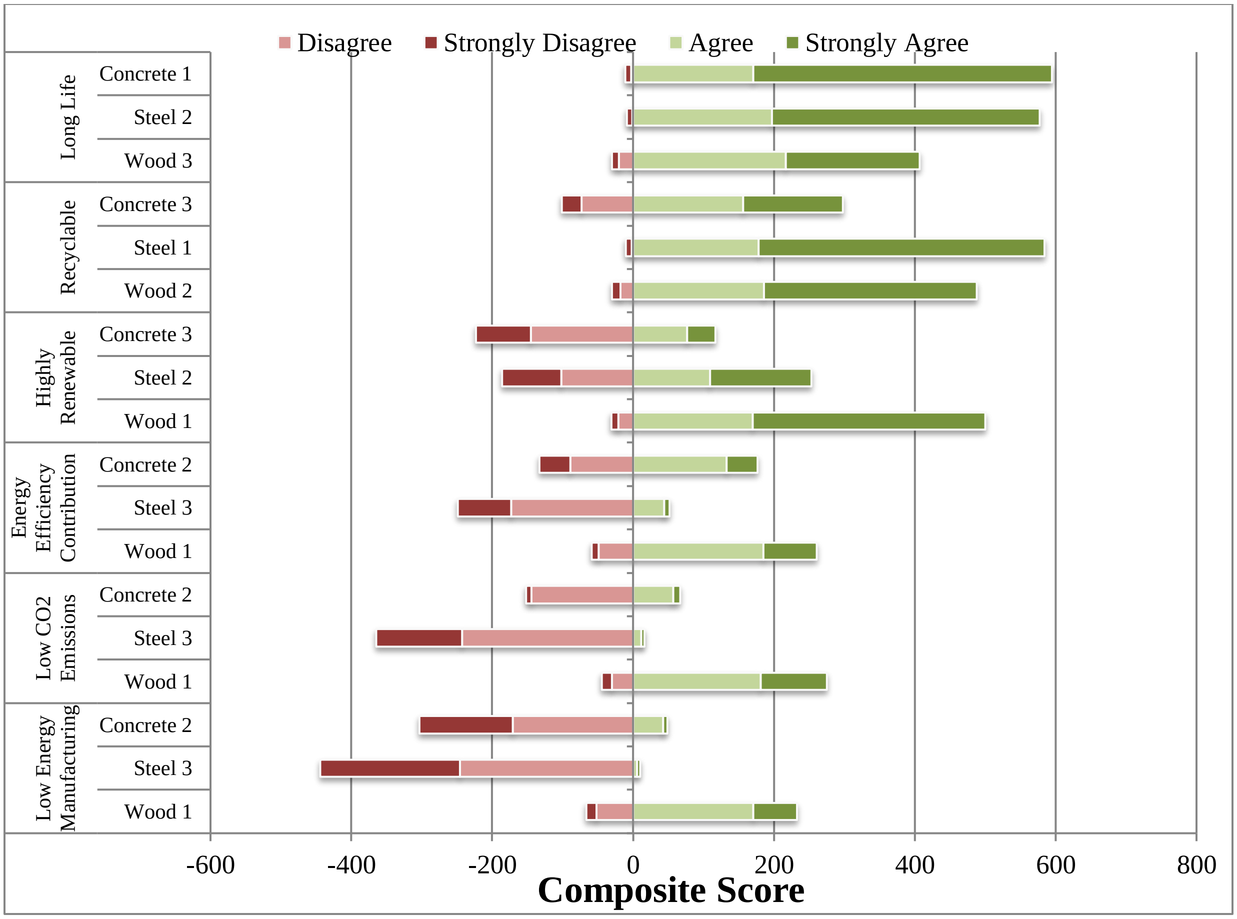


Figure 2-23 Comparisons of Perceptions between Concrete, Steel, and Wood

2.12 Adoption of Innovative Green Building Technologies and Products

Innovative green products and technologies have emerged to meet the needs of energy- and water-conscious home and business owners. As these new products and technologies have become more standard, architects have designed buildings that use them. This process synchronizes homes and provides the homeowner with energy and water savings while maximizing air and lighting efficiency. Architects were asked if they were aware of and/or utilized new products or technologies other than ECWPs as well as their level of use. Potential responses ranged from “I have not heard” of the product, “I am aware of the product/technology, but have not used it,” “I occasionally use it” (light users), and “I frequently use it” (heavy users). Figure 2-24 shows these use levels from the least utilized at the top to the most utilized at the bottom. Even though most architects were aware of solar power generation and water heating, these products had the lowest percentage of overall users. (11.1% and 10.6%, respectively). Most architects were at least aware of all products and technologies presented, with awareness of heat recovery ventilators (7.9%) and radiant barriers (8.4%) the lowest.

A follow up question measured architects' environmental perceptions of these new products and technologies, focusing on reducing the environmental footprint of a house (Figure 2-25). Respondents were asked to rate the importance of green technologies using a composite score in which "not at all important" earned -2 points, "not important" -1, "neutral" 0, "important" 1, and "extremely important" 2. Each of these ratings was based on the composite score to differentiate items that were rated either "not at all important" or "extremely important." The three most important items were energy efficient windows, energy efficient appliances, and water conserving fixtures. Even though it was rated as the 2nd most used in the previous question, engineered wood was rated 5th in terms of reducing the environmental footprint of a house. The least important item was concrete with reduced cement, which is logical because its environmental benefits are at the manufacturing level and not during the operation or function of a home.

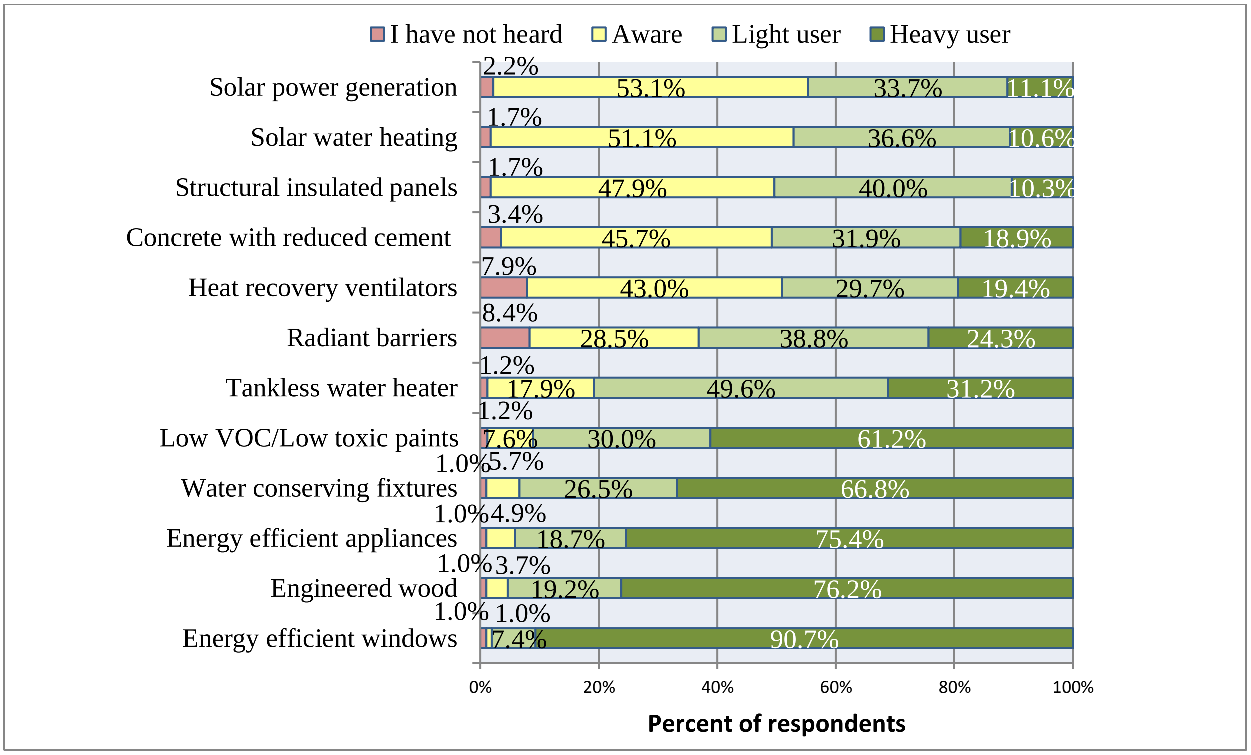


Figure 2-24 Use of Innovative Green Building Technologies and Products

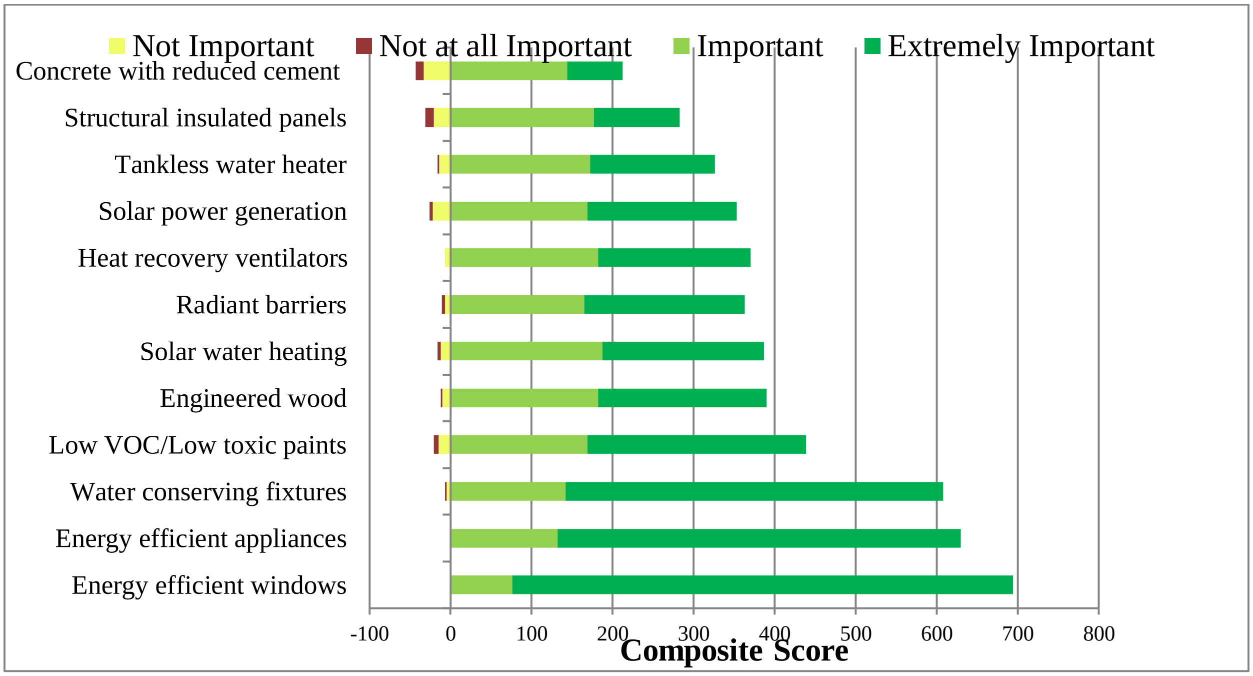


Figure 2-25 Perceived Importance of Green Technology and Products on Environmental Impact

2.12.1 Reason to Adopt Green Building Materials

Certain aspects of green building materials are important during the decision-making process of specifying materials. To understand which factors influence architects' decisions in the material specification process, respondents were asked to rate the importance of several factors using a five-point scale (Figure 2-26). Each product was rated as: "not at all important," "not important," "neutral," "important," or "extremely important." The area to the right in green is the aggregate percentage of respondents who considered the attribute important when deciding to specify a material and the red/yellow to the left is the aggregate percentage of respondents that thought the attribute was not important. There is a clear distinction between the most important factors and the second and third tiers of factors. *Long life*, *energy efficiency*, *low maintenance*, *availability*, *overall price*, and *homeowner demand* were the highest-rated attributes, with only *homeowner demand* having some "not important" responses. This could be because architects often do not work directly with homeowners, hence this factor may not strongly influence their decision making. The second tier of reasons included *locally produced*, *from a renewable source*, *recyclability*, and *made from recycled material.* This tier reflects architects who are focused on the environmental aspects of the materials they choose and/or the sustainable features of a product. Although this group has more "not important" responses, this could be because these factors are only considered when more important factors like price or availability are not as influential (i.e. price between recycled versus new materials is the same). A third tier of factors included *homebuilder demand*, *energy during manufacturing*, and *CO2 emissions during manufacturing.* This group of factors had the highest number of "not important" ratings, perhaps because only a small set of respondents worked directly for homebuilders and most builders use what is specified unless the material is not available. Materials that use less energy and have reduced emissions during manufacturing might not be an important factor now, but architects may start to consider the entire life cycle of a product during the specification process given the architecture 2030 initiative. This initiative aims to reduce energy use during building operations, and raise awareness of the effects of various design decisions to maximum building efficiency (Architecture 2030, 2019). The hope is that architects will be more considerate of the overall sustainability of the buildings they design and of materials that reduce a building's environmental footprint.

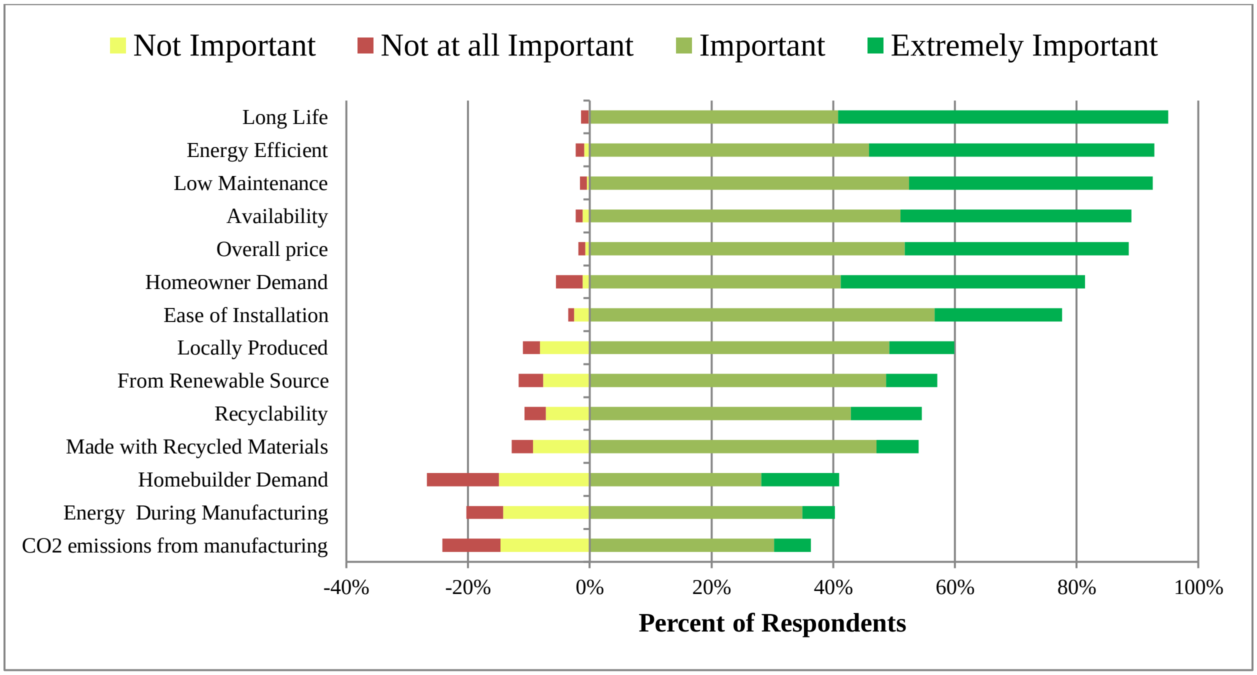


Figure 2-26 Architects' Perception of Importance in Selecting Building Materials

2.13 Summary

This survey of U.S. architects provides insights into their perceptions of building materials for residential homes, while also providing an understanding of their awareness and use of residential green building programs (GBPs) and environmentally certified wood products

(ECWPs). The results were based on the responses of 385 surveys completed by architects who had participated in the design of two or more residential homes. The highlights of these results are discussed below.

2.13.1 Summary of Residential Green Building Programs

The results show that almost all architects were aware of the LEED for Homes Program (>99%), and the National Green Building Standard (85%). Around 24% of architects have used LEED for Homes, but only 7% had used NGBS; 7% participated in both programs. While 74% of architects had not used one of the two main GBPs, there is an opportunity for growth in this sector as almost 30% of architects indicated that they planned to use LEED for Homes in the future and 20% planned to use NGBS. Only slightly over half of architects who had used other regional GBPs (27%) had not used either LEED for Homes or NGBS.

Architects' primary reasons for not using GBPs were *customers not willing to pay*, *no market demand*, and *documentation difficult*. Reasons such as *too expensive* and *not having adequate training* were also significant deterrents. The primary reasons for using GBPs were *differentiated the home, strong market demand*, and *homeowner specified*. Architects noted *documentation is easy* as a main reason for using the NGBS program; this could help with the future marketing of that program.

When comparing the two programs, architects who were aware of and/or had used both programs perceived LEED for Homes as superior regarding *brand recognition, influence on home sales,* and *environmental footprint of the home*. NGBS was perceived as superior regarding *costs of certification*, *easier documentation,* and *easier to understand*. This suggests that continuing to educate architects and potentially streamlining the process of home certification by requesting less paperwork and/or requirements could lead to increased use by residential architects.

The market implications from these results are that architects perceive LEED for Homes as having higher price premiums and having more complex documentation. The program would benefit by addressing these barriers with architects. NGBS has perceptions of straightforward documentation requirements and lower costs, but this program struggles with a lack of homeowner demand. Homeowners were more likely to specify LEED for Homes than NGBS, whereas homebuilders were more likely to specify NGBS. There are market opportunities for addressing these disparities in demand. Architects' primary incentive in using a GBP is their perception of GBPs' environmental friendliness, demonstrating that the environmental benefits of these programs are primary drivers of utilization.

2.13.2 Summary of Environmentally Certified Wood Products

When focusing on environmentally certified wood products (ECWPs), architects were generally aware of wood certified under the two primary programs in the U.S: 87% of architects were aware of the FSC label and 76% of the SFI label. Approximately 45% of architects have not used certified wood in any of their projects; 54% have used FSC-certified wood and 26% have used SFI-certified wood. Practically every user of SFI wood had also used FSC wood. There is room for substantial growth in the use of certified wood with more than half of architects utilizing ECWPs in 10% or less of their homes.

The primary reasons listed for not using ECWPs were *no customer demand, high cost,* and *not readily available*. Architects also mentioned *never feeling the need to use them* as a significant deterrent. This could be because of the perception that using certified wood provides little additional economic value.

The primary reasons for using ECWPs were *good for the environment*, *green building points*, and *being part of their practice*. Another highly rated reason was *customer demand*, specifically for FSC-certified wood. Architects who use ECWPs value the environmental benefits of certified wood beyond any structural or economic value. When comparing the two forest certification labels, FSC-certified wood was rated higher regarding *better availability*, *better for the environment*, and *higher homeowner and homebuilder awareness*, while SFI wood was close to FSC-certified wood in the perception of *sustainable forest management*.

The market implications from these results are that architects were generally aware of both programs but were more likely to have used FSC certified wood. This is most likely a result of being specified in LEED for Homes. As LEED's certified wood requirements have become more flexible, there is more opportunity for SFI to be utilized within its program. If availability of ECWPs has been an issue, the option for architects to specify wood from another certification system could increase the use of SFI certified wood. Architects that had not used ECWPs generally thought there was no demand in the marketplace, but this could be from them not participating in any GBPs. FSC is perceived as having better environmental benefits by architects when comparing the two programs. By accentuating the environmental benefits of all ECWPs, there can market growth for certified wood from both programs as architects prioritize highly renewable and easily recyclable building materials.

2.13.3 Summary of Material Attributes

Architects were asked to compare the environmental attributes of wood, steel, and concrete as structural and non-structural materials in a home. These environmental attributes were *recyclability, durability, renewability of the materials, energy efficiency within the home*, *low* CO_2 *emissions during manufacturing*, and *low energy use during manufacturing*. Wood received a positive rating on all attributes; the lowest rating was *low energy during manufacturing*, while concrete had a positive rating for *long life* and *recyclability*, and mixed perceptions of its *energy efficiency in a completed home*. Steel was also positively rated for *long life* and rated higher than wood for *recyclability*, but there were mixed perceptions regarding its *renewability* and *energy efficiency*. Thus, wood is generally perceived as being a more environmentally friendly material compared to either steel or concrete. Most architects had a negative perception of steel and concrete when considering the materials' respective environmental performances during the manufacturing processes.

The next phase is to take these preliminary findings and determine if certain factors significantly impact an architect's use of ECWPs and GBPs. These factors will be analyzed in depth and utilized in the design of models to ascertain explanations of the research questions and test the hypotheses presented in Chapter 1.

3. Market Segmentation of Architects and Factors Contributing to the Adoption of Green Building Programs and Environmentally Certified Wood Products

Submission Information

The results of this chapter will be submitted to the *Forest Products Journal*, a peer-reviewed journal focusing on the forest products industry and current state of wood science and technology.

3.1 Introduction

There are products at all stages of their life cycles within a category of goods. A product's current stage will determine its adoption or usage rate with consumers. After a product is introduced to the market, the segment of consumers who might consider or be "early" adopters of that product are determined. Marketers collect and analyze data to identify consumers who are willing to take certain risks with a new or advanced product, but some variables are more difficult to measure than simple demographics. These consumers could have underlying orientations or values that drive them to pursue innovative and upgraded products. Segments of consumers will be attracted to products based on certain attributes they identify as meeting their needs, and also aligning with their orientation. Individuals have protected themselves and the world through environmentally conscious purchasing (Ottman, 1992), including products made from renewable or recyclable materials or that utilize resources like energy or water more efficiently. Whether or not consumers are looking for products with these attributes, there may be economic thresholds that hinder the adoption of environmental products. Marketing techniques are continuously updated to find appropriate consumers for new products. While marketing techniques are not uniform, Barry and Weinstein (2009) write that "firms count on segmentation techniques that enable them to craft their selling strategies around a buyer's unique personality, beliefs and organizational influences" (p. 316). Once the target has been identified, segmentation allows firms to focus on their most profitable customers (Peppers & Rogers, 2004).

Market segmentation is relevant to the forest products marketing field, as revealed by studies of consumer perceptions of environmental certification (Ozanne & Smith, 1998). Other studies have focused on the forest products industry, including market segmentation of the post and beam markets in Japan (Roos, Eastin, & Matsuguma, 2005), and builder and contractor segments in the residential siding market (Sinclair & Stalling, 1990). More recent studies were aimed at consumer segments and their preferences for ECWPs; those showing strong tendencies toward certified products were more likely to display environmentally conscious behaviors and perceive certified products as beneficial to the environment (Thompson et al., 2010). Another study of consumers investigated how important previous purchases of green products were to future green purchases (Cai, Xie, & Aguilar, 2017). Some consumers who were asked about their perceptions of the sustainability of wood products were willing to pay more for products with environmental and socially sustainable attributes, even if the social impact of that purchase was indirect (Toppinen, Toivonen, Valkeapää, & Rämö, 2013).

When trying to measure consumer segments, Straughn and Roberts (1999) determined that demographics alone were not enough to segment green consumers. A combination of psychographic and demographic variables better segment users of green products (Thompson et al., 2010). This chapter analyzes variables taken from a survey of architects to determine if there are other attitudes and perceptions that influence architects' choices of building materials. These variables will also be analyzed for their ability to predict architects' adoption of GBPs and ECWPs, and to determine if there are similarities within groups of architects that use ECWPs with different frequencies. First, the theoretical framework that provides the foundation of these analyses will be discussed, and the main constructs defined. Then subsequent multivariate statistical methods and binary non-linear probability models test the significance of the hypotheses developed from these constructs.

3.2 Theoretical Framework

The theoretical framework for this chapter follows key themes regarding businesses adopting customer or profit orientations taken from marketing philosophy originally developed by McNamara (1972). These concepts were further developed by Kotler (1988) to define these orientation themes to include the more recent concept of environmental orientation (Banerjee, Iyer, & Kashyap, 2003; Menon & Menon, 1997). This chapter will also introduce adoption in the context of the residential construction industry, whereas most marketing literature was originally in the context of supporting organizations and their marketing operations. Although there are some philosophical differences between these marketing concepts, the literature reasonably supports the framework utilized below. These orientation and adoption constructs will be analyzed using factors determined from homebuilders' material purchase decisions (Ganguly, Eastin, & Rabotyagov, 2008; Ganguly & Eastin, 2007; Garth, Eastin, & Edelson, 2004) and the factors that influence participation in GBPs or using ECWPs (Bowers, Ganguly, & Eastin, 2014; Ganguly, Bowers, Eastin, & Cantrell, 2013; Sasatani, Bowers, Ganguly, & Eastin, 2015). There is a lack of research specifically targeting architects and their specification of materials within the housing sector. The following empirical investigation will contribute to the literature by identifying different segments of architects, their orientations toward building materials, and the factors that influence their adoption of GBPs and ECWPs.

3.3 Environmental Marketing

Environmental marketing (EM) encompasses the “marketing activities that recognize environmental stewardship as a core business development responsibility and business growth opportunity” (Coddington, 1993). It integrates the environment into business plans and decision making. Menon and Menon (1997) describe EM as a shift in managerial thought from viewing the natural and physical environment as an external influence on decision making to instead seeing it as a central marketing and management strategy. It responds to government and societal environmental awareness (Fraj-Andrés, Martinez-Salinas, & Matute-Vallejo, 2008) and benefits a firm’s external market image (Miles & Covin, 2000). Environmental marketing goes beyond firm awareness and the needs of consumers to generate profits; it also enhances the natural environment and minimizes damages to achieve sustainability (Coddington, 1993).

Peattie (1995) described three fundamental principles of EM: social responsibility, a holistic approach, and pursuit of sustainability. Social responsibility is welfare to society as a whole; the holistic approach utilizes a systems approach as opposed to separate individual functions; and the pursuit of sustainability for all stakeholders, even those with environmental interests. Stern (1993) examined the influence of social altruism and egoism on green behavior. Social altruism (concerns for the welfare of society) can be the sole driver of environmentally friendly market behavior, whereas egoism (concern for one’s own wellbeing) can inhibit willingness to pay the extra costs associated with protecting the environment. Thompson et al., (2010) discovered that environmental marketing of certified eco-labeled forest products appeals to a segment of environmentally conscious consumers for both value-added and non-value-added plywood. Those consumers exhibited a willingness to pay for certified products while also displaying environmentally conscious behaviors and perceived the purchase of certified products as “effectively benefitting” the environment. Other studies have identified consumers that value certification because of their environmental interests (Forsyth, Haley, & Kozak, 1999; Ozanne & Smith, 1998).

Environmental marketing appeals to consumers who have inherent market orientations toward products with environmentally friendly attributes. These consumers may also place great importance on the environment impacts of their purchasing decisions. The effects of orientation on decision making will be discussed below.

3.4 Market Orientation

An organization or individual’s orientation is described as an internal set of operating beliefs that make up its operating philosophy (Khandalla, 1977). Kotler and Mindak (1978) see market orientation as the underlying business philosophy of the firm. Narver and Slater (1990) proposed that market–oriented organizations are more likely to be innovative since they are sensitive to market needs. Jaworski and Kohli (1996) defined market orientation as the production of market intelligence pertaining to customers, competitors, and the forces affecting them. While market orientation was originally synonymous with customer orientation (Houston, 1986), Hunt and Morgan (1995) argued that market orientation has a dual focus on customer and competitors and therefore can be measured in both categories (Sørensen, 2009). Deshpandé and Farley (1998) also posited that market and competitor orientations are distinct and that only customer oriented activities should be included with market orientation. Sørensen (2009) argued that if the market orientation construct is too broad, its associated measures may hide true underlying drivers. A third orientation in the literature is an environmental orientation (Banerjee et al., 2003; Menon & Menon, 1997; Wood & Robertson, 1997). Three architect orientations are considered while trying segment survey respondents based on the attributes they consider when making material choices: competitor/economic orientation, customer/social orientation, and environmental orientation.

3.4.1 Economic Orientation

Economic, i.e. competitor, orientation is a combination of production orientation (low costs) (Cravens, Hills, & Woodruff, 1987) and competitor orientation (opportunities for competitive advantage) (Aaker, 1988; Day & Wensley, 1988); its goal is to maximize profitability and competitiveness. Competitors are organizations that offer similar products or services that can serve customer needs equally (Porter, 1980). A competitive environment can affect an organization's market orientation, especially if it already contains competitor-oriented firms. This environment leads to high buyer (customer) power and competitor concentration within the market, but ultimately results in low market growth and competitor hostility (Day & Wensley, 1988). "A competitor-centered perspective leads to a preoccupation with costs and controllable activities that can be compared directly with corresponding activities of close rivals" (Day & Wensley, 1988). This orientation and its focus on low cost tempers an organization's innovation with its market offerings. Ozanne and Vlosky (1997) asked how much respondents were willing to pay for certified items to gauge their economic and environmental orientations. Their study showed that economically oriented respondents were less likely to pay a premium for certified wood. This orientation values profitability and competitiveness, while a customer-focused orientation prioritizes embedded interconnected relationships with its stakeholders (Rowley, 1997).

3.4.2 Customer Orientation

Social or customer orientation seeks to understand one's buyer and market and create continuous added value (Narver & Slater, 1990). Firms must understand the customer's needs and adapt services or product mixes accordingly to retain high levels of customer satisfaction. Deshpande et. al. (1993) discussed firms that are "customer oriented" as putting the customer and their needs first. It also strengthens the relationship between customer and firm and strengthens the latter's organizational strategy. According to Day and Wensley (1988), a customer-focused approach has the advantage of examining all competitive choices that align with the customer's needs as well as their perceptions of what makes an organization superior, but this focus lacks a connection to the activities and variables controlled by management. In terms of a firm's innovative behavior, a customer orientation can help evaluate possible market segments, the importance of various markets, and their rate of growth (Gatignon & Xuereb, 1997). A customer-oriented seller creates value by increasing buyers' benefits compared to their costs (Narver & Slater, 1990). Scholars have also broadened the definition beyond current customers to include future consumer and societal needs (J. Narver, Slater, & MacLachlan, 2000).. At the same time, studies have refined stakeholders beyond the previous meaning of those obliged to shareholders, but to include customers as the primary stakeholder (Lusch & Laczniak, 1987). A firm's stakeholder orientation is more focused on addressing customer issues, like adopting issues that support environmental conservation (Ferrell, Gonzalez-Padron, Hult, & Maignan, 2010). In the forest products marketing literature, Roos et al. (2005) found that Japanese builders who were market oriented were inclined to use domestic species since they believed it was the best way to meet customers' demands in the post and beam market.

3.4.3 Environmental Orientation

Whereas most of the literature attempts to measure environmental orientation (EO) in the context of a firm's decision making and performance, this study focuses on architects and their decision-making processes during product selection. However, it is important to look at past research as the basis for measuring orientation within the forest products industry. Within firms, environmental orientation (EO) recognizes the environmental issues facing a firm and its "collective conscience that occurs over time and the knowledge that is gained is fused and internalized within standard operating procedures and values" (Banerjee et al., 2003). Banerjee et al. (2003) found that EO has a high impact on a firm's environmental strategy. Firms' eco-orientation is seen as a reaction to demands from society to meet ethical and moral responsibilities (Miles & Munilla, 1993). There are two elements to this type of orientation, external and internal: external EO involves relationships with external stakeholders, while internal EO encompasses internal values, standards of ethical behavior, and a commitment to protecting the environment (Banerjee, 2002).. In the context of this study, EO will be the tendency for an individual or organization to tailor its decision making toward attributes that benefit the environment. Many studies describe the environment as a moderator variable affecting market orientation, but Wood and Robertson (1997) describe EO as its own orientation that influences choices of environmental strategies (i.e. whether or not to pursue green building).

Consumers show their environmental interest by evaluating products based on the environmental responsibility of manufacturers rather than just on performance and price (Ozanne & Smith, 1998). There is a market segment of firms that sees the many consumers who want to purchase environmentally responsible goods and services as a source of competitive advantage (Roper, 1990; Straughan & Roberts, 1999). Research in the forest products marketing field has focused on market orientation from the perspective of wood product manufacturers and performance. One study measured the orientations of firms certified under the FSC program and found that they adopted FSC to have access to overseas markets (Yuan & Eastin, 2007). Vlosky and Ozanne (1998) found that larger wood products manufacturers in the U.S. were more environmentally oriented. Cao (2011) revealed that Chinese firms were more likely to adopt an environmental marketing strategy if they were environmentally oriented. This research will determine if architects in the U.S. residential sector have latent orientations when selecting materials for the homes they design. Specifically, it will establish whether some architects have environmental orientations with preferences for building green and specifying innovative or environmentally certified building materials.

3.5 Adoption

Incremental changes to the typical ways businesses operate differentiate mainstream business and entrepreneurial activity (Larson, 2002). Future product or service solutions are evolved from the current generation of product and practices. These new products or modifications to existing products can be considered what Rogers (1995) defines as an innovation: an idea, practice, or object that is perceived to be new by an individual or other unit of adoption. Jansson, Marell, and Nordlund (2010) showed how beliefs, values, norms, and habit strength determine willingness for eco-adoption. Innovative solutions, like the implementation of new design practices in residential green building programs, also provide a marketplace for innovative products that are more energy and water efficient than existing products, while also having the potential to reduce the carbon footprint of a home. Sustainability-focused organizations who are early adopters can develop core competencies that competitors have difficulty replicating (Nidumolu, Prahalad, & Rangaswami, 2009).

Individual readiness to adopt varies, particularly since only a small portion of the population has done so successfully (Rogers, 2003). Bass (1969) modeled adoption of consumer goods and determined when “innovators” would first adopt a new product. Early adopters of technical innovations are usually emulated by followers (Rogers, 1995) or, as Bass (1969) defined them, “imitators.” Rogers proposed that various communication channels affect perceptions of innovations; based on this theory, there is a stage in between awareness and adoption in which the perception of the new technology or innovation has enough inherent value to drive adoption (Rogers, 1995). Agarwal and Prasad (1998) demonstrated that potential adopters explore possible results from using an innovation to determine whether to adopt or not. They presented three perceptions that predict adoption behavior: relative advantage (the extent to which an innovation offers an advantage over current methods or products), ease of use (the effort needed to use the new technology), and compatibility (the extent to which an innovation is consistent with current “values, needs, and past experiences of potential adopter” (Agarwal & Prasad, 1998; Rogers, 1995)).

Green building products or technologies have typically altered previously existing products to elevate building efficiencies and create the narrative of an environmentally responsible consumer. Companies introduce new products to adapt to the needs of consumers as they become more aware of their individual environmental impacts. The housing industry has been resistant to dynamic changes of established practices and instead prefers to refine existing technologies (Koebel & Cavell, 2006). Since there has been increasing pressure on the forest products industry from non-wood products in the construction sector, industry innovation can provide a competitive advantage for forest products manufacturers (Hansen, 2010). A study by Hassell (2003) identified important factors in the adoption of innovations within the residential construction industry, including competition and the fragmentated nature of the industry. The latter was related to geography (e.g., different regulations and codes) and organization structure (e.g., communication between builders and within organizations). Relatively few studies have examined the residential construction industry’s process of adopting and diffusing new types of construction materials and technology (Blackley & Shepard III, 1996; Taylor & Levitt, 2004). Beal and Rogers (1960) performed early research on this topic, examining the diffusion of information regarding farm house construction, yet there have been only a few recent efforts to assess adoption of innovations (Lutzenhiser, 1994; McNicholas, 1994). While these studies assessed barriers to adoption within the construction sector, McNicholas did not specify whether this was residential or commercial construction nor the attributes of the innovations, and Lutzenhiser did not properly address research claims through an empirical process.

Table 3-1 summarizes the studies that have investigated the factors that influence the adoption of innovations within the residential construction industry. Within any industry, the adoption of innovations is a function of the industry’s characteristics, the interrelationships between industry companies and firm characteristics, and, above all, how the innovation is characterized (Porter, 2008). Ignoring any of these factors results in a partial understanding of the market characteristics and contradictory or non-generalizable outcomes (Porter, 2008). The studies below are mostly based on subjective evidence and are not substantiated by empirical evidence. Adoption studies lead to industry- or product-specific outcomes by revealing the differences between the studied industries and their products. This research looks at the end-use of ECWPs, participation in GBPs, and the drivers for adoption; asking architects why they adopt some innovations but not others can lead to critically important conclusions.

Table 3-1 Factors Impacting Adoption of Innovations within the Residential Construction Industry

Factor	**Studies**
Fragmented nature of the industry	Goldberg & Shepard, 1989; NAHB, 1991; Poitras & Duff, 1988; Ventre, 1979
Government regulations or building codes	Poitras and Duff 1988, Prestemon 1973
Inter-organizational networks/links	Colebourne, 1994; Lutzenhiser, 1994
Uncertainty of quality or lack of familiarity with the product	Prestemon 1973
Justification of the cost of adoption or profitability	Prestemon 1973, Colebourne 1994, Spall, 1971, Goldberg and Shepard 1989, NAHB Research Center 1991
Uncertainty related to market acceptance	Prestemon 1973, Spall 1971, Goldberg and Shepard 1989, NAHB Research Center 1991
Firm size	Oster and Quigley 1977, Spall 1971, Goldberg and Shepard 1989, NAHB Research Center 1991
Labor unionization	Oster and Quigley 1977
Builder education	Oster and Quigley 1977, Colebourne 1994, Spall 1971
Managerial experience	Spall 1971
Management intensity	Goldberg and Shepard 1989, NAHB Research Center 1991
Specialized inputs	Goldberg and Shepard 1989, NAHB Research Center 1991
Capital intensive equipment	Goldberg and Shepard 1989, NAHB Research Center 1991

Most studies regarding the use of innovative or sustainable construction materials have focused on the consumer since they will ultimately incur the cost of the products or materials in a finished home. Often in the adoption of new products and technology, innovative organizations pay attention only to early customers (or early adopters) and do not focus on other potential customers. Information provided through technology transfer programs and university research and outreach have helped early-adopting homebuilders learn about new technologies and innovations; however, homebuilders usually wait for established manufacturers to offer these new products, instead of utilizing smaller, lesser known ones (Koebel & Cavell, 2006). While this study does not directly measure innovativeness, it is important to understand the adoption of innovative or “green” products as a potential indicator of future adoption of other innovative programs or products: in this case, the adoption of other residential GBPs or other green building products and technologies for a home. Adoption in the forest products industry has mainly examined innovation of technologies in certain segments like furniture (Xiaozhi Cao & Hansen, 2006), sawmills (Knowles, Hansen, & Shook, 2008), material substitutions (Eastin et al., 2001), industrial products (Fell et al., 2003), and the residential construction industry (Ganguly, 2008).

3.5.1 Adoption of Green Building Programs and Environmentally Certified Wood Products

The first ECWPs on the market were finished goods and value-added products used within a home. Structural products like lumber can also come from certified forests, but many originate from non-certified sources to meet demand. Softwood lumber and structural engineered wood products produced in the U.S. are mainly consumed within the residential construction sector (including repair and remodeling), making it the largest potential market for ECWPs in the U.S. (WWPA, 2016). From a wood products marketing perspective, it is vital to understand how architects specify ECWPs in their designs and the factors impacting their use. Structural ECWPs are not standard use within the industry, signaling room for growth in this sector. The acceptance of ECWPs requires market confidence in certification programs as well as specifiers and end-users' awareness and appreciation of the environmental attributes of certified wood (Sasatani, Ganguly, Eastin, Chen, & Bowers, 2015). A study by Ganguly, Eastin, and Rabotyagov (2008) found that homebuilders' environmental awareness of and willingness to try innovative building materials increased their use of ECWPs. While builders utilize ECWPs at the construction site, architects' specification of them could play an even more crucial role in their use. While homebuilders and remodelers frequently specify materials, some homeowners work directly with architects; this homeowner and architect relationship could heavily influence decisions to use of innovative building materials. This relationship could be even more significant if the home is designed to meet the thresholds of a GBP.

Awareness of ECWPs has slowly grown among end-users and consumers (Ozanne & Vlosky, 2003), but this growth has largely been on the consumer products level as more companies offer FSC- or SFI-certified products. However, this increased customer awareness of the benefits of certified wood has not led to an increased demand for ECWPs in the housing sector. Gaining awareness of different certification programs takes time, and eco-labels must be understood before they are adopted (Thøgersen, Haugaard, & Olesen, 2010). Customers, scholars, and environmental NGOs remain skeptical about the effectiveness of forest certification programs in reducing tropical deforestation since there are other factors driving this issue (Dauvergne & Lister, 2010; Gronroos & Bowyer, 1999; Ozanne & Vlosky, 2003; Rametsteiner, 2002) that have affected consumers' perceptions of the trustworthiness of the organizations that certify forests (Vlosky, Ozanne, & Fontenot, 1999). While the general feeling among U.S. wood-products manufacturers was that certification was more critical for tropical forests than temperate forests (Vlosky & Ozanne, 1998), certification programs focused on protecting tropical forests could hinder the ability to provide a reliable supply of certified wood products (Bass, Thornber, Markopoulos, Roberts, & Grieg-Grah, 2001), even though tropical species are not typically used for the structural components of a home.

A substantial amount of the literature on ECWPs has focused on customers' willingness to pay (WTP) a premium for certified wood; most scholars believe that consumer demand and WTP drive the market for ECWPs. Haener and Luckert (1998) identified that a green price premium impacted forest certification. The WTP premium for a home built with certified wood products was 1.3% (Gronroos & Bowyer, 1999), whereas other products have shown a greater range between 1.4% and 18.7% (Aguilar & Cai, 2010; Aguilar & Vlosky, 2007; Forsyth et al., 1999; Ozanne & Vlosky, 1997). Meta-analyses of all WTP studies of forest-product-related items actually show an increase in WTP over time (Cai & Aguilar, 2013), which may indicate consumer support of ECWPs. If customers are unwilling to pay a premium for ECWPs, many forest-product companies ask for non-market-based incentives (like GBPs) to offset the additional cost associated with the certification process (Vlosky & Ozanne, 1998). Another study by Vlosky and Ozanne (2007) tried to measure different segments of the building sector WTP for ECWPs, revealing that architects are more willing to pay a premium than contractors and retailers. On average, architects would pay an 11.3% premium for a certified wood stud. Other studies suggest that customers prioritize the price and other tangible attributes of the home higher than its environmental attributes when purchasing new homes or other wood products (Anderson & Hansen, 2004; Gronroos & Bowyer, 1999; Rametsteiner, 2002). There is insufficient evidence to demonstrate the universal appeal of ECWPs among consumers and end-users, but a study of homebuilders did find that the environmental benefits of ECWPs were more influential to purchasing than high costs (Estep et al., 2013). While home center chains sell varying amounts of ECWPs to support their corporate social responsibility efforts without passing significant costs to the consumer (Dauvergne & Lister, 2010), this effort has led to an unreliable supply of ECWPs for end-users. Kozak et al. (2004) suggested that proper dissemination of information regarding the benefits of forest and wood certification among potential customers not only increases the demand for certified wood products, but could also encourage these customers to pay a price premium for certified wood. WTP could be the ultimate hurdle to the adoption of ECWPs if price thresholds are deemed too great. In that case, designing with ECWPs becomes too much of a financial burden and is not perceived to be offset by potential benefits (either environmental attributes or points toward green building certification).

3.6 Review Summary

As the literature review revealed, there have been few analyses of architects' drivers to adopt building products and innovations within the U.S. residential construction industry. Most studies have been qualitative, providing crucial initial exploration to gauge an industry's current status and needs. As the next step, a large nationwide survey of architects can provide data that help determine regional and other demographic differences of adopters and non-adopters. By comparing the differences and similarities within these groups, the factors that determine these groupings can be discovered and analyzed. Furthermore, past studies of eco-labeled products have mostly been at the customer level regarding purchase of value-added wood products for home improvements (Thompson et al., 2010). This study specifically looked at commodity lumber products used in the design of a residential home to determine the appeal of or aversion to environmentally certified lumber. In most cases, lumber is specified based on performance as a structural building material with no discernible difference between certified or non-certified structural softwood lumber (since all structural lumber must meet uniform wood grading and quality standards). This is the crux of the marketing challenge confronting certified structural lumber, a commodity product that is usually hidden within the walls, floor, or roof of a home. For these ECWPs, it becomes more difficult to command a price premium without other non-market-based incentives. GBPs' point-based systems provide an opportunity to increase the demand for certified structural lumber that could potentially command a modest price premium even though it contributes only a small fraction of the total cost of building materials.

3.7 Research Questions

Chapter 3 utilizes the survey findings from Chapter 2 to address particular questions regarding architects' market orientation, market segmentation, and participation in residential GBPs and specification of ECWPs.

- Do architects have particular market orientations that affect their selection of building materials (economic, social, or environmental)?
- Do architects differ in their perceptions of building materials?
- Do architects prefer innovative building products that influence their adoption of GBPs and ECWPs?
- Which factors influence architects' adoption of GBPs and ECWPs?
- Are there factors that limit the use of ECWPs and residential GBPs?
- Are there links between the use of residential GBPs and the use of ECWPs?
- Are there similarities within groups of architects with varying levels of ECWPs use?

These research questions will be developed into the following hypotheses and tested with statistical methodologies. These processes and models will be described in more detail to ensure the statistical tests are accurate and appropriate measures for these questions.

3.8 Model and Hypotheses

This section reiterates the hypotheses from Chapter 1 and the empirical testing to follow. Architects' survey responses will be analyzed to determine if different market orientations exist. Then the survey respondents will be segmented into groups to verify if there are architects who are more likely to participate in GBPs and specify ECWPs. Groups will then be compared for statistically significant differences between the groups to discover if there are variables that can determine group membership.

H1: Different market segments of architects exist who are more likely to participate in GBPs

H2: Different market segments of architects exist who are more likely to specify ECWPs

The next step will utilize a prediction model to determine the factors influencing the adoption behavior of architects participating in GBPs. A prediction model can provide a likelihood or probability that certain factors will result in adoption.

H3a: Architects who are independent (work for themselves) are more likely to participate in GBPs

H3b: Architects who work directly with homeowners are more likely to participate in GBPs

H3c: Architects who have been in business longer are more likely to participate in GBPs

H3d: Architects who conduct business in urban/suburban areas are more likely to participate in GBPs

H3e: Regional differences exist between architects who participate in GBPs

H3f: Architects who have participated in other green building programs are more likely to participate in GBPs

Similar hypotheses will be tested for the adoption of ECWPs to determine if the factors predicting architects' participation in GBPs are similar to those that determine an architect who specifies ECWPs. Participation in LEED for Homes and NGBS will be used as independent variables to measure their influence on predicting the adoption of ECWPs.

H4a: Architects who are independent (work for themselves) are more likely to specify ECWPs

H4b: Architects who work directly with homeowners are more likely to specify ECWPs

H4c: Architects who have been in business longer are more likely to specify ECWPs

H4d: Architects who conduct business in urban/suburban areas are more likely to specify ECWPs

H4e: Regional differences exist between architects who specify ECWPs

H5a: Architects who have participated in other green building programs are more likely to specify ECWPs

H5b: Architects who have participated in LEED for Homes or NGBS are more likely to specify ECWPs

The factors that were determined from architects' orientations toward material attributes will be entered into the adoption prediction model. The survey also measured architects' preferences for other high environmental impact building products; it will be determined if those preferences indicate an architect who is more progressive in their selection of certified building materials or participation in GBPs.

H6a: Environmentally oriented architects are more likely to participate in GBPs

H6b: Innovative technology-oriented architects are more likely to participate in GBPs

H7a: Environmentally oriented architects are more likely to specify ECWPs

H7b: Innovative technology-oriented architects are more likely to specify ECWPs

Architects who rated the environmental attributes of wood higher than other materials may be more likely to specify ECWPs. Also, their perceptions of price premiums on ECWPs will be the input of WTP for certified wood to analyze how significantly it impacts ECWP adoption.

H7c: Architects who rate the environmental attributes of wood highly are more likely to specify ECWPs

H8: Architects are not willing to specify ECWPs because of their higher prices

Below are diagrams of the prediction models for both participation in GBPs (LEED for Home and NGBS) (Figure 3-1) and specification of ECWPs (FSC and SFI) (Figure 3-2).

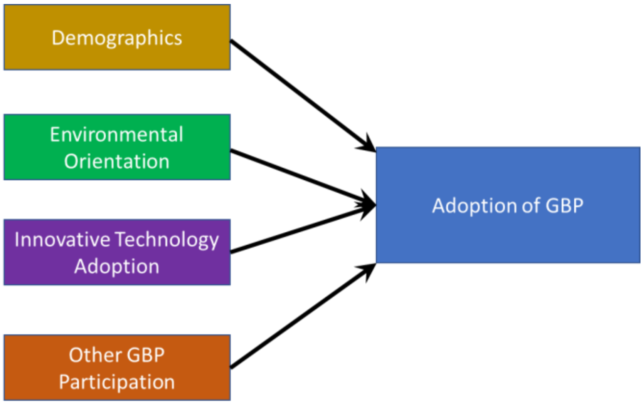


Figure 3-1 Prediction Model for Adoption of GBPs

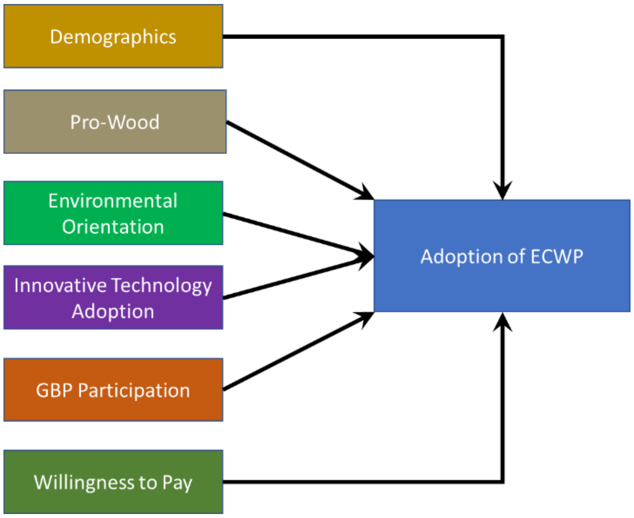


Figure 3-2 Prediction Model for Adoption of ECWPs

Finally, after the model has discovered the drivers for using ECWPs and GBPs, it will be important to highlight any differences in the users of different green building programs analyzed in this survey. To determine if differences exist between architects that specify ECWPs at varying frequencies, it would be important to determine if similarities exist between occasional users of ECWPs versus frequent users of ECWPs.

H9: Similarities exist within groups of heavy users and light users of ECWPs

3.9 Constructs Measured

The constructs measured in this study come from previous market studies on the forest products industry, orientation, and brand awareness. The survey's questions relate to demographic measures, adoption of innovative green building products, GBPs, ECWPs, and perceptions of material attributes and preferences. Table 3-2 summarizes these constructs in the process of determining the significant influences on architects' participation in GBPs and specification of ECWPs in homes they design.

Table 3-2 Constructs Measured for this Study

Construct	Description	Source	Use
Willingness to Pay	Perception of price premium of certified wood	Ozanne and Vlosky (1997)	Use of certified wood
Demographics	Firm characteristics	Koebel 2006 and Developed for this study	Certified wood & green building
Economic Orientation	Material attributes that have an economic affiliation	Cravens, Hills, and Woodruff (1987)	Certified wood & green building
Customer Orientation	Material attributes that have a customer affiliation	Cravens, Hills, and Woodruff (1987)	Certified wood & green building
Environmental Orientation	Material attributes that have an environmental affiliation	Miles and Munilla (1993)	Certified wood & green building
Brand Awareness	Based on respondent's knowledge of existence of brand	Sinclair and Seward (1988), Aguilar and Vlosky (2008)	Certified wood & green building
Innovativeness	Experience with innovative building materials	Ganguly (2008)	Certified wood & green building

3.10 Methods

Statistical methods are employed to analyze variables of interest and discern differences within the data. Orientation and market segmentation will use multivariate statistical methods to find correlation patterns and measure similarities within groupings of architects. To measure adoption, probability theory will be used to make statistical inferences with the data and determine the significant factors influencing whether an architect is likely to participate in a GBP or specify a home with ECWPs. These methods will be described in more detail in the following sections.

3.11 Results

Based on the survey data presented in Chapter 2, statistical methods were utilized to test hypotheses and formulate conclusions to the research questions. The survey variables were analyzed for their influence on architect market segmentation and GBP and ECWP adoption in the U.S. residential sector. The following results were based on the 385 completed survey responses.

3.12 Market Segmentation

Market segmentation is a method of grouping consumers into segments that differ from each other yet contain some similarities. If significant differences between segments exist, it is easier to identify these unique segments in the marketplace. For example, if different segments of architects reside within the residential housing sector, it would be helpful for marketers to find the proper segment for promoting environmentally friendly building materials.

The objectives of this section are: first, to determine if architects have inherent orientations based on psychographic questions regarding their specification of building materials; second, to determine if there are distinct groups of architects that have similar traits within these groups; and third, if these segments predict the use of GBPs and ECWPs. Factor analysis methods will be utilized to find variable groupings within the survey questions to determine if different orientations exist (economic, social, environmental). Clustering methods are then utilized to perform market segmentation; clusters will be based on a similarity matrix from the same psychographic questions regarding material attributes. The questions in these analyses are in Section 5.1 of the survey (Appendix A).

3.12.1 Orientation

Surveys can measure constructs by designing questions based on either established or developed scales for a specific industry or population of interest. Marketing surveys use multiple questions to measure concepts that would be difficult to understand with only one question. A field of questions can potentially capture a facet of that construct (i.e., an environmental orientation) by measuring the degree of correlation between responses. Factor analysis is one way to identify the common variance underlying questions while trying to parse out systematic error (Lattin, Carroll, & Green, 2003). This process groups responses together with other like variables based on correlation methods.

This section considers whether underlying latent factors or constructs can account for the market orientation of architects among several measured variables. To collect this data, survey questions were developed to measure architects' orientation constructs and material attributes influencing material choices. Scales to measure similar constructs (i.e., orientation) were available from previous studies, but were not appropriate for measuring the residential construction market. While developing a relevant survey instrument, three orientations from the marketing literature were identified: economic, social (customer), environmental. A scale implanting two to six items was selected for each orientation construct with respect to its content or face validity. Items were tested for clarity and appropriateness by the American Institute of Architects, industry experts, and marketing academics. The online survey (Appendix A) was pre-tested and evaluated for clarity of the scale items and measures. Based on their feedback, all items remained in the survey.

Architects were asked about the attributes that influenced their specification of building materials. Each respondent was asked how important each of the following attributes was when specifying building materials using a rating from 1 to 5, with 1 being *not at all important* and 5 being *extremely important.* A correlation matrix showing all variables from Section 5.1 of the survey are in Appendix B. The correlations between the questions were used to check the convergent and discriminant validity. Most of the variables showed strong correlation with the others; *CO2 emission during manufacturing* and *energy use during manufacturing* had the highest correlation (0.775), while *homebuilder demand* and *longevity of the material* had the lowest correlation (0.05), which was not statistically significant.

To meet the assumptions of factor analyses (FA), the correlation of all measured variables with at least one other variable should be higher than .30. All variables met this requirement (the lowest was 0.408), thus factors should be discernable from the data. The Kaiser-Meyer-Olkin measure of adequacy for these analyses was .888, demonstrating the reliability of the relationships between pairs of variables (a value greater than .6 is required for good FA). Bartlett's test of sphericity was significant, but this is common in data with large sample sizes (χ^2 (91) = 2527.3, $p < .001$). The anti-image correlation matrix contains the negatives of partial correlations between pairs of variables with the effects of other variables removed. If the diagonals of the matrix are all greater than .5, then the variable should be included in the FA (min = .687).

In exploratory FA, an attempt is made to describe and summarize data by grouping together correlated variables. Principle Components Analysis (PCA) produces these grouped components, whereas FA produces "factors" ascertained by a similarity matrix that has been rotated so it is more interpretable by changing underlying mathematical properties (e.g., uncorrelated factors are orthogonal) (Tabachnick & Fidell, 2007). The goal of using FA in this research is to reduce the number of measurement variables to a smaller number of factors to test underlying processes (e.g., the different orientations among architects).

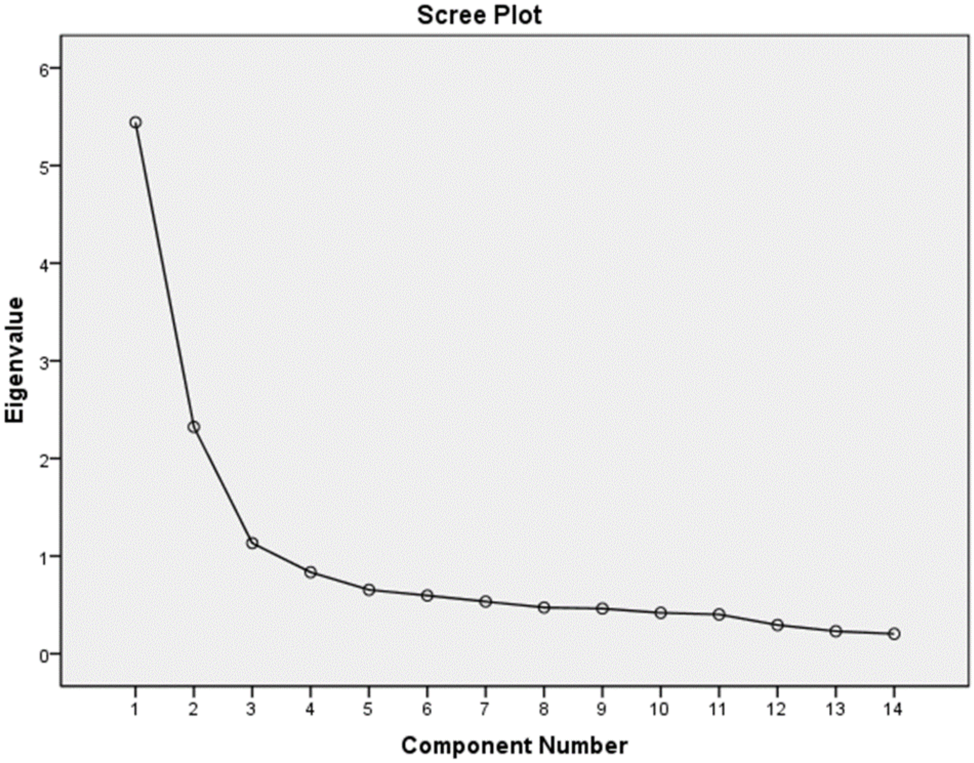


Figure 3-3 Three-Factor Scree Plot for Architect Orientation

The number of factors retained in the factor analysis followed the Kaiser-Guzman guidelines, which dictates that any eigenvalue over 1.0 should be retained for further analysis. The cumulative variance shows that three factors explain 63.6% of the variance (Table 3-4). The three factors retained show how variables are “loaded” onto designated factors so that there is zero correlation between factors. Table 3-3 shows the “factor loading” of the variables with a higher number, resulting in a variable that is more representative of that factor. These coefficients range from 0 to 1 and are grouped in their relevant factors.

Once the rotated loading matrix is available, the relationships are discernable. The communality of a variable is the variance accounted for by the factors. Table 3-3 shows the communalities extraction and the factor loadings for the three-factor solution.

Table 3-3 Rotated Varimax Loadings for Architect Orientations

Importance of each attribute	Communalities Extraction	Orientation Environmental	 Economic	 Social
C02 emission during manufacturing	0.695	**0.831**	0.032	0.060
Energy use during manufacturing	0.738	**0.850**	0.041	0.117
Made from recycled materials	0.718	**0.823**	0.193	0.060
Made with renewable raw materials	0.766	**0.858**	0.168	0.042
Recyclability of the material	0.717	**0.828**	0.175	-0.001
Locally produced materials	0.597	**0.741**	0.220	0.010
Homeowner demand	0.577	0.089	0.309	**0.688**
Homebuilder demand	0.763	0.055	0.089	**0.867**
Energy efficiency	0.557	0.501	**0.550**	-0.059
Overall price	0.518	-0.043	**0.651**	0.303
Availability	0.505	0.114	**0.663**	0.229
Low maintenance	0.621	0.176	**0.763**	0.090
Ease of installation	0.534	0.102	**0.695**	0.199
Longevity and durability	0.592	0.280	**0.704**	-0.134

Extraction Method: Principal Component Analysis.

Cronbach’s alpha tests a measure’s reliability and is commonly used when trying to assess the internal consistency of a survey consisting of multiple Likert scales. For environmental orientation, Cronbach’s alpha was .914, demonstrating internal consistency based on the average inter-item correlation. For economic orientation, Cronbach’s alpha was .800, which is also strong based on the .7 standard typically used in research. For social orientation, Cronbach’s alpha was .574; while this is considered low or poor by most research standards, it was more difficult to measure with only two scale variables. Since these questions did not load heavily onto another factor, they will be maintained. These two scales had the highest correlation with each other; some allowance can be made for a large sample size. Factor scores are coefficients that are similar to those used in regression modeling. These scores are computed by weighting variables scores to create factor scores. The belief is that each subject has the same latent factor structure with different scores on the factors themselves. Furthermore, factor scores should be nearly uncorrelated if the factors are orthogonal, and therefore can be useful if these scores are considered estimates. Factor scores that were calculated from the loading matrix will be utilized again within the adoption prediction model.

To determine how the orientation factors relate to each of the variable questions, factor means are calculated based on the average response to each loading per factor. The factor means and standard deviations are shown in Table 3-4 with the explained variance for each factor. Economic orientation had a large negative skewness (long left tail) and an extremely large positive kurtosis (large peak with short thick tails), denoting most of the responses are close to the mean. This data is not assumed to be normal, but precautions should be taken when variables show these tendencies; however, these scenarios are more likely when there are grouped variables.

Table 3-4 Three Factor Means and Variance

	Environmental	Economic	Social	Total
Factor Mean	3.39	4.24	3.62	
Standard Deviation	0.789	0.531	0.901	
Skewness	-0.715	-2.19	-0.936	
Kurtosis	0.731	10.956	1.229	
% of explained variance	38.90%	16.60%	8.10%	63.60%

3.12.2 Architect Orientation Clusters

The application of cluster analyses to the three-factor solution allows us to divide architects into differing market segments. Cluster analysis employs multivariate resemblance methods that measure the similarity between either objects or the variables that describe them. This is a precursor to subsequent ordination procedures or classification procedures such as clustering. The selection of associated coefficients facilitates the assessment of resemblance between objects or descriptors within a condensed square matrix of association values. Gower's coefficient (Gower, 1971) is a general coefficient that can combine different types of data that is prevalent in this survey. For each descriptor, the difference $|y_{1j} - y_{2j}|$ is computed and the value is divided by the largest difference found for that descriptor in all observations in the study. Pearson's correlation coefficient r is a commonly used metric to quantify resemblance among descriptors. The coefficient of correlations from a similarity matrix and the individual coefficients can be tested for statistical significance. Factors that describe architects' orientations were the variables in the data matrix and architects were the objects or observations. This data was utilized to calculate a similarity matrix for further analyses. The compared variables were ordinal, and Gower's coefficient was used to compare a data matrix with different data types. Following these procedures allowed for a cluster analysis to be performed using Ward's method, which takes the total sum of squared deviations of every object from the mean of its assigned cluster. As the total sum of squares increases so does growth in cluster membership.

When attempting to identify a particular cluster solution from several options, the starting point moves from each individual to eventually the entire group or sample residing within one cluster. Identifying the best cluster solution relies on experience since it combines the use of statistical measures and judgement (Ganguly, Eastin, Crespell, & Gaston, 2010). In deciding on an optimal clustering solution, the following principles were considered: 1. Distinct cluster formation results when more individuals have joined a cluster and the length of the lines on a cluster dendrogram are at their longest before a larger cluster is formed. This equates to stronger membership within those distinct cluster groups, and 2. Clusters need to have a reasonable number of members so that the solution has a discernable meaning.

Clusters

The first attempt at cluster formation resulted in the formation of a two-cluster solution (Appendix C). Utilizing Ward’s method to measure the deviations of each object from its cluster center, the length of the dendrogram lines for the two-cluster result were the longest. When attempting to define differences between the clusters, it was determined that the two-cluster solution resulted in one group that had rated all attributes higher than the other group. This did not provide a discernable meaning between clusters, so a three-cluster solution was proposed and analyzed while still providing statistical significance between clusters. It is optimal to have statistical significance across factors using the least number of clusters, but the groupings need to be defined.

The Kruskal-Wallis test is the analysis of variance by ranks and can be used when the parametric single-factor ANOVA is applicable. This nonparametric test is particularly desirable when k samples do not come from a normal population or when variances are heterogeneous. Based on this testing of clusters between each of the scale variables, mean ranks of the clusters were significantly different from each other at the $p < 0.01$ level. This provides credence to the idea that the clusters are distinct segments.

Based on the updated cluster analysis, there were 3 distinct clusters that explained the architect groupings. The first cluster rated the environmental attributes the highest, but also rated economic traits that could be considered environmental attributes highly: both *energy efficiency* and *long life and durability* were rated higher than they were by other clusters (Figure 3-4). The psychology term “enviro-centric” is appropriate for this group of architects who value and are influenced by the environment, since “enviro” with “centric” means one who is an environmentalist at their center or core. Based on the philosophy of environmentalism, the focus is on the individual and their value for the environment by “making consistent and committed efforts to care for the environment” (Obinyan, 2014). Like many other behavioral terms, enviro-centric could have a place in the marketing literature to describe an interest in environmentally conscious products and programs. This green segment of the marketplace continues to flourish, and companies like Patagonia and IKEA continue to use environmental sustainability as one of their main initiatives. Other companies like Best Buy are rebranding themselves by becoming one of the top electronics recycling companies in the world.

Cluster 2 rated *homebuilder demand* higher than Cluster 1, but also rated all the environmental attributes the lowest (Figure 3-4). Cluster 2 will be labeled as “conventional,” since they are not as competitively driven as Cluster 3 when measuring social attributes based on client demand. They consider economic attributes (all greater than the midpoint =3), but most likely are comfortable with their existing materials and products and uninterested in the environmental attributes (factor mean of 2.57 or not important) (Table 3-5). They did not rate any of the attributes the highest of all three clusters, but the categories they rated highest were *long life and durability*, *overall price*, and *low maintenance*.

Cluster 3 would be the “market-driven” architect. They rated the social (customer) attributes highest and were second highest in all the environmental attributes (Figures 3-4, 3-5). They rated most of the economic attributes the highest (Figure 3-6), and the largest differences in the attribute means were for *overall price*, *availability* and *ease of installation*. While these were not their highest-rated attributes, this segment of architects is focused on designing homes that are low cost, stay on schedule (availability), and do not require complicated installation methods.

With high ratings of the social attributes, Cluster 3 most likely values environmental attributes when their customers request them. Clusters 1 and 2 also rated economic attributes highly, but not higher than Cluster 3 (besides *energy efficiency* and *long life* for Cluster 1). Clusters 1 and 2 did not work as frequently for homebuilders (33.9% and 32.3% respectively) as Cluster 3 (40%), which is reflected in the *builder demand* factor (Figure 3-5); this higher frequency was not significantly different from the other clusters with the chi-square tests of independence.

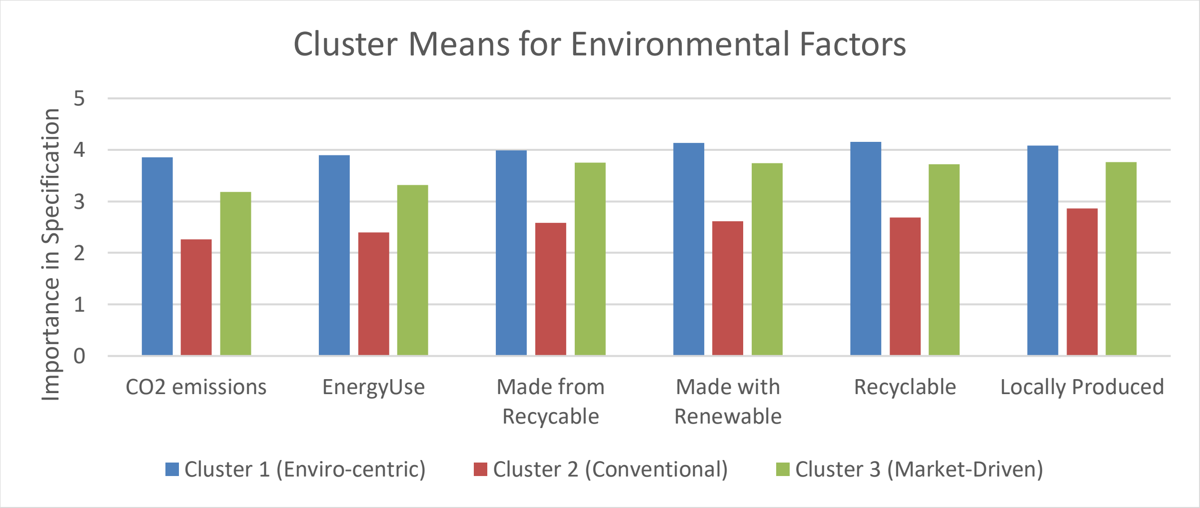


Figure 3-4 Cluster Means for Environmental Factors

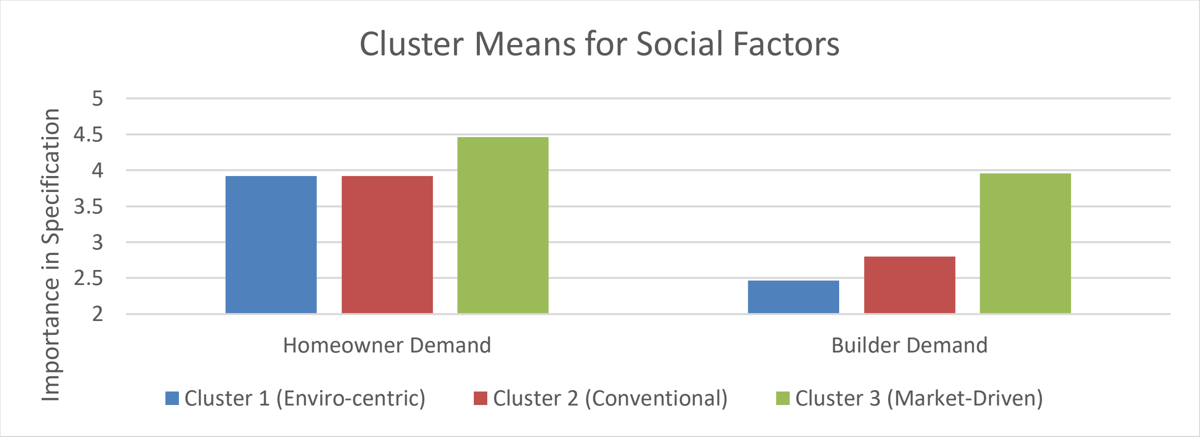


Figure 3-5 Cluster Means for Social Factors

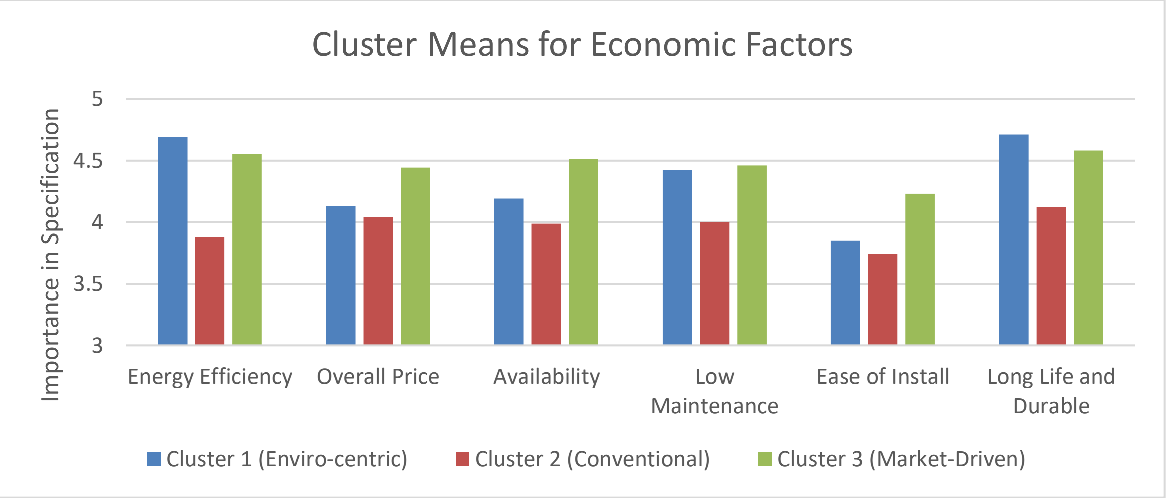


Figure 3-6 Cluster Means for Economic Factors

Table 3-5 provides the cluster means for each of the orientation factors. This is an aggregate of all the scale variables for each factor. Comparison of the means showed a highly significant difference when comparing the means for the social and environmental orientation factors ($p < 0.01$) with a less significant difference between the economic factors ($p < 0.05$). The minimum and maximum mean of the respondents in each cluster are shown for the environmental attributes. This factor had the largest difference between clusters. The enviro-centric cluster contained 118 architects while the conventional luster and market-driven Cluster 3 were slightly larger with 124 and 143 members each. The mean years in business were not significantly different from each other, but it was interesting that the enviro-centric cluster had the highest average for years in business. This is contrary to the literature that suggests younger people tend to be more environmentally conscious (Straughan & Roberts, 1999).

Table 3-5 Cluster Factor Means Scores

Orientation	Enviro-Centric	Conventional	Market-Driven	F-Value
Economic[a]	4.26	3.97	4.44	2.08
Social[b]	3.19	3.36	4.20	20.0
Environmental[b]	4.02	2.57	3.57	2.84
Min for Env Scale	3.17	1.00	2.33	
Max for Env Scale	5.00	3.67	4.33	
N	118	124	143	
Years in Business[c]	25.61	23.82	23.05	1.288

a ANOVA significant variance at 0.05 level
b ANOVA significant variance at 0.01 level
c ANOVA variance not significant

3.12.3 Similarities of Architect Segments

The cluster analyses supported that different segments of architects exist based on distinct orientation factors (3-factor solution). With these cluster formations, it is also important to verify if members of each cluster share characteristics. By comparing the clusters and the membership within, other variables can be assessed for their significance in predicting cluster membership (e.g., demographic variables). Each of the demographic questions (Question 4 on the survey) in Appendix A were tested for their interdependence based on membership in any of the 3 clusters. These contingency tables test whether expected frequencies are similar to observed frequencies. If the calculated chi-squared (χ^2) value is small, the hypothesis that the variables are similar is not rejected. A large χ^2 shows that two variables are related in some way or influence the membership in that group. Computation of the chi-square value is shown by Equation 3-1. In Table 3-6, the tested categorical variables are shown with their associated χ^2 value and significance level (p-value). As mentioned previously, the variable “client type” showed some variability; the market-driven cluster had the highest percentage of homebuilders, but this was not found to be significant (p = 0.39), while the other clusters had more homeowner clients. The other categorical variables did not show significant interdependence, except regarding census regions (Table 3-7), for which the conventional cluster had more observations than expected in the South and Northeast. The enviro-centric cluster had a higher presence than expected in the Midwest, while the market-driven cluster had observations very close to their expected cell counts. Testing each of the segments for within-group similarities revealed that demographic variables were insignificant and did not provide additional information about segment membership.

Equation 3-1 Chi-Square (χ2) formula

$$\sum_{ij} (f_{o} - F_e)^2 / F_e$$

Table 3-6 Categorical Variables Tested for Interdependence between Clusters

Variable	df	χ2	p-value
Client Type	2	1.885	0.390
Region	6	5.312	0.504
Employment	2	0.747	0.688
Area Conduct Business	4	5.051	0.282

Table 3-7 Cluster Membership by Region

	Enviro-Centric	Conventional	Market-Driven	Total
Northeast	**20/25.1**	31/26.7	31/30.2	82/82
Midwest	**27/21.8**	19/23.1	25/26.1	71/71
South	35/37.7	**44/40**	44/45.3	123/123
West	32/29.4	**27/31.2**	37/35.4	96/96
Total	114/114	121/121	137/137	372/372

[a] Chi-Square = 5.31, df=6, not significant at the 0.05 level

Table 3-8 identifies and gives a general description of the market segments and their members' characteristics. Based on the frequency of the segments having specific traits, the likelihood of a member of this segment having these traits is higher than expected even though many of the variables significantly differ between the segments. An enviro-centric architect is more likely to work for a firm, work with homeowners, be located in an urban area in the Midwest, have more years of experience, be more likely to have used another GBP, and have a higher environmental orientation. Conventional architects were more prominent in the South and Northeast, were more likely to be independent, and had a slightly negative environmental orientation. Market-driven architects had the least amount of experience on average, were widespread throughout the country, were more likely to work for a homebuilder, and were more economically and socially oriented.

Table 3-8 Architect Market Segment Descriptions

	Market Segment			
Variable	Enviro-Centric	Conventional	Market-Driven	Significant
Employment	Firm	Independent	Firm	No
Client Type	Homeowner	Homeowner	Builder	Yes
Area of Business	Urban	Urban/Small Town	Urban	No
Region	Midwest	South or Northeast	Wide-Spread	No
Years in Business	More Experience		Least Experience	No
Other GBP	Most Likely	Least Likely		No
Orientation	Environmental	Non-Environmental	Economic and Social	Yes

3.12.4 Architect segments and participation in GBPs and specification of ECWPs

The last part of this section seeks to determine whether certain clusters are more likely to participate in GBPs or specify ECWPs. Again, contingency tables are utilized to test the interdependence between the clusters and GBP and ECWP use. The clusters and the LEED for Homes- and NGBS-use variables were tested; the results are shown with their associated χ^2 value and significance level (p-value) in Tables 3-9 and 3-10. The enviro-centric cluster showed the highest percentage of LEED for Homes use (32.3%) and interdependence was significant at the $p < 0.01$ level ($\chi^2 = 12.99$). NGBS had a higher percentage of market-driven users (10.5%), which aligns with their greater amount of homebuilder clientele (Table 3-10). Conventional architects had the lowest percentage of LEED for Homes use (12.9%), but a slightly higher percentage using SFI-certified wood (5.6%) than the enviro-centric segment. There was a low percentage of NGBS use overall, which could be a result of the NGBS program being marketed more toward homebuilders. Architect segments did not show interdependence with NGBS use and it was not significant at the $p = 0.11$ level ($\chi^2 = 4.40$).

Table 3-9 Architect Segments and Participation in the LEED for Homes Program

	Architect Segments[a]			
	Enviro-Centric	Conventional	Market-Driven	Total
Non-User LEED	80	108	107	295
%	67.8%	87.1%	74.8%	76.6%
User LEED	38	16	36	90
%	32.2%	12.9%	25.2%	23.4%
Total	118	124	143	385

[a] Chi-Square 12.99, df=2, significant at $p < 0.01$

Table 3-10 Architect Segments and Participation in the NGBS Program

	Architect Segments[a]			
	Enviro-Centric	Conventional	Market-Driven	Total
Non-User NGBS	113	117	128	358
%	95.8%	94.4%	89.5%	93.0%
User NGBS	5	7	15	27
%	4.2%	5.6%	10.5%	7.0%
Total	118	124	143	385

[a] Chi-Square 4.40, df=2, not significant at $p > .10$

The clusters and the FSC- and SFI-use variables were tested; the results are shown with their associated χ^2 value and significance level (p-value) in Tables 3-11 and 3-12. The enviro-centric cluster showed the highest percentage (66.9%) of FSC use and interdependence was significant at the p< 0.01 level (χ^2 =26.35). SFI had a similar percentage of enviro-centric and market driven users (30.5% and 29.4%, respectively) (Table 3-9). Conventional architects had the lowest percentage of use for both FSC- and SFI-certified wood. There was a lower percentage of SFI use overall but there was still interdependence between architect segments (p < 0.01, χ^2 =9.50). This lower use could be a result of SFI not being accepted by LEED for Homes during this timeframe.

Table 3-11 Architect Segments and Specification of FSC-Certified Wood

	Architect Segments[a]			
	Enviro-Centric	Conventional	Market-Driven	Total
Non-User FSC	39	80	59	178
%	33.1%	64.5%	41.3%	46.2%
User FSC	79	44	84	207
%	66.9%	35.5%	58.7%	53.8%
Total	118	124	143	385

[a] Chi-Square 26.35, df=2, significant at p < 0.01

Table 3-12 Architect Segments and Specification of SFI-Certified Wood

	Architect Segments[a]			
	Enviro-Centric	Conventional	Market-Driven	Total
Non-User SFI	82	105	101	288
%	69.5%	84.7%	70.6%	74.8%
User SFI	36	19	42	97
%	30.5%	15.3%	29.4%	25.2%
Total	118	124	143	385

[a] Chi-Square 9.50, df=2, significant at p < 0.01

These results show that different segments of architects exist who are more likely to participate in GBPs and specify ECWPs. All were significant except the use of NGBS, which is mostly likely a result of architects' low participation. Since we were unable to find demographic variables that defined segment membership, basing segment membership on architects' inherent orientations provides the most significant factor influencing segment membership.

3.13 Adoption of GBPs and ECWPs

After the segmentation of architects, the orientation factors can be implemented into a prediction model to determine factors that significantly influence the adoption of GBPs and ECWPS. To measure these outcomes, demographic and other variables of interest from the survey were entered into the prediction model. Four models were developed with the variables that influence participation in either the LEED for Homes or NGBS programs and specifying either FSC- or SFI-certified materials. Other variables include an innovativeness score variable related to other green products use, and the grouping of architects based on the similarities of their environmental perceptions of wood, steel, and concrete using clustering methods. These variables, in addition to demographics, willingness to pay (WTP) for ECWP, and participation in another regional GBPs, will be independent variables for following prediction models.

3.13.1 Measure of Green Product Adoption

To measure innovativeness with green product use, architects were asked about their awareness and use of 12 energy- and resource-efficient and low toxicity products that are designed to be used in residential homes (Chapter 2, Figure 2-24). The chosen products were at varying stages in their product life cycle (introductory, growth, mature), but at least six of the products were past the introductory phase (at least 10% adoption). To compute an innovativeness score based on use of the 12 products, the products were separated into even groups based on overall use. An adoption greater than >50% was considered “complete adoption” by Ganguly et al. (2008) and was set as the threshold. Six of the products (Figure 3-7)—energy efficient windows, engineered wood, energy efficient appliances, water conserving fixtures, low VOC paints, and tankless heaters—all had greater than 75% use by architects and were frequently used by 30%. These product use thresholds were similar to those established by Koebel et al. (2006). These products are considered “incremental” because they improve performance based on existing technologies, or “modular” since they work within existing mechanisms (Henderson & Clark, 1990). These products are common in most new homes and are occasionally required by new building codes. The other six products (Figure 3-7)—radiant barriers, heat recovery ventilators, concrete with reduced cement, structural insulated panels, solar water heating, and solar power generation—all ranged from 63% (radiant barriers) to 45% (solar power) in total use by architects, with none of these products exceeding 25% frequent use. Industry professionals deemed these products to be early in their product adoption phase and not as commonly used in residential homes. They are considered “modular” or “radical,” which advances the price and performance frontier by the existing rate of progress (Taylor & Levitt, 2004).

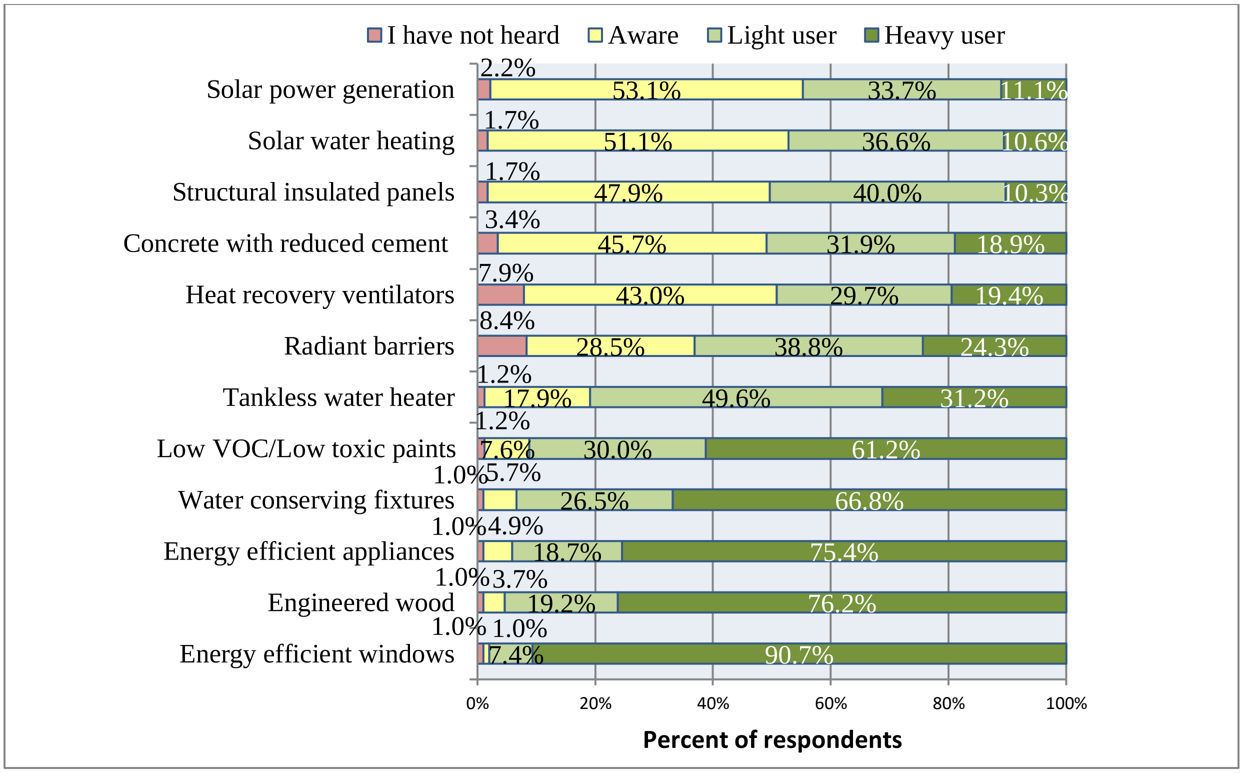


Figure 3-7 Use of Innovative Green Building Technologies and Products

To achieve an innovativeness rating, the frequency of use of a green product (either occasional or frequent) was scored alongside its place within its adoption life cycle, based on ratings given by architects that had designed with green products. Commonly used products are "mature" in their adoption, while a product that is still infrequently used is in its "growth" phase (Kotler, Wong, Saunders, & Armstrong, 2005). For example, most new homes utilize energy efficient windows, thus they would be defined as a "mature" product, whereas utilizing solar power for electricity or water heating is still relatively uncommon in new homes, and would thus be defined as still in its "growth" phase. Table 3-13 shows the scoring system and the distribution of the scores. For example, if an architect had occasionally used 4 of the mature products (1 point each) and 2 of the growth products (3 points each), and had frequently used 1 of the mature products (2 points each) and 1 of the growth products (4 points each), their score would be: (4*1) + (2*3) + (1*2) + (1*4) = 16. The distribution of scores and their associated statistics are shown in Figure 3-8 and Table 3-13. The means for each combination show that the highest points were attained on average within the Frequent*Mature category (mean=8.03, mid-point=6), a logical conclusion given that most of these products are commonplace within homes. The Occasional*Growth category was the next highest in average points, but the mean was relatively low (6.34) compared to the mid-point score (9). The other category means were low on average compared to the mid-point of their scoring range: Occasional*Mature (mean=1.51, mid-point=3) and Frequent*Growth (mean=3.84, mid-point=12) were the lowest contributors to overall scores (7.7% and 19.5%, respectively).

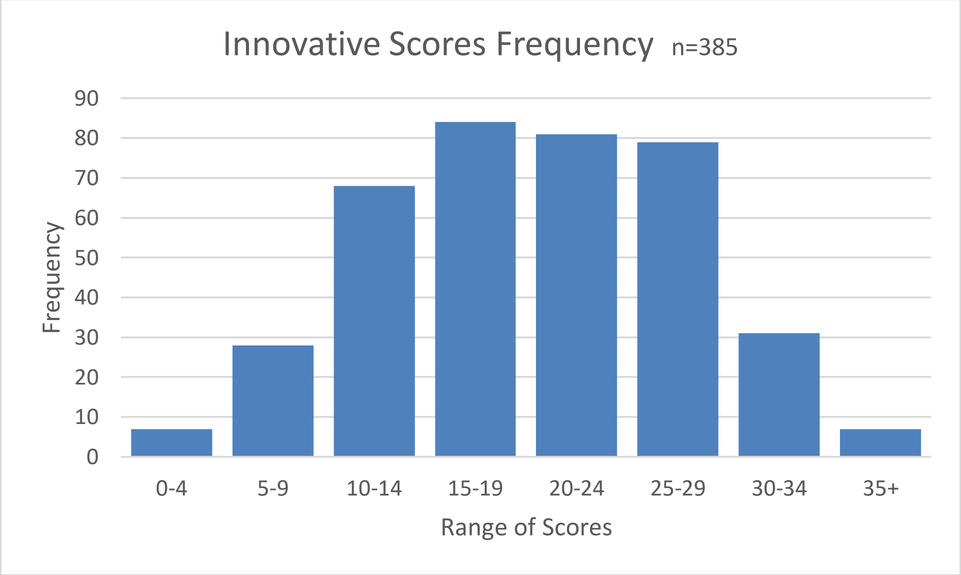


Figure 3-8 Distribution of Innovative Score Frequency

Table 3-13 Innovative Scoring System for Green Products Used in Residential Construction

Green Building Product	Product Life Cycle	Number of Products	Innovative Use	Score for each Combination			
Use	Stage	Range	Points	Range	Mean	S.D.	% of Total
Occasional	Mature	(0-6)	1	(0-6)	1.51	1.36	7.7%
Frequent	Mature	(0-6)	2	(0-12)	8.03	3.20	40.7%
Occasional	Growth	(0-6)	3	(0-18)	6.34	4.54	32.2%
Frequent	Growth	(0-6)	4	(0-24)	3.84	5.20	19.5%
Sum of all 12 products Scores=				(0-60)	19.72	7.54	

*Architect could either be occasional or frequent for each product, not both.

The distribution shows a normal distribution of the data with the mean and median very close together and the skewness and kurtosis well within normal levels as shown by Table 3-14. Quartiles show that 50% of architects had an innovative score between 14 and 25, which is well within the range of one standard deviation from each side of the mean (12.18 and 27.26), thus the data shows good dispersion. These innovation scores will be an independent variable within the ECWP and GBP adoption model.

Table 3-14 Frequency Distributions Statistics

Mean	19.72
St. Dev	7.54
Median	20
Min	0
Max	36
Skew	-0.117
Kurtosis	-0.523
Quartile 25	14
Quartile 50	20
Quartile 75	25

3.13.2 Measure of Construction Material Environmental Attributes

The following analyses consider architects' perceptions of the environmental impacts of residential building materials made from wood, steel, or concrete. Conroy (2018) showed that architects valued environmental impacts when deciding between building materials, but they were not as important as aesthetics, building codes, and costs (Conroy, 2018). Other studies found that architects had positive perceptions of the environmental impacts of wood-based building products (Kozak & Cohen, 1999; O'Connor, Kozak, Gaston, & Fell, 2004; Robichaud, Kozak, & Richelieu, 2009). Architects' material choices are a few of many design decisions that could impact the future of home construction while helping to reduce the environmental footprint of a home. Those that perceive the environmental impacts of wood-based building materials as better than steel- or concrete-based building materials could be more likely to design with ECWPs. As discussed in Chapter 2, architects possessed varying perceptions of the environmental attributes of three basic residential structural materials: wood, steel, and concrete (Section 2.12). The survey data was analyzed to determine if there were statistically significant differences between groups of architects with varying perceptions.

As described in the previous section, cluster methods were employed to determine if there were distinct groups of perceptions of the environmental attributes of the three main building materials used for structural and non-structural elements of a home. Utilizing hierarchal clustering methods, an evaluation of the environmental attributes of wood, steel, and concrete are assessed; these materials are then ranked based on which material was rated the best for each attribute. Architects had the choice to rate the three building materials on a five-point scale measuring if they 1- *strongly disagreed* to 5 – *strongly agreed* that the material embodied that environmental attribute. The list of attributes was *low energy use during manufacturing, low CO2 emissions during manufacture and transport, contributes to high energy efficiency within the home*, *resource is renewable, longevity of material,* and *recyclability of material.* An architect's perceptions of different building materials may be similar, but aggregating responses can establish an overall view of the general perceptions of each material.

Results of Architects' Perceptions

A two-cluster solution was formed from the material environmental attributes questions. The differences between architects that rated the environmental impacts of the three building materials formed into two discernable clusters, shown in Appendix C. Cluster 1 had 210 members and Cluster 2 had 175 members. Ward's method to measure the deviations of each object from its cluster center revealed that the length of the dendrogram lines for the two-cluster result were the longest and therefore the most significant difference (Appendix C). The differences in the clusters are shown for each material in Tables 3-15, 3-16, and 3-17. Higher values show that a respondent strongly agrees with a material's environmental performance in that category.

Table 3-15 Cluster Means for Environmental Impacts Questions for Wood

Environmental Impact Questions for Wood

	n	Low Energy Manufacturing	Low CO2 Emissions	Energy Efficiency Contribution	Highly Renewable	Recyclable	Long Life
Cluster 1	n=210	3.34	3.49	3.56	4.11	4.16	3.84
Cluster 2	n=175	3.51	3.66	3.42	4.17	4.04	3.97
Total mean	n=385	3.42	3.57	3.50	4.41	4.10	3.90
Mann-Whitney U	(p-value)	0.013	0.012	0.251	0.262	0.329	0.108

Table 3-16 Cluster Means for Environmental Impacts Questions for Steel

Environmental Impact Questions for Steel

	n	Low Energy Manufacturing	Low CO2 Emissions	Energy Efficiency Contribution	Highly Renewable	Recyclable	Long Life
Cluster 1	n=210	2.20	2.41	2.76	3.87	4.47	4.47
Cluster 2	n=175	1.63	1.84	2.25	2.28	4.32	4.27
Total mean	n=385	1.95	2.15	2.52	3.15	4.40	4.38
Mann-Whitney U	(p-value)	<0.001	<0.001	<0.001	<0.001	0.086	0.006

Table 3-17 Cluster Means for Environmental Impact Questions for Concrete

Environmental Impact Questions for Concrete

	n	Low Energy Manufacturing	Low CO2 Emissions	Energy Efficiency Contribution	Highly Renewable	Recyclable	Long Life
Cluster 1	n=210	2.73	2.89	3.35	3.25	3.83	4.46
Cluster 2	n=175	2.00	1.98	2.85	2.16	3.07	4.36
Total mean	n=385	2.40	2.48	3.12	2.75	3.49	4.41
Mann-Whitney U	(p-value)	<0.001	<0.001	<0.001	<0.001	<0.001	0.381

Comparing the cluster means from Tables 3-15, 3-16 and 3-17, Cluster 1 rated steel or concrete higher than Cluster 2 for every environmental attribute (highlighted in blue). Cluster 1 rated wood lower than Cluster 2 for four of the material attributes, but higher than Cluster 2 for *energy efficiency contribution* and *recyclability*. The total mean of both clusters rated wood higher than steel or concrete for all the attributes besides *long life* and only higher than concrete for *recyclability*. While Cluster 1 on average considered wood to be better for the environment than steel or concrete, their mean values for steel and concrete attributes were considerably higher than those of Cluster 2. To test whether the cluster means (highlighted in green) are significantly different from each other, the non-parametric Mann-Whitney U test was performed since the responses were measured on an ordinal scale. For wood, two of the attribute means were significantly different from each other at the $p<0.05$ level: *low energy use during manufacturing* and *low CO2 emissions during manufacturing*. The other four attribute means were not significant, but *long life* was close at $p=0.11$. This shows that architects agree about wood's impact on the environment more than they do about the other materials. For steel, the only attribute not showing a significant mean difference was *recyclability*, but it was marginal at the $p<0.1$ level (highlighted in yellow). This should be the attribute that most architects should agree over. All other attributes for steel were significantly different at the $p<0.001$ level. For concrete, the only attribute not showing a significant mean difference was *long life*, an opinion that should be shared by all architects. All other attributes for concrete were significantly different at the $p<0.001$ level.

There was a significant difference between the mean ratings of wood for the two attributes that pertain to its impact on the environment during manufacturing, but architects did not differ in opinion regarding the four other product attributes. However, they had significantly different perceptions of steel and concrete besides the *recyclability* of steel and the *long life* of concrete. Cluster 1 will be considered "pro-steel/concrete" due to its higher ratings of those materials' attributes. Cluster 2 did not believe that steel and concrete have favorable environmental impacts beyond *long life* and *recyclability*, but they rated wood higher on only four attributes, making it difficult to label Cluster 2 as "pro-wood." While this cluster will be considered "pro-wood" for clarity based on its higher ranking of the four attributes, it is distinctly more "anti-steel/concrete" than "pro-wood." These clusters will be inputs for the ECWP model as independent categorical variables to determine their influence on the adoption of FSC- and SFI-certified wood.

3.13.3 Demographic Measures

Demographic variables measured by the survey are shown in Table 3-18, as well as in greater detail in Chapter 2. The demographic *employment type* attempts to determine whether the architect was independent and thus more likely to make individual decisions on material choice and types of designs. *Customer type* measures whether architects work for a homeowner who typically requests custom designs and material choices or a homebuilder who tends to build similar or spec homes that require repeat material choices. This measure was similar to a survey of home builders in Japan who either worked directly with the customer or designed spec homes (Sasatani, Eastin, & Roos, 2010). Working directly for the customer, or being customer oriented, means incorporating customer requests when making material and design choices.

Location type is a variable of interest for all nationwide surveys but is particularly important to building material use. Both use of and preferences for environmentally friendly materials vary within these regions (Ganguly et al., 2008; Ganguly & Eastin, 2007). *Area size*, and corresponding population density, help measure the differences in construction practices based on population. Studies show that urban/suburban areas have higher concern for and awareness of environmental issues (Samdahl & Robertson, 1989; Zimmer et al., 1994). The last demographic variable, *years in business*, relates to architect experience. Studies indicate that younger individuals are more sensitive to environmental concerns and might be more inclined to adopt environmentally focused practices and products (Straughan & Roberts, 1999).

Table 3-18 Demographic Variables Used in the Adoption Model

Demographic	Variables	Data Type	Measure
Employment Type	Independent, Firm	Nominal	Individual vs. Collective
Customer Type	Homeowner, Homebuilder	Nominal	Custom vs. Spec
Location in U.S.	East, Midwest, South, West	Nominal	Regional Differences
Area Conduct Business	Urban, Small City, Rural	Nominal	Community Differences
Years in Business	Years – Log Transformed	Continuous (Log)	Experience

These variables, including the factor scores from the previous orientation analyses (Section 3.13.1), the innovative scoring, the WTP levels, material preferences clusters, and participation in a GBP will be independent variables within the ECWP adoption model. Other variables measured by the models for the adoption of GBPs are architects' orientation, innovative scoring, and use of another regional GBP. The adoption of GBPs model will not include WTP or material preference since they measure building material adoption and are incongruous with a GBPs model. The ECWP model will include the variable asking about participation in another GBP since architects and may have designed with ECWPs during any green building certification program.

3.13.4 Logistic Regression

Logistic regression is a measurement tool that can predict the presence or absence of an outcome. It can also predict a discrete outcome, such as group membership, from a variety of variable types. Logistic regression techniques do not make assumptions about the distribution of the predictors and allows for flexibility predictors, which do not need to be normally distributed or correlated. Since architects could use both the LEED for Homes and NGBS programs, it would be wise to model the adoption of each program separately. The same will be performed for ECWPs, but the model will be adjusted to measure the effects of both GBPs on certified-wood adoption.

The linear model for transformed probabilities under logistic regression are as follows:

$$\text{logit } p = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots\ldots \beta_k x_k$$

The parameters values are estimates from maximum likelihood methodologies using numerical optimization. Logit p also can be defined as logit $p = \log[p/(1-p)]$ and is known as the link function or "log odds." The produced model is nonlinear and the outcomes are complex, but fundamentally seek to find the best linear combination of predictors to maximize the likelihood of obtaining the observed outcome frequencies. In this situation of modeling binary outcomes or adoption, the dependent variable (y) takes a value of 0 or 1. The binary logistic model does not contain an error term since the probability of the event happening is modelled directly, which will determine the variability in a binary outcome.

Binary logistic regression models were created to test the significance of the survey's variables when predicting the adoption of GBPs and ECWPs. To compare differences between adopters of the LEED for Homes and the NGBS programs and FSC- and SFI-certified wood, separate models were developed for all four outcomes.

3.13.5 Adoption of GBPs

Adoption of GBPs was determined by utilizing a binary logistic regression model with a categorical dependent variable. The independent variables consisted of categorical independent variables (e.g., *demographics*) and scale variables (*orientation* and *innovation scores*). Only architects that were aware of a particular GBP were modeled since it was assumed that architects that were not aware would have zero probability of adopting. Table 3-19 provides the full model for the adoption of LEED for Homes with all variables and their influence on predicting use. There were 369 cases used for this model. Using the backward stepwise likelihood ratio (LR) technique, the model is reduced with indicator variables removed one at a time; the model is progressively modified as the -2 log-likelihood ratio is reduced until only significant variables remain. The best-fitting model is the reduced model with four variables remaining. The parameter estimates, Beta (B), indicate either a positive or negative influence on LEED adoption; in this case all are positive. The Wald statistic is the ratio of the Beta over the Standard Error (S.E.), and indicates the significance of the variable to the model. For LEED adoption, *innovation score* has the highest influence (19.23); *NGBS use* (7.97) and *participating in another regional GBP* (8.65) are also highly influential. The variables were all significant at the $p < 0.01$ level except *environmental orientation*, which met the $p < 0.10$ cutoff. This variable was kept in the final model since its removal did not significantly lower the LR. Exp(B) is the predicted change in the odds per unit change in a parameter; for example, if the B for NGBS is increased by one unit, that respondent is 3.628 times more likely to adopt LEED for Homes. The pseudo r-square term indicates the proportion of the variance the model explained, Cox and Snell's R^2 and Nagelkerke R^2 get smaller as variables are removed from the model. Cox and Snell's R^2 is an imitation of the R^2 used for ordinary least squares (OLS) estimation in linear regression. It is an estimate based on maximum likelihood but has an upper bound less than 1. Nagelkerke is an adjustment of the Cox and Snell's post hoc, but provides a more reliable estimate of R^2 (Burn & Burn, 2008). The Nagelkerke R^2 for the reduced model is 25.1%, indicating a moderately good fit for the relationship between the adoption of LEED for Homes and the significant predictor variables.

Table 3-19 Adoption Model of LEED for Homes

	Full Model					Stepwise Reduced Model				
n=369	B	S.E.	Wald	p-value	Exp(B)	B	S.E.	Wald	p-value	Exp(B)
Intercept	-4.017	1.084	13.73	<0.001	0.018	-3.679	0.509	52.257	<0.001	0.025
NGBS_Use	1.277	0.473	7.275	0.007	3.585	1.289	0.457	7.967	0.005	3.628
Env	0.296	0.164	3.251	0.071	1.344	0.261	0.158	2.731	0.098	1.298
Econ	0.249	0.17	2.156	0.142	1.283					
Social	-0.112	0.144	0.599	0.439	0.894					
Innovative Score	0.099	0.023	17.667	<0.001	1.104	0.098	0.022	19.628	<0.001	1.103
Other GBP	0.912	0.316	8.312	0.004	2.488	0.88	0.299	8.65	0.003	2.412
EMPLOY	-0.191	0.289	0.436	0.509	0.826					
CLIENT	0.314	0.287	1.195	0.274	1.368					
NEast	0.173	0.408	0.179	0.672	1.188					
MidW	0.111	0.427	0.067	0.796	1.117					
South	0.013	0.373	0.001	0.972	1.013					
West	a									
Urban	0.377	0.695	0.295	0.587	1.458					
Town	-0.114	0.772	0.022	0.882	0.892					
Rural	a									
Years	-0.023	0.22	0.011	0.918	0.978					
-2 Log likelihood	328.719					334.947				
Cox & Snell R^2	0.179					0.166				
Nagelkerke R^2	0.271					0.251				

a = reference category

Table 3-20 provides the full and reduced models for the adoption of NGBS with all the variables and their influence on predicting use. There were 309 cases used for this model. The best-fitting model is the reduced model with three variables remaining. The B estimates for *LEED use*, *client type* and *being from the South* were positive toward NGBS adoption. *Client type* was significant at the p<0.001 level and had the highest influence based on Wald (10.83). *LEED use* and *being from the South* were significant at the p <0.05 level. The significance of *client type* is understandable since the NGBS program was designed by the National Association of Home Builders; a positive parameter estimate indicates that homebuilders are architects' main clients. The Nagelkerke R^2 for the reduced model is 16%, which indicates a low goodness of fit for the relationship between the adoption of NGBS and the significant predictor variables. It can be difficult to achieve a well-fitting model with only a few predicting variables.

Table 3-20 Adoption Model for NGBS

	Full Model					Stepwise Reduced Model				
n=309	B	S.E.	Wald	p-value	Exp(B)	B	S.E.	Wald	p-value	Exp(B)
Intercept	-5.734	2.026	8.013	0.005	0.003	-3.001	0.387	60.06	<0.001	0.05
LEED_Use	1.385	0.492	7.935	0.005	3.995	-1.152	0.568	4.12	0.042	0.316
Env	-0.049	0.241	0.042	0.838	0.952					
Econ	-0.237	0.226	1.103	0.294	0.789					
Cust	0.369	0.239	2.389	0.122	1.446					
InnoScore	0.02	0.037	0.29	0.59	1.02					
Other GBP	0.281	0.513	0.3	0.584	1.324					
EMPLOY	0.37	0.476	0.603	0.437	1.447					
CLIENT	0.781	0.451	3.001	0.083	2.184	1.393	0.423	10.83	0.001	4.027
NEast	-0.382	0.608	0.396	0.529	0.682					
MidW	-0.122	0.628	0.038	0.846	0.885					
South	-1.173	0.658	3.178	0.075	0.309	0.897	0.426	4.436	0.035	2.453
West	a									
Urban	-0.006	1.103	0	0.996	0.995					
Town	0.049	1.204	0.002	0.967	1.05					
Rural	a									
Years	0.683	0.476	2.062	0.151	1.981					
-2 Log likelihood	152.51					160.31				
Cox & Snell R^2	0.095					0.071				
Nagelkerke R^2	0.211					0.16				

a = reference category

3.13.6 Adoption of ECWPs

The adoption of ECWPs was determined by utilizing a binary logistic regression model. Only architects that were aware of a particular ECWP were used in the model since it was assumed that architects who were not aware have zero probability of adopting. Table 3-21 provides the full and reduced models for the adoption of FSC wood and all the variables and their influence on predicting use. There were 325 cases used for this model. The best fitting model is the reduced model with nine variables remaining. The B estimates for the variables were positive except for *economic orientation* (-0.438) and *years in business* (-0.369), indicating that an architect with a high *economic orientation* is less likely to adopt FSC wood. For FSC adoption, *innovation score* had the highest influence based on Wald (25.15); *environmental* or *economic orientation* (6.783 and 7.664) were also highly influential. *Innovation score* was significant at the $p < 0.001$ level, while the orientation variables were significant at the $p < 0.01$ level. *Participating in another regional GBP* or *LEED for Homes* were both significant, supporting the hypothesis that GBPs influence ECWP adoption. *Being from the Midwest* was significant at the $p < 0.1$ level; this is interesting since its housing market has been the slowest to recover but could be due to a high proportion of custom homes that include green materials and features. *Area of business* was significant for both *urban* and *small towns* ($p < 0.05$), indicating that being from rural area has a negative effect on adoption. *Years in business* was a negative parameter significant at the $p < 0.05$ level, indicating that older architects or firms were less likely to adopt FSC-certified wood products, aligning with findings that younger respondents have greater environmental awareness. The Nagelkerke R^2 for the reduced model is 32.5%, indicating a high goodness of fit for the relationship between the adoption of FSC wood and the significant predictor variables.

Table 3-21 Adoption Model for FSC wood

	Full Model					Stepwise Reduced Model				
n=325	B	S.E.	Wald	p-value	Exp(B)	B	S.E.	Wald	p-value	Exp(B)
Intercept	-2.162	1.123	3.704	0.054	0.115	-3.245	0.714	20.649	<0.001	0.039
LEED_Use	0.712	0.369	3.73	0.053	2.038	0.72	0.359	4.035	0.045	2.055
NGBS_Use	0.326	0.586	0.309	0.578	1.385					
Env	0.412	0.158	6.743	0.009	1.509	0.394	0.151	6.783	0.009	1.483
Econ	-0.453	0.165	7.563	0.006	0.636	-0.438	0.158	7.664	0.006	0.646
Cust	-0.11	0.144	0.584	0.445	0.896					
InnoScore	0.12	0.024	23.88	<0.001	1.127	0.113	0.022	25.154	<0.001	1.119
Material Clus	0.279	0.287	0.945	0.331	1.322					
Other GBP	0.574	0.356	2.598	0.107	1.776	0.577	0.344	2.821	0.093	1.781
WTP FSC	-0.14	0.18	0.601	0.438	0.87					
EMPLOY	-0.195	0.289	0.456	0.5	0.823					
CLIENT	-0.03	0.302	0.01	0.92	0.97					
NEast	0.337	0.418	0.651	0.42	1.401					
MidW	0.629	0.455	1.91	0.167	1.877	0.702	0.366	3.679	0.055	2.017
South	-0.256	0.366	0.489	0.484	0.774					
West	a									
Urban	1.295	0.561	5.318	0.021	3.65	1.223	0.555	4.847	0.028	3.397
Town	1.35	0.645	4.383	0.036	3.857	1.318	0.645	4.178	0.041	3.735
Rural	a									
Years	-0.337	0.196	2.942	0.086	0.714	-0.369	0.186	3.933	0.047	0.691
-2 Log likelihood	334.74					341.61				
Cox & Snell R^2	0.254					0.238				
Nagelkerke R^2	0.347					0.325				

a = reference category

Table 3-22 provides the full and reduced models for the adoption of SFI wood and all the variables and their influence on predicting use. There were 284 cases used in this model. The best-fitting model is the reduced model with six variables remaining. The B estimates for the variables were all positive; *innovation score* (p<0.001) had the highest influence based on Wald (30.64). NGBS use was an indicator of SFI adoption, potentially due to the green building points it awards for SFI wood. Similar to the NGBS model, architects' *client type* was significant in the SFI model (p<0.05). Living in the South was the most significant region affecting SFI adoption with the Northeast and Midwest were both marginally significant. This suggests a negative effect for architects from the West. The Nagelkerke R^2 for the reduced model is 23.2%, indicating a moderately good fit for the relationship between the adoption of FSC wood and the significant predictor variables.

Table 3-22 Adoption Model for SFI wood

	Full Model					Stepwise Reduced Model				
n=284	B	S.E.	Wald	p-value	Exp(B)	B	S.E.	Wald	p-value	Exp(B)
Intercept	-4.87	1.402	12.07	0.001	0.008	-4.443	0.659	45.496	<0.001	0.012
LEED_Use	0.174	0.335	0.268	0.605	1.19					
NGBS_Use	1.061	0.502	4.456	0.035	2.888	1.041	0.485	4.607	0.032	2.833
Env	0.061	0.167	0.134	0.715	1.063					
Econ	-0.021	0.155	0.018	0.894	0.98					
Cust	-0.047	0.145	0.105	0.745	0.954					
InnoScore	0.122	0.026	22.658	0	1.129	0.126	0.023	30.635	<0.001	1.134
Material Clus	-0.292	0.299	0.954	0.329	0.747					
Other GBP	-0.39	0.364	1.148	0.284	0.677					
WTP SFI	0.103	0.189	0.296	0.587	1.108					
EMPLOY	0.134	0.303	0.196	0.658	1.143					
CLIENT	0.653	0.296	4.872	0.027	1.921	0.713	0.285	6.244	0.012	2.04
NEast	0.691	0.433	2.551	0.11	1.996	0.804	0.417	3.711	0.054	2.234
MidW	0.605	0.452	1.793	0.181	1.831	0.771	0.428	3.236	0.072	2.161
South	0.923	0.386	5.721	0.017	2.518	0.999	0.376	7.062	0.008	2.717
West	a									
Urban	0.409	0.709	0.332	0.565	1.505					
Town	0.864	0.772	1.254	0.263	2.372					
Rural	a									
Years	0.077	0.223	0.12	0.729	1.08					
-2 Log likelihood	305.01					310				
Cox & Snell R^2	0.182					0.167				
Nagelkerke R^2	0.252					0.232				

a = reference category

3.14 Similarities Within User Groups

Architects that have adopted ECWPs have been identified by their significant demographic and psychographic variables. This adoption process can be taken a step further by defining user groups by the frequency with which they specify ECWPs by utilizing discriminant analysis (DA)methods. DA is an analysis of dependence method where the dependent variables are categorical in nature and are divided into observations of mutually exclusive and collectively exhaustive groups. In a simple two-group DA, there only needs to be a single dichotomous dependent variable to indicate group membership. In situations with multiple data, G-1 dichotomous variables are needed to indicate group membership across G groups. The core assumption of discriminant analysis is that each group must be sampled from a multivariate normal population and the population covariance matrices must be equal (Lattin et al., 2003). By utilizing discriminant analyses, distinct groups can be compared to discover the variables that influence the similarities of within-group membership. In this case, to discover the need to compare within-group similarities of occasional (light) and frequent (heavy) users of ECWPs.

The variables that determined the adoption of FSC- and SFI-certified wood products were used as predictor variables for the grouping or binary dependent variable. A total of 210 cases were used for the DA. Table 3-23 shows the selected ANOVAs indicating significant differences between the means of *LEED for Homes use*, *environmental orientation*, *innovation score,* and *use of another regional GBP* at the $p<0.01$ level. The Box's M tests homoscedasticity; a significance less than 0.05 suggests a significant difference between group covariance matrices (Table 3-24). The results show that there is not a significant difference between covariance matrices at $p=0.086$.

Table 3-23 Test of Equality of Group Means by DA

	Tests of Equality of Group Means				
	Wilks' Lambda	F	df1	df2	Sig.
User of LEED	0.927	16.048	1	204	<0.001
User of NGBS	0.997	0.56	1	204	0.455
Environmental Orientation	0.905	21.517	1	204	<0.001
Economic Orientation	0.997	0.595	1	204	0.441
Social Orientation	0.997	0.583	1	204	0.446
Innovation Score	0.887	26.094	1	204	<0.001
Other GBP	0.965	7.429	1	204	0.007
Client (Homebuilder)	0.999	0.155	1	204	0.695
Northeast Region	0.998	0.373	1	204	0.542
Midwest Region	0.999	0.117	1	204	0.733
South Region	0.999	0.163	1	204	0.687
West Region	0.992	1.543	1	204	0.216
Years in Business	0.996	0.787	1	204	0.376

Table 3-24 Box’s M Test of Covariance Matrices

Test Results

Box's M	11.283
F Approx.	1.845
df1	6
df2	112945.4
Sig.	0.086

One discriminate function contained 100% of the total within-group variability and the eigenvalue of .228 (Table 3-25). The table’s canonical correlation indicates the overall measure of association between each group and its discriminant scores; the results of this study (0.431) indicate to a moderate correlation. Table 3-26 displays the Wilk’s Lambda test, which tests the null hypothesis of equivalent group means. The lambda value is the proportion of the total variance of scores not explained by this group mean difference. The high value 0.814 and the significant level p<0.001 in this study suggest that the means of the groups are different. Table 3-

27 shows the results of computing standardized canonical discriminant function coefficients and the relative importance of independent variables to predicting group membership. The results show that *innovation score* has the highest positive influence on group membership (heavy users). The function at the centroid displays within-group mean canonical scores; heavy users have a score of 0.685.

Table 3-25 Eigenvalue and Canonical Correlation

	Eigenvalue	% of Variance	Cumulative %	Canonical Correlation
Function 1	0.228	100	100	0.431

Table 3-26 Wilk's Lambda Test of Equivalent Group Means

	Wilks' Lambda	Chi-square	df	Sig.
Test of Function 1	0.814	41.646	3	<0.001

Table 3-27 Standardized Canonical Discriminant Function Coefficients and Centroids

Standardized Function Coefficients	
User of LEED	0.37
Environmental Orientation	0.545
Innovation Score	0.551
Function at Centroid	
Light User ECWPs	-0.33
Heavy User ECWPs	0.685

The discriminant function performed a reasonable analysis of light vs. heavy use of ECWPs with four significant predictors of group membership. To evaluate if cases were accurately classified, the function was tested for its effectiveness of predicting group membership. Table 3-28 provides the count and percentages of correct and incorrect case classification of light and heavy ECWPs users. The function incorrectly classified 11 light users as heavy users and 39 heavy users as light users (highlighted in red). This analysis classified 76.2% of cases correctly, showing that the discriminant function is moderately significant at predicting light and heavy ECWP-user groups. This significance is determined by the probability distribution of the groups. The classification result is higher than predicting group membership by chance alone (56%).

Table 3-28 Classification Results of Predicted Group Membership

		Predicted Group Membership		
		Light User	Heavy User	Total
Count	Light User	131	11	142
	Heavy User	39	29	68
%	Light User	92.3	7.7	100
	Heavy User	57.4	42.6	100

a. 76.2% of original grouped cases correctly classified.

3.15 Summary

Finding particular market segments of architects can help promote new and innovative building materials and technologies. Segmentation techniques revealed three different segments of architects: enviro-centric, conventional, and market driven. These segments were not discernable by demographic variables; however, psychographic variables led to the discovery of latent orientations toward specifying building materials based on different attributes. Three orientations—economic, social (customer), and environmental—were reliable measures of the construct and had significant differences between their factor means.

Based on this chapter’s analyses, it is suggested that market segments were predictors of GBP (LEED only) and ECWP use (both FSC and SFI). The enviro-centric segment was more likely to have participated in LEED, as opposed to the market-driven segment that was more likely to use NGBS (not significant). The enviro-centric segment was more likely to use FSC wood and had a comparable use of SFI wood to the market-driven segment. Conventional architects had the lowest use of ECWPs and LEED, but slightly higher use of NGBS than the enviro-centric segment. Demographics were moderate indicators of adoption but did not provide much differentiation between architect segments. Marketing innovative programs and technologies that focus on these segments can potentially increase awareness and eventual use of GBPs and ECWPs. It might be difficult to persuade the conventional segment to participate in GBPs and use ECWPs, but with their higher than average economic and social orientation they could be convinced if there is increased market demand from homeowners in the South or Northeast. The market-driven segment is most likely to work with homebuilders, so continued promotion of LEED for Homes nationwide could result in an increase of homebuilders specifying the program.

For GBP adoption models, *employment type*, *years in business, area of business* were not variables that predicted use. However, architects that worked with homebuilders were more likely to use the NGBS program. The variable *Region* showed that being in the South did somewhat influence NGBS use whereas if an architect had used another GBP, they were more likely to use both LEED and NGBS; this supports the theory that familiarity with one program eases further adoption. If an architect had an environmental orientation or had a high innovation *s*core, they were highly likely to have used LEED, but neither of these variables were predicted NGBS use. The market implications from these models show that psychographic measures and other material- and GBP-use factors better profiled adopters of GBPs. The model predicting NGBS adoption had the lowest goodness of fit, with only three independent variables being significant. With the low levels of adoption of NGBS by architects, insight into homebuilder's usage of NGBS could determine other factors that influence the adoption of NGBS.

For the ECWP adoption model, *employment type* and *client type* were not demographics that predicted use; however, architects that worked for homebuilders were more likely to use SFI wood. The variable *years in business* and being from the West had a negative influence on FSC adoption. Architects that had used another GBP were more likely to use FSC certified wood, but not SFI. Architects' participation in LEED predicted FSC adoption and NGBS use predicted SFI use; these ECWPs align with the programs that reward them points in a certified home. Architects' environmental orientation and high innovation score predicted FSC use, but only innovation score predicted SFI use. For willingness to pay, the results indicated that WTP did not have a significant effect on adoption and was there for not a factor for architects in adopting ECWPs.

The market implications of the ECWP models suggest that architects that participate in the LEED for Homes or NGBS programs influenced whether they adopted ECWPs. It would be a successful marketing strategy to communicate the benefits of ECWPs toward architects who design green homes but do not use ECWPs. There were regional and areas of business that helped predict the use of ECWPs, but the South was shown to be the most significant region for ECWP adoption (SFI). Architects that have homebuilders as a client could be the target market for increased ECWP use because they more likely participate in NGBS, which accepts ECWPs from most forest certification standards. Psychographic measures influenced FSC adoption, but the negative influence from an economic orientation could be offset by highlighting the benefits of differentiating their home by designing with ECWPs. These additional market opportunities exist with environmentally conscience consumers.

For users of ECWPs, to discern if light and heavy users were different, significant variables of the ECWP adoption models showed that *innovation score, environmental* *orientation*, and *LEED use* were indicators of heavy users. Architects with a latent orientation toward the environment are the primary target for green products and technologies. With the goal of increasing architects use of ECWPs and other innovative building products, crossing the GBP participation barrier would have the greatest influence on expanding the market for these goods. Additionally, it would move these products from the growth to mature phase.

There are other deeper values (orientation) and drivers that lead to adoption, such as familiarity with and use of other innovative green products and technologies (*innovation score*) and working with homebuilders that may already be using these products in GBPs. Architects' adoption of GBPs was indicated by their participation in other GBPs; however, this might not be a driver to adoption but rather a barrier which, once passed, made it easier to participate in other programs. The influence of innovation score on GBP adoption could be due to an architect's previous participation in a GBP and use of innovative green products to achieve points toward certification. Furthermore, innovation score did affect ECWP use; therefore, architects who are familiar with and use these innovative products and technologies can be one indicator toward finding other architects willing to try green products.

4. Transparency: Perception or Reality – Quantifying Environmental Friendliness

Submission Information

The results in this chapter will be submitted to *Sustainability*, a peer-reviewed journal that publishes related to sustainability and sustainable development. It focuses on all elements of environmental, cultural, economic, and social sustainability of human beings.

4.1 Introduction

Residential home design and construction continues to evolve with a focus on improving a home’s efficient use of building materials to minimize construction costs and waste. It has also been increasingly important to find ways to reduce energy and resource consumption within the home during its lifetime. Performance guidelines for homes are becoming more stringent as building codes require energy-efficient appliances and water-conserving fixtures. Residential Green Building Programs (GBPs) allow consumers to purchase homes that are built with energy-efficient materials and designed to reduce a building’s environmental impact. The new generation of residential GBPs allow for the submission of Environmental Product Declarations (EPDs) that document the environmental impacts of the building’s materials so the overall impact of the materials comprising a home can be estimated with greater precision. GBPs are rewarding such transparency with additional points that help increase the environmental rating of the building.

Most residential homes utilize wood-based materials for the majority of their structural materials, although many homes also use steel and concrete. Past studies have analyzed homes constructed from varying materials and compared the environmental footprint of the home in reference to the energy consumed during the material manufacturing phase and the atmospheric emissions generated during the extraction, production, and transportation of the materials used in the home (Lippke, Wilson, Perez-Garcia, Bowyer, & Meil, 2004). The process for this accounting methodology is called a product Life Cycle Analysis (LCA). The LCA allows for a thorough analysis that aggregates all the processes used in the production of one unit of material (which is specified by that particular industry). That unit of material can then be assessed for its relevant emissions to the air, water, and waste stream. This chapter considers architects' perceptions of the environmental impacts of three structural building materials (wood, steel, and concrete). This chapter will also compare the LCA data for glued-laminated timbers (Bowers, et al., 2017) on a functional unit basis against the LCA data for steel beams and precast concrete beams.

There are two main research questions that are discussed within this chapter. First, do architects have accurate perceptions of the environmental impacts of comparable building materials? Second, how does the LCA data for structural beams manufactured from wood, steel, and precast concrete compare, on a functional unit basis, when used to build a home?

4.1.1 Life Cycle Assessment

LCA is a methodology through which an environmental profile can be established for a product or system over a defined life cycle (e.g., beginning with the acquisition of raw materials through the end of life of a building) (ISO, 2006a). According to ISO 14040 (2006b), this environmental profile is a collection and assessment of inputs and outputs during a product systems life-cycle and the potential environmental impacts that are caused. LCA is used with increasing frequency to evaluate the environmental performance of buildings and construction materials (Buyle, Braet, & Audenaert, 2013). By implementing the LCA methodology, the environmental impacts of products can be evaluated and compared based on their overall emissions to the air, water, and land, as well as energy use during raw material extraction, product manufacturing, transportation, use, and end-of-life scenario (e.g., recycling, incineration, or disposal in a land fill).

The LCA data of building materials helps us understand the impacts that different materials can have on the overall environmental profile of a building. The structural materials of a building can represent up to 50% or more of its embodied energy (Asif, Muneer, & Kelley, 2007). The manufacture of building materials and subsequent construction of the building, plus the energy consumed during building operation, are the largest contributors of CO_2 emissions in the U.S., which is not likely to change soon (USGBC, 2019b). Most building materials do not have a direct environmental impact during a building's use phase since there are no changes to the material after installation unless there is required maintenance, or the building is remodeled. The environmental impacts of building materials are highest during their "cradle-to-gate" life-cycle phases, which include raw material extraction, material transportation, and collective manufacturing processes. Emissions from the manufacture of non-wood construction materials have a greater impact on the environment than comparable wood materials (Buchanan & Levine, 1999). For example, Buchanan and Levine (1999) state that "if the use of wood in housing increased at the expense of [more] energy intensive materials [such as steel or concrete], the emission reduction can be up to fifteen times the amount of carbon stored in the extra wood products" (p.436).

Multiple studies have shown that a building's total CO_2 emissions from its material inputs can be reduced by increasing the amount of wood-based materials used in construction (Goverse, Hekkert, Groenewegen, Worrell, & Smits, 2001; Gustavsson & Joelsson, 2010). Building with wood also provides other added benefits like fire resistance and sequestered carbon, which is stored in wood products throughout the useful life of the building (Zabalza Bribián, Valero Capilla, & Aranda Usón, 2011). Other research has compared the total energy use over 100 years for buildings made using wood, steel, and concrete, revealing that the wood home used 15% less total energy (this did not include energy from heating and cooling during the operation of the building) (Upton et al., 2008). Comparisons of homes made from wood and concrete showed a substantially lower carbon footprint for wooden homes (Sinha et al., 2016), and wood-framed homes have the additional benefit of carbon sequestration, which offsets many of their environmental burdens (Lippke et al., 2004).

LCA analyses of component assemblies (e.g., walls, floors, and roofs) have shown that wood has the lowest levels of embodied energy when compared to similar components made from steel and concrete (Glover, White, & Langrish, 2002). A study comparing wall components in a house found that a palletized wooden wall had a 34% reduction in embodied energy than a comparable masonry wall (Monahan & Powell, 2011). Werner and Richter (2007) found that when non-wood materials were utilized in a building, their impacts dominated the environmental profile of a building. Comparisons of the life cycles analyses of various home components can clarify how architects and builders' materials choices affect environmental impact.

Even though the use of a building during its operative life represents the largest consumption of water and energy resources, modeling the environmental impacts of building materials provides data that can help evaluate the overall sustainability of the building by incorporating deconstruction and end-of-life scenarios into the overall LCA. Mora (2007) believed that sustainability should be integrated into a building project by considering its entire life cycle. Thus, residential structures that are designed with a focus on being "green" can have many of these sustainable elements included during design. Best practices that minimize waste during construction are highly beneficial, with as much as 22% of the embodied construction energy going into waste (Hammond & Jones, 2008). Thormark (2006) found that choosing recyclable building materials could be one of the most important measures for reducing total energy use. Buildings that are designed to be easily disassembled (cradle-to-grave) encourage reuse and thereby minimize demolition waste (Thormark, 2006; Zabalza Bribián et al., 2011). A completed LCA can be evaluated for impacts along all phases of the life cycle to identify hot-spots or areas that can be improved in the future.

LCAs provide crucial information for the next generation of home construction as architects design structures with the entire life cycle of a building in mind. This includes using materials with the potential to be reused or recycled as well as designing entire buildings that could be reused or redesigned with minimal impacts on the environment. Even though there is substantial literature documenting the environmental friendliness of wood products, it remains vital to establish new data comparisons as life cycle inventories and energy inputs into systems routinely change over time. Comparing different building materials used in the same end-use application can provide architects and designers with objective data on the environmental performance metrics of each material and ultimately assist them in specifying building materials that reduce the environmental footprint of the homes they design.

4.1.2 Building Materials in Residential Construction

Building materials used in residential construction are made from a wide variety of materials. Wood is one of the most common materials for both structural members and interior finishes (e.g., cabinets, flooring, doors, windows, and moldings) in houses. Most foundations and building materials that will be in direct contact with the ground tend to be inert (e.g., steel and concrete) since they are more resistant to decay and moisture. Other structural components (e.g., wall studs) are more likely to be wood products since these materials are unlikely to be exposed to moisture. Structural members such as beams that are designed to support floor and roof loads are typically made from either wooden glulam beams, steel I-beams, or pre-cast reinforced concrete that incorporates steel rebar.

Glulam beams are engineered, stress-rated structural building materials that are typically made from two or more layers of lumber (e.g., lamstock) that are glued together with the wood grain of the lamstock oriented parallel to the length of the beam. The lamstock can be joined together end to end, edge to edge, and face to face, so that the size of a glulam beam is limited only by the pressing capabilities of the manufacturing plant and/or the transportation system. Glulam beams produced by manufacturers who are members of APA- The Engineered Wood Association are certified with an APA Engineered Wood System (EWS) trademark and their manufacturing process is tested for compliance to ANSI/AITC Standard A190.1-2012 to verify product quality (AITC, 1983). Large glulam is typically a specialty product with some smaller and precut sizes (e.g., garage door headers) readily available at larger lumber and contractor yards. Larger sized beams are cut to length to minimize waste and allow for ease of transportation to the construction site.

Steel beams are manufactured from structural steel for use in residential construction. Steel beams are produced in a hot-rolling mill and come in a variety of cross-sections, including I-beams, H-beams, wide flange beams and sheet piling (World Steel, 2011). Steel beams are available for direct purchase from steel distributors and are used by residential builders in various structural applications. They are typically specified in applications with beam depth restrictions or when the beam will be subject to extremely heavy bending loads.

Pre-cast concrete beams are reinforced with steel rebar to improve their bending strength. Pre-cast concrete beams are generally manufactured to specific design criteria and special ordered for individual projects. Concrete beams can be manufactured in a wide variety of shapes and sizes, but the most common dimensions are rectangular, inverted T-beams and L-beams. Precast concrete beams are typically designed with pretensioned concrete to help reduce deflection when loads are placed on the beam. Precast concrete beams and columns are not commonly used in residential construction projects, although there are some benefits to utilizing concrete beams in applications that require extreme fire resistance or are in highly corrosive environments (e.g., along sea shores) (PCI, 2018).

The designer or architect often has many material options to consider when specifying beams. Occasionally, there will be structural or sizing requirements that favor one type of material over another, but within the residential construction sector wood, steel, and concrete can usually be used interchangeably depending on the preferences of the architect, designer, or customer. Research has shown a wide range of environmental impacts associated with each material. For example, columns made of wood were found to have fewer cradle-to-gate environmental impacts, lower global warming potential emissions, and lower acidification than either steel or concrete (Rossi et al., 2011).

The Consortium for Research on Renewable Industrial Materials (CORRIM) has developed life cycle models inventorying all commonly produced wooden building materials in the U.S. This data is available from the U.S. life cycle inventory databases used by LCA practitioners, and also in the design and engineering software utilized by architects and engineers interested in modeling the environmental impacts of their building designs and components. The updated life cycle inventory (LCI) of glue-laminated wooden beams manufactured in the Pacific

Northwest region (Bowers et al., 2017) will be utilized in the comparative analyses of wooden, steel, and pre-cast concrete beams performed in this study. The LCI data for steel and precast concrete beams will be obtained from their respective industry LCI databases (Athena Sustainable Materials Institute, 2015; World Steel Association, 2011).

4.2 Research Hypotheses

Two main hypotheses are considered in this chapter. As shown in Chapter 3, architects possess varying perceptions of the three main home building materials across the different environmental attributes. However, do these perceptions still hold regarding a few of the most relevant environmental aspects (i.e. CO_2 emissions and energy use) of each building material during its cradle-to-gate LCA? Questions from the survey (Chapter 2) that are related to respondents' perceptions of the environmental attributes of different building materials (wood, steel, and concrete) will be analyzed to determine if there are differences in architects' perceptions based on energy use during manufacturing and CO_2 emissions during manufacturing and transport (these refer to a material's environmental impact from "cradle-to-gate"). These will be tested to determine if groups of architects exist with differing perceptions for wood, steel, and concrete and explore if these different groups of architects have similar traits within these groups.

H10: Similarities exist within the group of architects who rate wood-based materials as having lower environmental impacts than steel and concrete

If hypothesis H10 cannot be rejected, then proceeding with a comparative analysis of beams made from these three materials would be useful to discern whether beams constructed of these three materials have differing environmental impacts when performing an identical function within a residential home. If differing perceptions exist, it may influence architects' choices between wood, steel, and concrete when trying to reduce the environmental impacts of the homes they design. Quantifiable data from these building materials' life cycle assessments could be used for a functional unit comparison outlined in ISO 14040/14044. A functional unit comparison must be performed to properly evaluate each building materials' impact by utilizing each material for an identical function. The comparison of wood, steel, and precast concrete beams will be discussed in the LCA section of this chapter. This comparison will provide the data needed to evaluate whether environmental burdens from the three beams differ based on a functional unit analysis.

H11: The environmental burdens accrued from the production and transportation of wood, steel, and concrete beams vary based on functional unit design scenarios.

The following section determines if architects have differing perceptions of the three materials (similar to Chapter 3). Afterwards, a comparative LCA of beams made from wood, steel, and concrete is presented with their respective environmental impacts. Measuring perceptions versus reality can be important in determining deficiencies in information distribution and where gaps remain in the literature. This research attempts to fill those gaps by assessing architects' perceptions of the materials and then promoting the material attributes that possess environmentally friendly characteristics.

4.3 Architects' Perceptions of Building Materials

The following analysis considers architects' perceptions of the environmental impacts of beams made from wood, steel, or concrete. A survey of architects by Conroy (2018) showed that architects valued environmental impacts when deciding between building materials, but this was not as important as other attributes such as aesthetics, building codes, and costs. Other studies have found that architects' had positive perceptions regarding the environmental impacts of wood-based building products (Kozak & Cohen, 1999; O'Connor et al., 2004; Robichaud et al., 2009). The material choices that architects make are a few of many design decisions that could impact the future of home construction while helping to reduce the environmental footprint of a home. The fundamental reasoning behind providing LCA data is to document and quantify the environmental impacts associated with using each material. As discussed in Chapter 2, architects possessed varying perceptions of the environmental attributes of three basic residential structural materials: wood, steel, and concrete. The survey data was analyzed to determine if there were statistically significant differences between groups of architects with varying perceptions.

A cluster analysis was performed to assess whether architects were dissimilar in their perceptions of different building materials' environmental impacts. Based on survey questions assessing material preferences, two questions in particular (e.g., low energy during the manufacturing process and low CO_2 emissions during manufacture and transportation) refer to a material's environmental impact from "cradle-to-gate." If these analyses had taken a "cradle-to-grave" approach into consideration, then other questions regarding renewability, longevity, and recyclability of materials would be relevant, but are outside the scope of this research.

As outlined in Chapter 3 (Section 3.13.2), multivariate resemblance is a quantitative measure showing the similarity between either objects or the variables that describe them and is a precursor to subsequent ordination or classification procedures such as clustering. The coefficients of correlation from a similarity matrix can be tested for statistical significance. In this instance, an evaluation of the environmental attributes of three different building materials—wood, steel, and concrete—are assessed. Each respondent was asked to evaluate each building material using a rating from 1 to 5, with 1 being *Strongly Disagree* and 5 being *Strongly Agree* that the material in question has qualities of that particular attribute. An architect's perception of the different building materials may be similar, but aggregating responses can establish an average view of the general perceptions for each material. Characteristics describing the attributes of the three materials were the variables in the data matrix and architects were the objects or observations. This data was utilized to calculate a similarity matrix for further analyses. The compared variables were ordinal, and Gower's coefficient was used to compare a data matrix with different data types. Following these procedures allowed for a cluster analysis to be performed utilizing Ward's method, which takes the total sum of squared deviations of every object from the mean of its assigned cluster. As the total sum of squares increases so does the growth in cluster membership.

When attempting to identify a particular cluster solution from several options, the selection of clusters is based on maximizing cluster variation, and the starting point is from each individual to eventually the entire group or sample within one cluster. Identifying the best cluster solution relies on some experience since it combines the use of statistical measures and judgement (Ganguly et al., 2010). In deciding on an optimal clustering solution, the following principles were considered: 1. Distinct cluster formation results when more individuals have joined a cluster and the length of the lines on a cluster dendrogram are at their longest before a larger cluster is formed. This equates to stronger membership within those distinct cluster groups and 2. Clusters need to have a reasonable number of members so that the solution has a discernable meaning.

Results of Architects Perceptions

Similar to the results in Chapter 3 (Section 3.13.2), the analyses resulted in the formation of a two-cluster solution. The main difference was that these analyses only implemented the questions referencing "cradle-to-gate" attributes. The differentiation between architects that rated the environmental impacts of the three building materials are shown with two discernable clusters in Appendix D. Utilizing Ward’s method to measure the deviations from each object from its cluster center, the length of the dendrogram lines for the two-cluster result were the longest and it was determined to have the most significant differences between the groups (see Appendix D). Cluster 1 had a membership of 163 members and Cluster 2 contained 222 members. The differences in the clusters are shown in Figure 4-1 with the cluster means for each material rating. This chart shows whether a respondent strongly agrees with a material’s environmental performance for that particular question with a higher value equating to being better for the environment. Each of the cluster means was tested against the midpoint (neutral=3) to determine if respondents from that cluster agreed or disagreed with that material having an environmental impact based on the two attributes. Based on results, the cluster mean for each material attribute was significantly different than 3 (neutral). This test verifies that the members of each cluster believe that each of the materials has environment impacts from cradle-to-gate. The closest cluster mean to 3, Cluster 1- concrete’s energy use (3.12), was significantly different at the $p<0.05$ level ($p=0.02$).

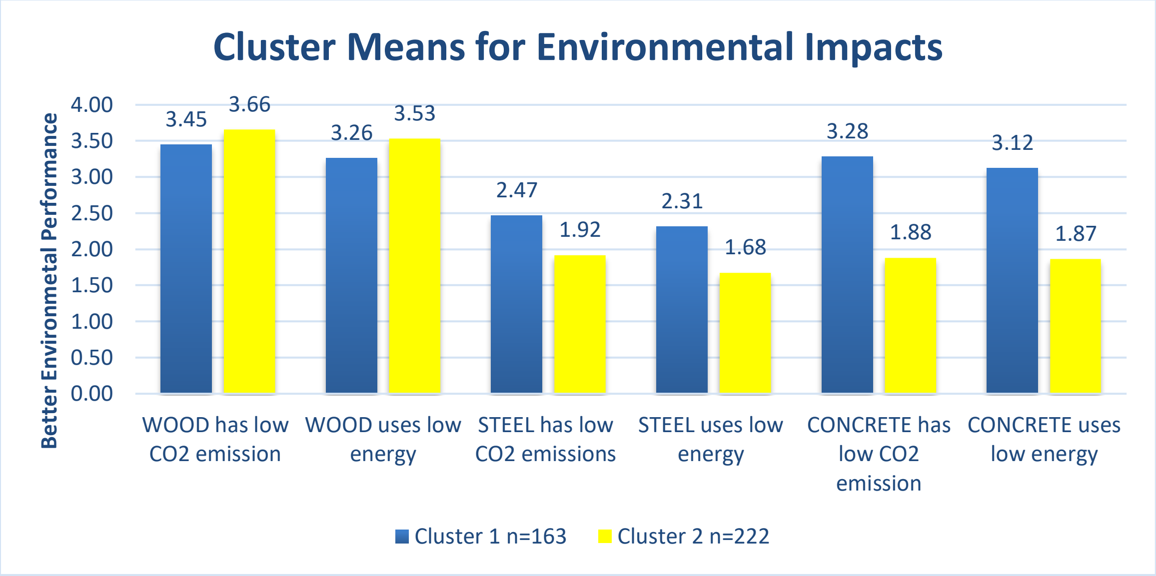


Figure 4-1 Cluster Means for Environmental Impacts Questions

From Figure 4-1, Cluster 1 rates steel or concrete as having lower CO_2 emissions and energy usage than Cluster 2, while Cluster 2 rates wood better for those two attributes. Cluster 1 still rates wood, based on the mean, better for the environment than steel or concrete, but their mean value for steel and concrete were considerably higher than Cluster 2. To test whether the means are significantly different from each other, the non-parametric Mann-Whitney U test was performed since the responses were measured on an ordinal scale. The mean ratings for steel and concrete were significantly different at the $p < 0.001$ level of significance, while for wood, the mean ratings were significantly different for energy usage at the $p < 0.001$ level and for CO_2 emissions $p < 0.01$ level. There was more agreement between clusters over wood's impact on the environment compared to the other materials, but there was still a significant difference between clusters to reject the null hypothesis of homogeneity with architects' perceptions on wood. Based on these results, Cluster 1 will be referred to as pro-steel/concrete while Cluster 2 will be referred to as pro-wood.

4.3.1 Similarities of Architect Clusters

The cluster analyses supported the hypothesis that architects have varying perceptions of wood, steel, and concrete based on the similarity matrices of the respondents (2-cluster solution). With these cluster formations, it is also important to verify if there are similar characteristics of the members within each cluster. By comparing the clusters and the membership within, other variables can be assessed for their significance in predicting cluster membership (e.g., demographic variables). Each of the demographic questions (question 4 on the survey) in Appendix A were tested for their interdependence based on their membership in either of the two clusters. These contingency tables test whether expected frequencies are similar to observed frequencies. If the calculated chi-squared (χ^2) value is small, the hypothesis that the variables are similar is not rejected. A large χ^2 shows that two variables are related in some way or influence the membership in that group. Computing the chi-square value is shown by Equation 4-1. In Table 4-1, the categorical variables tested are shown with their associated χ^2 value and significance level (p-value). The variable client type was shown to be significant ($p = 0.04$) with Cluster 2 (pro-wood) having more homeowners as their client type, while Cluster 1 (pro-steel/concrete) had more small and medium homebuilders as their client type. The other categorical variables did not show significant interdependence, but for census regions, Cluster 2 (pro-wood) did have a higher frequency of architects from the South and West.

Equation 4-1 Chi-Square (χ^2) Formula

$$\sum_{ij} (f_o - F_e)^2 / F_e$$

Table 4-1 Categorical Variables Tested for Interdependence between Clusters

Variable	df	χ2	p-value
Client Type	4	9.929	**0.042***
Census Region (4)	3	5.234	0.155
Employment	1	0.69	0.406
Area Conduct Business	2	2.357	0.308

With differing perceptions of material attributes and some insight into group membership, it is advisable to take the next step of conducting a comparative life cycle assessment of the three different building materials to determine their actual environmental impacts. This would provide credence to whether these perceptions are factually accurate. Life cycle inventory data and the resulting environmental impacts of these building materials would be available to architects who are looking for quantitative data to support the materials choices for their designs. This information could be distributed to firms that might be less likely to design with materials that are more environmentally friendly (i.e., architects that work for small and medium homebuilders). Having this type of data available can benefit architects when they select structural building materials for their home designs. The following research will follow ISO 14040/14044 protocols and the FPInnovations product category rules (PCR) for wood products (FPInnovations, 2015) to provide relevant data on the energy use, material inputs, transport, and required environmental impacts from the functional unit of one glulam beam carrying floor load in a residential home scenario. This data will then be part of comparative analyses with steel and concrete beams providing the same function. The required elements of a life cycle assessment will be provided for perspective into all the inputs required during a glulam beam’s life cycle. These inputs are provided to help detect and assess hotspots within the system where there is potential for improvement in resource and energy use. These improvements could eventually lead to future technological developments within the forest products industry.

4.4 Goal and Scope

This LCA was designed as a functional unit analysis utilizing the updated CORRIM LCI data on material and energy inputs associated with the production of glued-laminated timbers produced in the U.S. Pacific Northwest region (Bowers et al., 2017). This study provides a "cradle-to-installed" LCA of one basement beam in a residential home from which the energy use, associated outputs, and environmental impacts can be measured. This analysis will utilize data from the region and then compare the emissions and energy use with beams produced from different materials (steel and concrete) that provide the same function within a home.

The scope of this work includes the LCA of glulam from the PNW region of the United States from cradle (seedling) to installation (permanent fixture) within a home in Seattle, Washington, U.S.A. End-of-life scenarios will be discussed, but will not be taken into consideration in this research since there are multiple unknowns regarding recycling and disposal of materials after demolition. The glulam data originated from glulam mills in 2013 to update the LCI database, which is required for Environmental Product Declaration (EPD) protocols of glued-laminated timber produced in the U.S. The data was obtained by surveying manufacturers in this region and was consistent with CORRIM protocols for performing LCIs of wood products (Puettmann, Taylor, & Oneil, 2014). These protocols follow ISO 14040/14044 standards for conducting life cycle assessments (ISO 2006a, 2006b), and meet the requirements of the PCR for North American Structural and Architectural Wood Products (FPInnovations, 2015). The treatment of biogenic carbon was taken from the Norwegian solid wood PCR (Aasestad, 2008) and the collected LCI data was used to conduct the life cycle impact assessment (LCIA) based on

TRACI, version 2.1 (Bare, 2012).The steel and concrete LCI information were taken from their respective EPDs (Athena Sustainable Materials Institute, 2015; World Steel Association, 2011) and the material requirements for the comparative analyses and impacts for each of these materials were calculated using standard beam load and span tables (APA, 2016; AISI, 1993; PCI, 2018). Material requirements were based on design thresholds for a residential beam installation and to meet the assumptions for a functional unit comparison.

Description of Industry

Glulam facilities in the U.S. are primarily located in the Pacific Northwest and Southeast regions of the country. Larger manufacturers are typically located closer to the wood resource input, in this case lamstock,[6] so that most of the raw material inputs arrive by truck. Most glulam plants have been in existence for 20 years or more and utilize one of two laminating technologies, either cold curing (no added heat) or radio frequency curing. Besides typical air emissions from energy use and equipment combustion, wood waste is generally the main byproduct of the glulam manufacturing process.

4.5 Description of Product

Glulam is an engineered, wood-based structural product that consists of two or more layers of lumber that are glued together with the grain of the layers parallel to the length of the beam or column. These layers are typically referred to as laminations (Figure 4-2) made from suitably selected and prepared pieces of wood either in a straight or curved form, with the grain of all pieces essentially parallel to the longitudinal axis of the member. The maximum lamination thickness permitted is 50 mm (2 in.), and the laminations are typically made of standard 25 or 50

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[6] Lamstock is defined as a special grade of wood used in constructing laminated beams. In this study, lamstock was cut to 1.73" x 3.75", 1.73" x 5.875", 1.73" x 7.75", 1.73" x 9.75" and 1.73” x 11.75”.

mm (nominal 1 or 2 in.) thick lumber. All glulam properties are tested to adhere to ASTM D3737 – 12 Standard Practice for Establishing Allowable Properties for Structural Glued-Laminated Timber (Glulam) (ASTM International, 2012). Most architectural beams used for residential construction projects carry a 2400F V-4 1.8E designation. These designations mean that the beam can withstand 2400 psi bending force (Fb), V4 defines that the layup of the beam is unbalanced with the outer tension laminations (taking much of the bending stress) only in the bottom of the beam, and 1.8E is the Modulus of Elasticity (MOE) or 1,800,000 psi and meets design requirements providing the stiffness of the beam.

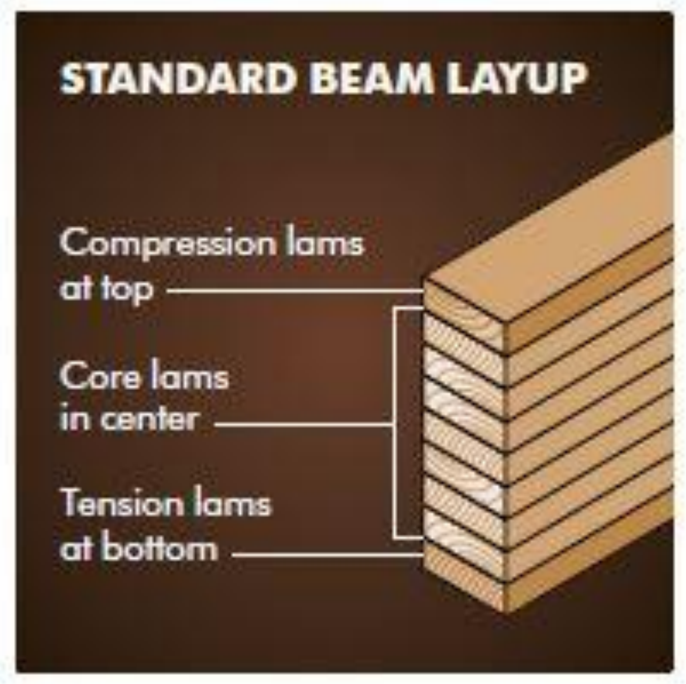

Figure 4-2 Glulam Layup (*Source: APA*)

Glulam beams are used as concealed or exposed structural beams and columns in residential and commercial construction, warehouse roof beams and purlins, church arches, and girders and deck panels for timber bridges. Glulam comes in a variety of sizes with production based on a volume basis, typically board feet (1 board foot = 0.0024 m^3), and sold by retailers on a linear basis. Approximately 60% of glulam produced in the U.S. is used in domestic new residential and remodeling construction (Schuler, Adair, & Elias, 2001). The next largest segment is the nonresidential market representing 31%, and the remainder sold to industrial (4%) and export (5%) markets. Glulam can be made from any wood species provided its mechanical and physical properties are suitable and can be properly glued together. In the PNW region glulam is primarily made from Douglas-fir (*Pseudotsuga Menziesii*), with the balance coming from Alaska yellow cedar (*Cupressus nootkatensis*) and Port Orford cedar (*Chamaecyparis lawsoniana*).

Glulam is produced from softwood lumber called lamstock. Lamstock is classified as a special grade of lumber used in the construction of laminated timbers. Sizes of lamstock lumber produced in the PNW are shown in Table 4-2, alongside the relative mix of lamstock sizes utilized for glulam production during the time of the study.

Table 4-2 Lamstock Sizes Used in the Production of Glued-Laminated Timbers, PNW

Nominal Dimension	**Actual Dimension**		**Actual Dimension**		**Mix %**
Depth x Width	Depth (mm)	Width (mm)	Depth (in)	Width (in)	
2x4	44.45	95.25	1.75	3.75	24.3%
2x6	44.45	149.225	1.75	5.875	51.2%
2x8	44.45	196.85	1.75	7.75	15.6%
2x10	44.45	247.65	1.75	9.75	5.3%
2x12	44.45	298.45	1.75	11.75	3.2%

4.6 Functional and Declared Unit

A declared unit, as defined within the PCR for glulam timbers, is one m^3 of final product packaged for shipment. A declared unit is utilized when the function and reference scenario for the whole life cycle of a wood building material cannot be stated (FPInnovations 2015). Unit conversions for the U.S. industry standard measure of 1 board foot = 0.0024 m^3. As per the PCR

(FPInnovations, 2015), “a functional unit shall be defined based on the functional use or performance characteristics of the product integrated into a building or other type of construction use phase” (p. 7). Since the use will be defined (basement beam) in this example, the functional unit will be used for the analysis and can be estimated based on design and loading requirements. Also, this research is not being utilized for an EPD and therefore this methodology for comparative analyses is appropriate (one glulam beam installed to design specification). There is little information to be gained from comparing the same amount of material (e.g., one m^3) for their environmental impacts since each material would perform differently under designated scenarios. For this research, a fully functioning glulam beam carrying floor joists in a residential home was sized utilizing the American Institute of Timber Construction beam capacity tables (AITC, 2012). For a glulam beam spanning 16 feet, the estimated material requirements would be 0.1622 m^3 of material, or a beam with the dimensions of 3 1/8” in width by 16” in depth. This estimate will be used to figure input requirements and their associated outputs allocated to the functional unit of the product based on the mass of the product and coproducts in accordance with ISO 14040/14044 standards (ISO, 2006a, 2006b).

4.7 System Boundaries

To compartmentalize the various stages of the glulam life cycle and the inputs and outputs for each stage, a system boundary is specified to account for the stages considered for a particular products’ LCA. Most LCAs are required to consider the inputs and outputs from cradle (raw material extraction) to gate (ready for shipment for use). Since this study is looking at the functional unit of one glulam beam, the construction phase will be added to the system boundary. Structural materials like glulam beams are inert after installation and are assumed to have no environmental impact during the use phase of their life cycle, hence this phase will not be part of the system boundary. According to the PCR and the provisions of ISO 15686-1, a 60-year reference service life is assumed for structural products being part of a "permanent building" (FPInnovations, 2015)

To consider the system boundaries of glulam, Figure 4-3 shows the stages that are included from cradle-to-installation. These stages consist of a resource extraction module (A_1), transportation modules (A_2), and lamstock and glulam manufacturing and fabrication modules (A_3). The extraction module includes forest regeneration and stand management, if any, and all harvesting methods utilized during the felling and processing of trees in preparation for transport to a mill. Excluded from the extraction module are maintenance and repair of equipment, as well as building and maintenance of logging roads, logging camps, and weigh stations. The transportation of logs from the woods to the mill is accounted for in the transportation module (A_2) (Figure 4-3). Lumber manufacturing (A_3) includes the sawmill production of lamstock, drying, grading, and packaging (Milota 2015). There was energy generated on-site from trimmings, shavings, and wood waste; this energy was reused (red arrow) for drying the lumber in a kiln. The glulam complex was modeled with a single unallocated unit process. This unit process starts with end-jointing, face-bonding/curing, planing (finish and fabrication), and packaging (A_3) (Figure 4-3). Outputs to the system boundary include one 60' glulam ready to be shipped, air and water emissions, solid waste, and co-products. Glulam beams are usually custom ordered by builders from lumber or specialty forest products distributers where the beam will be cut to length, while some smaller glulam will be stocked by building materials suppliers for standard size applications (e.g., garage door header, etc.). The co-products are no longer tracked once they leave the system boundary. The construction process (A_5) considers onsite fabrication and installation of the product and any transportation (A_4) from the manufacturing site to the building site and any intermediate storage (wholesale distributor, etc.). For this research, the building site is a home in the Seattle Metro area from which materials and data will be considered. The next section provides details for each of the main stages regarding how the data were obtained for the LCI model. This helps to eliminate uncertainties with how and when primary and secondary data are utilized within the model. The cradle-to-installed LCA of glulam consists of five main life-cycle stages: forest operations, lumber and lamstock production, glulam production, transportation, and installation. Material and energy inputs through these stages were measured and tracked by utilizing a mass allocation methodology.

4.7.1 Glulam Production

The following are the main stages involved in the life cycle of glulam from seedling to a finished and installed glulam within a residential home. Each stage will be briefly outlined with the main inputs and outputs from the system. More detailed analyses about the specific steps and associated data regarding these stages and pertinent data relevant to the glulam EPD are discussed within the CORRIM PNW glulam report (Bowers et al., 2017).

Forest Resource Stage

The forestry operations stage of the system includes the growing of seedlings, site preparation, planting, fertilization, and final harvest, which varies for each region (Johnson, Lippke, Marshall, & Comnick, 2007). Assumptions about management activities were based on three levels of management intensity (low, medium, and high) in the PNW with a total yield of 501 m^3 per hectare (Puettmann, Oneil, & Johnson, 2013). This value was used to carry forward the environmental burdens of reforestation on a m^3 basis. Private lands that are forested in this study were based on the PNW average of 45 years between planting and harvest (US Department of Agriculture Forest Service, 2000). Harvesting activities include felling, skidding, processing, and loading logs obtained from both commercial thinning and timber harvest operations. Inputs into the forest resources stage include seeds, electricity used during greenhouse operations, fertilizer used during seedling production and forest stand growth, and the fuel and lubricants needed to power and maintain equipment used for site preparation, fertilization, and harvest operations. The primary output for this stage is a log destined for the sawmill with the associated emissions from the fuel combusted by the various harvesting equipment. Primary transportation

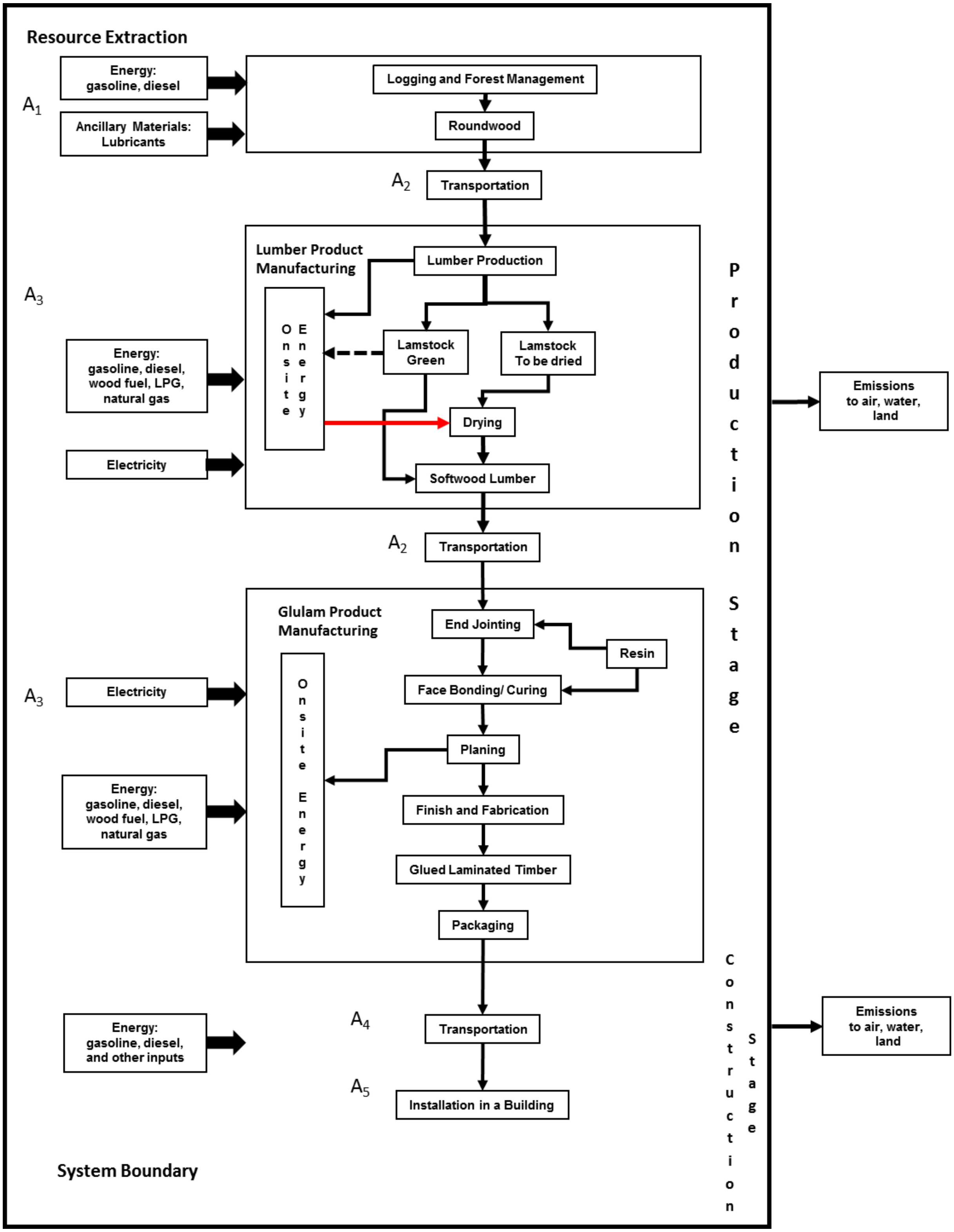

Figure 4-3 System Boundary of Glued Laminated Timber from Cradle to Gate

consists of hauling the logs from the woods to a sawmill; this transport is included with the inputs to the primary manufacturing facility (A_2) (Fig. 4-3).

Lamstock Manufacturing

After transportation from the forest, the logs are unloaded, scaled to measure volume, and stored for additional dimensional stability while drying. Forklifts and/or lift trucks transport the sawlogs to the debarker to begin the lamstock production process. Logs are processed at the mill into green lamstock, which has a moisture content greater than 19%. Most sawmills utilize the residuals from these processes for fueling an on-site boiler for energy to run a dry kiln. Once the lamstock has dried (16% moisture content), it will be transported unplaned (rough) to the glulam facility. Inputs at this stage include logs with their bark, water use, electricity, and potentially on-site power and steam generation from a boiler. Outputs from this module include lamstock, sawdust, chips, bark, and fuelwood (Milota 2015).

Glulam Manufacturing

Lamstock is transported to the glulam manufacturing plant where it can be sorted and processed. Machine e-rated lamstock is utilized for tension laminations (bottom lamination) because most tension stress will be concentrated in the bottom layer of the beam. Balanced beams can be produced that have the e-rated lamstock in the top and bottom laminations for applications where a beam is placed over multiple columns and will be taking tension loads in opposite directions (i.e. a cantilever beam). In addition to the lamstock, the phenol-resorcinol-formaldehyde (PRF) and melamine-urea-formaldehyde (MUF) resins are the only other raw material input at this stage. Electricity is used for radio frequency curing, figure jointing, and for processing the beam to its final dimensions. Glulam beams are typically manufactured in lengths that are longer than the length of the lamstock lumber obtained from the sawmills. To produce longer glulam beams, the ends of the lamstock are finger jointed so that the lumber can be joined together end to end. Resins are then applied to finger joints and cured using radio-frequency curing.

To face-bond the laminations for the glulam, either radio-frequency or cold-curing of resins can be used. Resin is applied by a glue-extruder and assembled to the required layup for the specific type of beam and a form or hydraulic press applies pressure. Once dried, the beam is considered cured, removed from the presses, and all four sides are sanded or planed to remove the adhesive squeezed out during pressing. Each glulam beam is then individually wrapped for protection before shipping. Final product density for PNW glulam, excluding resin, averages 546 kg/m^3 at 13% moisture content.

Transportation

Lamstock for glulam production is transported by truck in the PNW. The LCA incorporated an appropriate diesel tractor-trailer from the U.S. Life Cycle Inventory database (NREL, 2016) based on transportation distances and the mass of logs used at each mill location. Some of the glulam production facilities were located next to or near lamstock facilities, thus minimizing transportation distances. Other materials, such as resins and packaging materials, are brought in by truck in containers or by liquid container trucks. Table 4-3 shows the average one-way distance from the various manufacturers to the glulam production facility in the Pacific Northwest. For the glulam leaving the manufacturing facility, it is assumed that the beams were transported by semi-truck to a lumber and building products distributor in the greater Seattle region where it would be eventually be shipped by a mid-sized delivery truck to residential construction sites. Inputs were the fuels needed to transport the materials, with emission outputs from fuel combustion.

Table 4-3 Delivery Distance PNW One-Way Lamstock to Glulam Facility

Material delivered to Facility	Delivery Distance (km)	
	km	miles
Dry Lamstock, Truck	173	108
Resin	224	139
Strapping	390	242
Wrapping Material	486	302

Construction and Installation

According to the PCR, the construction stage includes all material, ancillary material, and energy inputs, and any additional processing up to the end-of-waste state or disposal of final residues. Since the inputs and outputs from this stage were unknown at this time, this process has been designated a dummy process or place holder until data could be collected. During the construction stage, it can be assumed that typical residential construction methods are utilized in placing and securing the glulam beam during installation (A_5). Depending on the construction site, a lift or small crane will set the beam into place. For this study, it was assumed that the beam was placed on pre-cast concrete columns attached to the home's foundation. Inputs to the system at this stage are the electricity generated on site for tools and equipment and additional nails, bolts, and other materials required for securing the beam in place. Outputs from the system are the associated emissions from equipment electricity requirements and any waste generated from on-site fabrication. All impacts related to any losses that occur during this stage would be included.

4.8 Data Quality and Process Inputs

The forest resource and harvesting data were collected from earlier studies of forest operations in the PNW (Johnson et al., 2007) and lamstock manufacturing data was collected from sawmills in the PNW (Milota, 2015). Primary glulam manufacturing data was collected utilizing surveys from glulam mills located in the PNW in 2013 (Bowers et al., 2017). A listing of data sources for all secondary data is available in Appendix E. Life cycle inventory results are not presented in this document and can be found with the respective products EPDs. Information gathered for this study included all material inputs (lamstock, resins, and packaging), water, electricity and fuel use (including transportation), and emissions. Unit process inputs for the glulam mills located in the PNW are listed in Table 4-4.

Table 4-4 Unit Process Inputs and Outputs for Glued-Laminated Timber Production for One Finished Glulam Beam

Products	**Unit/m^3**	**Value**
Glue-Laminated Timber	m^3	0.1622
Glue-Laminated Timber (kg)	kg	82.88
Co-Products (Sawdust, Shavings, Trimmings)	kg	11.66
Materials/Fuels	**Unit/m^3**	**Value**
Electricity, at Grid	kWh	11.56
Natural Gas	m^3	0.01
Diesel	L	0.15
LPG	L	0.4
Gasoline	L	0.01
Wood Waste Combusted in Boiler	kg	4.13
Transport, Truck	tkm	17.91
Melamine Urea Formaldehyde Resin	kg	0.24
Phenol Resorcinol Formaldehyde Resin	kg	1.25
Sawn Lumber, Rough, Kiln Dried	m^3	0.19
Sawn Lumber, Rough, Green	m^3	0
Wrapping Material – Packaging	kg	0.68
Strapping – Packaging	kg	0.03
Spacers – Packaging		0
Emissions to Air	**Units/m^3**	**Value**
Particulates. Unspecified	kg	0.01
VOC, Volatile Organic Compounds	kg	0.008
2-Proponol	kg	0
Ethanol	kg	0
Acetaldehyde	kg	0
Methanol	kg	0
Phenol	kg	0.099
Formaldehyde	kg	0.004
HAPS	kg	0.056

4.9 Mass Balance

Table 4-5 shows the mass balance of the glulam material inputs and outputs for the PNW region. The wood and resins going into the production of one glulam beam (0.1622 m^3) during the manufacturing process results in either the glulam beam, shavings from planing, trimmings from the ends, and wood waste or scrap. Unaccounted inputs are assumed to be lumber from a previous year. The output of a finished glulam was 251.42 kg oven dry mass.

Table 4-5 Mass Balance of Glulam Manufacturing per Functional Unit of PNW Glulam (0.162 m^3)

	PNW		
	OD kg	Mass	CoVw[1]
Feedstocks	**INPUTS**	(%)	(%)
Lamstock	90.67	95.82%	4.16%
Unaccounted Inputs (Lumber)[2]	2.52	2.66%	
Additives			
Phenol-Resorcinol-Formaldehyde Resin	0.97	1.02%	47.56%
Melamine-Urea-Formaldehyde Resin	0.19	0.20%	68.55%
Catalyst/Fillers/Extenders	0.27	0.29%	41.20%
Total Additives	1.43	1.52%	23.10%
Total Inputs	94.62	100%	
Products	**OUTPUTS**		
Glulam	82.84	87.54%	0.47%
Co-Products			
Shavings	4.82	5.09%	135.12%
Trimmings	6.85	7.24%	62.76%
Waste	0.12	0.13%	0.00%
Total Co-Products	11.79	12.46%	39.25%
Total Outputs	94.62	100%	

[1] Coefficient of Variation for the weighted average of input and outputs. PNW: 4 response

[2] Unaccounted for inputs are assumed to be lumber on-site prior to the year of the survey

4.9.1 Energy, Water, and Waste

Energy requirements for glulam production are presented in Table 4-6 for one glulam beam (0.1622 m^3). Non-renewable energy use in the PNW region consisted mainly of electricity generated from natural gas. The majority of raw material energy consumption occurs during the glulam production stage with only a small portion arising from forestry operations. Lamstock production generated most of its energy from wood waste and relied less on fossil fuel inputs. All primary transportation steps are assigned to the transport of logs (roundwood) to the mill or lamstock, resins, packaging and transport to the glulam production phase. Energy figures are expressed in megajoules (MJ), and electricity in kilowatt hour (kWh). The PNW utilizes electricity from the WECC grid, with coal, natural gas, and hydro-generated power the three largest contributors (NREL, 2016). Energy consumption from non-renewables, renewables (wind, hydro, and solar), and nuclear fuels, water use, and solid waste are shown in Table 4-6.

Table 4-6 Energy Consumption, Water Usage, and Waste per 1 PNW Glulam Beam (0.162 m^3)

	Unit	Total	Forestry Operations	Lamstock Production	Glulam Production
Total Primary Energy	MJ	832.23	34.07	568.46	229.70
Non-Renewable Fossil	MJ	274.08	33.68	111.07	129.33
Non-Renewable Nuclear	MJ	22.02	0.33	9.42	12.27
Renewables, Other	MJ	14.29	0.06	4.28	9.95
Renewable, Biomass	MJ	521.85		443.69	78.16
Fresh Water	L	74.49	2.30	61.42	10.77
Solid Waste	kg	1.41	0.04	0.62	0.75

4.9.2 Beam Span

As the functional unit of the beam was previously defined, the specifics regarding its installation are relevant so analyses could be replicated. Beam span is the length of the beam from center to center of the columns or walls upon which a beam would be placed. In most residential applications a beam carries a continuous load that is evenly distributed along the length of the member (Figure 4-4). Depending on the design of a home, the beam might be required to carry additional concentrated loads (point loads) from other beams attached to it (i.e., around a stairwell), framing from floors, or a roof above (i.e., joist from the hip of a roof). Beams need to be sized with the appropriate width and depth for its designed span while accounting for all loads the beam will carry to stay within design limits.

Figure 4-4 Glulam Beam on Precast Concrete Column Carrying Floor Load (*Source: Anthony Forest Products)*

The beam span for this application was specified at 16’ in total length from center to center of the columns, allowing for 6” of bearing length for proper support of each end of the beam on precast concrete columns (Figure 4-5). Pre-case concrete columns were selected because of their compatibility with all three beam materials (wood, steel, and concrete). Standardizing the column used in this study provides consistency with the beam comparisons. The beam in this scenario carries 16’ of floor joists on each side with typical joist hangers. This design would have the beam carrying 16’ of total floor space (256 sq. ft), which is ½ of the length of the joists connected from each side. The joists would be spaced evenly at 16” on center, which is standard residential construction practice. The beam in this scenario only carries a continuous floor load with a live load of 50 pounds per square foot (psf) with no walls or concentrated loads on top of the beam.

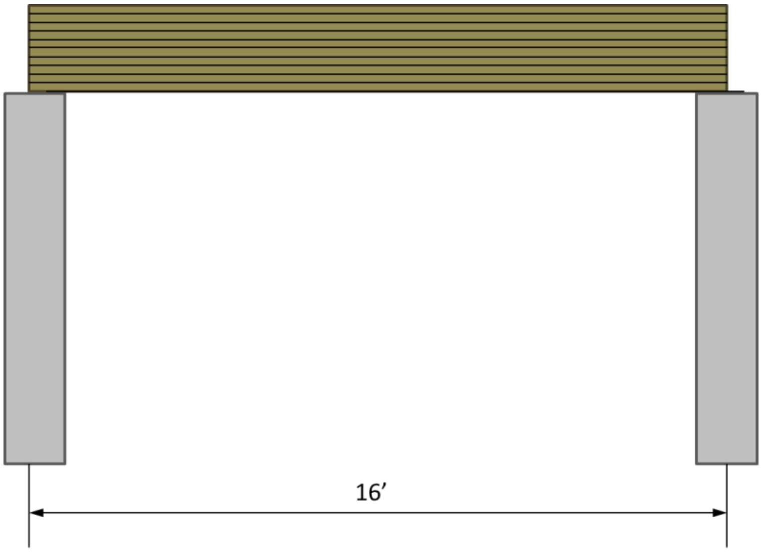

Figure 4-5 Glulam Length and Layup on Pre-Cast Concrete Columns

Standard beam sizing charts were utilized to determine the dimensions of the beam required to meet span and design loads (APA, 2016; AISI, 1993; PCI, 2018). Glulam typically used for this function are unbalanced (tension lam on the bottom), with a 24F-V4 layup to meet floor design standards of an L/360 floor deflection[7]. Once the beam was sized, volume and mass (for steel) could be calculated to determine its environmental impact. Information on steel sizing equates to the following nomenclature: 1st number = approximate depth (inches) and the 2nd number = weight per foot (lb./ft) (i.e. W12 x 70 is 12” depth and 70 lb./foot) (AISI, 1993). Since the U.S. residential construction industry utilizes imperial units, the following analysis will also for ease in comparison. Precast concrete beam sizes are solid with pre-tensioned rebar and are measured on a volume basis. The nomenclature uses the width of the beam followed by its shape

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[7] L=span length in inches and is divided by the design requirement for live loads (360 or higher), to determine the amount of deflection a member can have for the corresponding spam under full design loads.

and depth (i.e. 12RB16 is 12” wide with 16” of depth; the RB signifies rectangular beam). The precast beam required was estimated utilizing a similar load table used for glulam and steel beams (PCI, 2018).

4.9.3 Allocation and Calculation Rules

A mass allocation methodology was utilized to ensure comparability with previous reports and LCAs; the steel and precast concrete LCAs were also based on mass allocation during this period. In the future, an economic allocation based on product revenue should be followed when the total revenue between the main product and co-product is more than 10% (FPInnovations, 2015). Calculations for the glulam LCA utilized Simapro version 8.0+ (PreConsultants, 2016). The TRACI 2.1 V1.01 impact method (Bare, 2012) was used to quantify the environmental impacts of the forest operations, lamstock production, and glulam manufacturing.

4.10 Comparative Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) calculates impact indicators, such as global warming potential and smog. These impact indicators provide general yet quantifiable indications of potential environmental impacts. The target impact indicator, the impact category, and means of characterizing the impacts are summarized in Table 4-7. Environmental impacts are determined using the TRACI method (Bare 2012). The five impact categories reported are consistent with the requirement of the wood products PCR (FPInnovations 2015) and are briefly described in Table 4-7. Each impact indicator is a measure of an aspect of a potential impact. This LCIA does not make value judgments about the impact indicators, meaning that no single indicator is given more or less value than any of the others. Additionally, each impact indicator value is stated in unique units, thus indicators should not be combined or added.

Table 4-7 Selected Impact Indicators, Characterization Models, and Impact Categories

Impact Indicator	**Characterization Model**	**Impact Category**
Greenhouse gas (GHG) emissions	Calculate total emissions in the reference unit of CO_2 equivalents for CO_2, methane, and nitrous oxide.	Global warming
Releases to air decreasing or thinning of the ozone layer	Calculate the total ozone-forming chemicals in the stratosphere including CFC's HCFC's, chlorine, and bromine. Ozone depletion values are measured in the reference units of CFC equivalents.	Ozone depletion
Releases to air potentially resulting in acid rain (acidification)	Calculate total hydrogen ion measured in SO_2 equivalents for released sulfur oxides, nitrogen oxides, hydrochloric acid, and ammonia. The acidification value of kg SO_2 eq. is used as a reference unit.	Acidification
Releases to air potentially resulting in smog	Calculate the total substances that can be photochemically oxidized. Smog forming potential of O_3 is used as a reference unit.	Photochemical smog
Releases to air potentially resulting in eutrophication of water bodies	Calculate total substances that contain available nitrogen or phosphorus. Eutrophication potential of N-eq. is used as a reference unit.	Eutrophication

Functional unit analyses become important when the product is put into the use phase. Wood is measured in their declared unit of cubic meters (m^3), while steel is measured in kilograms (kg) and concrete in tons (metric). This is the methodology used when performing an LCA from cradle to gate. Comparative LCIAs are utilized when there are differing products or services that could perform the same function with varying degrees of inputs from the technosphere or environment. To perform a comparative analysis, the life-cycle inventories and impacts would be compared with each other in the same "function." This does not necessarily mean that the product in use will be the same size, weight, or installed using an identical process during home construction. Products compared by functional unit analyses should be able to meet the same requirements in terms of load capacity and other structural criteria. For beams, these criteria are deflection limits, bending limits, and shear limits. Utilizing data from the EPDs of different products using differing product category rules may not be comparable (FPInnovations, 2015). To overcome issues with these comparisons, beam estimates were for simple spans with the beam capacities from published literature. Advanced calculation should be performed by licensed architects and engineers.

4.10.1 Comparative Assumptions

Regarding the comparative LCA of the wood, steel, and concrete beams, the formulation of assumptions followed CORRIM guidelines (Puettmann et al., 2014) and ISO 14044 standards (ISO, 2006b). The designed comparative scenario is based off common residential design dimensions.

1. All flow analyses of wood through the system were determined on an oven-dry weight basis.
2. Transportation stages included the moisture content of the glulam for proper mass calculations.
3. Similar technology and geographic regional data were used for transportation from manufacturer to the construction site.
4. Energy inputs from the installation stage were not available, but the results would not change significantly since similar processes would be involved for the beams.
5. Data available in the U.S. Life Cycle Inventory database were used when available.
6. Material requirements were estimated for beam load and span tables which determined the beam dimensions necessary for various design scenarios.

4.10.2 Comparative Results

The LCIA comparing the three beams in an identical function are shown in Table 4-8. First comparing energy usage, glulam utilized 139% less primary energy than steel and 357% less energy than concrete during the extraction and manufacturing stages. This resulted in 741% and 2144% reductions in global warming potential than steel and concrete beams respectively (Figure 4-6). The steel beam performed better in the measurement of smog (-98%). Table 4-8 shows the other impact indicators and energy-use breakdown during the cradle-to-gate (A_1 to A_3) stages. For the construction stages (A_4 and A_5), Table 4-9 shows the impacts of transportation from the manufacturer to the job site if distance was kept constant since actual distances from all three materials were unknown. Transportation is the largest contributor to energy use during this stage; comparing the impacts of the mass of these materials will determine where distribution centers are located to minimize these contributions. When distances remained equal, the steel beam required slightly less energy to transport (-0.8%); this is because the mass of the glulam beam is higher when the moisture content inside is included in transport calculations. Both beams used significantly less energy than concrete beams during this stage (-1,311%), as shown in Figure 4-7, but concrete beam manufacturing is usually done closer to the construction site. This scenario was for comparison purposes only and it is assumed that transportation distances would vary greatly and might include transport by rail. The weight and size of concrete and steel beams are a few of the factors that would contribute to differences in energy use during the installation phase, but data from this phase was outside of the scope of this research and is regarded as a dummy variable for the construction stage. Inputs to consider in future research would be increased energy use from onsite welding equipment for steel or concrete attachments, whereas glulam installation only needs saws and drills for proper anchoring and joist attachments.

Table 4-8 Comparisons between Wood, Steel, and Concrete Beams Cradle-to-Gate, Functional Unit

Extraction and Manufacturing A_1 through A_3

Impact Indicator		Glulam	Steel	Concrete
Global Warming	kg CO2 eq	19.32	162.56	433.56
Acidification	kg SO2 eq	0.195	0.457	7.255
Eutrophication	kg N eq	0.007	0.037	0.435
Ozone depletion	kg CFC-11 eq	2.16E-09		2.76E-03
Smog	kg O3	3.96	0.08	85.03
Energy Use				
Total Primary Energy	MJ	832.23	1991.36	3,801.91
Non-Renewables	MJ	296.09	1931.62	3730.66
Renewables	MJ	536.13	59.74	66.89

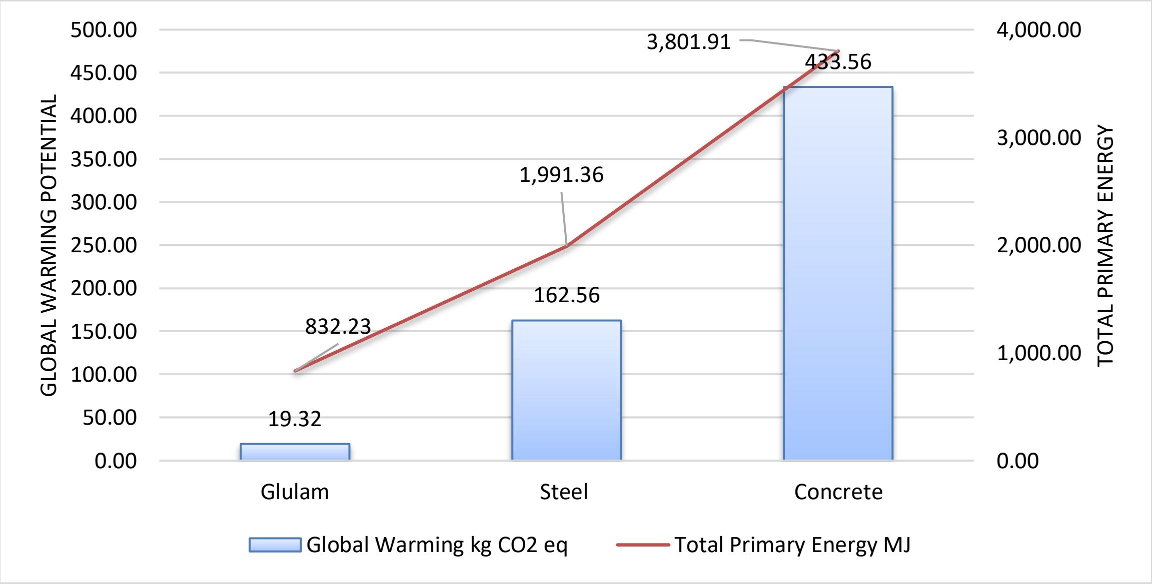

Figure 4-6 Energy Use and Global Warming Potential for Wood, Steel, and Concrete Beams, Cradle to Gate

Table 4-9 Comparisons between Wood, Steel, and Concrete Beams Construction Stage (Transport Only), Functional Unit

		Glulam	Steel	Concrete
Mass	Tons (Metric)	0.091	0.102	1.451
Moisture Content	MC (%)	1.13	1	1
Distance	km	100	100	100
ton*kilometers	tkm	10.283	10.200	145.100
Total Primary Energy	MJ	13.12	13.01	185.12
GW Potential	kg CO2 eq	0.95	0.95	13.45
Percent Change	%		-0.8%	1311.1%

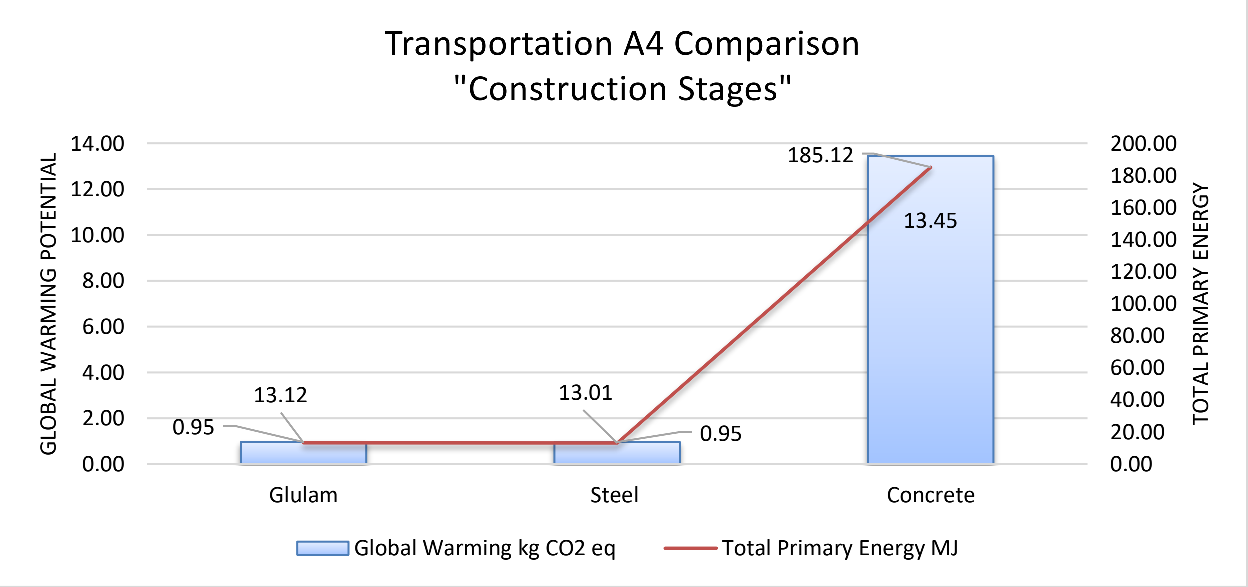

Figure 4-7 Energy Use and Global Warming Potential for Wood, Steel, and Concrete Beams, Construction Stages

4.10.3 Carbon Balance and Treatment of Biogenic Carbon

The approach to the treatment of biogenic carbon was taken from the Norwegian Solid Wood Product PCR (Aasestad, 2008); the North American PCR (FPInnovations, 2015) has adopted an identical approach to ensure comparability and consistency. Biogenic carbon is the carbon stored within wood (or from another life form) that is released during decay or other end-of-life scenarios through emissions to the atmosphere. The North American PCR approach is followed here for global warming potential (GWP) reporting, therefore the default TRACI 2.1 impact assessment method was used. This default method does not count the CO_2 emissions released from the combustion of woody biomass during manufacturing. Other emissions associated from wood combustion (e.g., methane or nitrogen oxides) do contribute to and are included in the GWP impact category. For a complete list of emissions factors for the GWP method used, see Bare (2012). Using this method, 19 kg CO_2 equivalent were released in the production of one glulam beam (0.162 m^3), which includes lamstock and resin production. That same 0.162 m^3 of glulam stores 152 kg CO_2 equivalent (Table 4-10).

Table 4-10 Carbon Balance per One Glulam Beam (Functional Unit), PNW

	kg CO_2 equivalent PNW
Released forestry operations	2.46
Released lumber manufacturing	7.67
Released glulam manufacturing	9.19
CO_2 eq. stored in product	152.09

If considering end-of-life scenarios of wood products, carbon sequestration impacts are measured in accordance with the FPInnovations PCR. There are two types of scenarios, conversion processes and emission processes. Conversion processes consist of end-of-life, landfill, anaerobic landfill, and landfill capture in place. Emission processes consist of recycling, direct combustion, aerobic landfill, no landfill gas capture, fugitive landfill gas, and landfill gas combustion. For wood products at the end of their service life, most get landfilled (80%), combusted (10%), or recycled (10%) (NCASI, 2018).

4.10.4 Steel Recycling and End of Life

Most steel can be recycled, which is accounted for in the LCI of steel when the recycling and an end-of-life LCA is measured. The LCI of steel considers its high recyclability to minimize measured impacts to the environment. The Steel Industry considers “avoided burdens,” since most steel is eventually recycled and reused and thus does not have to undergo primary production stages again, so this consideration has not been met with much concern from LCA practitioners (World Steel Association, 2011). There are also environmental benefits from using scrap steel in most production facilities. Currently the recycling rate for steel in the construction industry is approximately 85%. The general life cycle equation for this “closed material loop recycling methodology” can be applied in addition to the cradle-to-gate methodology through system expansion. When these end-of-life scenarios, including “avoided burdens” through recycling, are included, the calculation below is used:

$$\text{LCI for 1 kg of steel product including recycling} = X - (RR - S)\times Y\times(Xpr - Xre)$$

X = cradle-to-gate LCI of the steel product.
(RR – S) is the *“net amount of scrap”* produced from the system.
RR is the end-of-life recycling rate of the steel product.
S is the scrap input to the steelmaking
Y is the process yield of the EAF (i.e. >1 kg scrap is required to produce 1 kg steel).
Xpr is the LCI for 100% primary metal production, assuming 0% scrap input.
Xre is the LCI for 100% secondary metal production, from scrap assuming 100% scrap input.

This research did not include an end-of-life scenario since there are too many variables to account for to properly address the potential outcomes of these three building materials. Utilizing scrap steel in the production of structural steel greatly reduced the environmental burdens of the steel manufacturing process. In the future, other scenarios implementing recycled products like timbers for glulam, steel from scrap, and concrete from deconstructed aggregate would make end-of-life scenario comparisons more credible.

4.10.5 Concrete Recycling and End of Life

With the reutilization of building materials from demolished buildings, concrete from recycled aggregate is becoming more common in the marketplace. There are more facilities accepting concrete to break apart and grind for reuse and more manufacturers are using recycled concrete in their mixtures. This recycling is not yet accounted for in their end-of-life scenarios but is another topic for future research.

4.11 Interpretation

As defined by ISO 14040/14044 (ISO, 2006a, 2006b), the term life cycle interpretation is the phase of the LCA where the findings of either the LCI or the LCIA, or both, are combined consistent with the defined goal and scope to reach conclusions and recommendations. This phase in the LCA reports the significant issues based on the results presented in the LCIA of this report. Additional components report an evaluation that considers completeness, sensitivity, and consistency checks of the LCIA results, uncertainty, conclusions, limitations, and recommendations.

4.11.1 Identification of Significant Issues

The objective of this element is to structure the results from the LCIA phases to help determine the significant issues found in the results presented in previous sections of this report. From the previous section regarding beam sizing and material requirements, load and span tables were implemented to estimate the beams necessary to meet particular design scenarios. These volumes and mass estimates were particular to these designs and approximate what would be used in an actual home. Architects may have a plethora of requirements when sizing a beam for a particular project and there are many factors that cannot be accounted for in this beam comparison study. The data utilized is sufficient for the comparative analyses conducted in this research but should not be used for real design scenarios looking to substitute these various materials. If adjustments and specific beam sizes are required, then more detailed engineering calculations would be required, but these are outside the scope of this research.

4.11.2 Consistency, Completeness, and Uncertainty

Evaluating a LCA's completeness, sensitivity, and consistency can offer confidence in its results. The completeness check process verifies whether information from the life cycle phases of an LCA are sufficient for reaching the goals and scope of the study while conclusions can be made from sound interpretations of the results. Three life cycle stages for the glulam extraction, transportation, and manufacturing phases (forestry operations, lamstock production, and glulam production) were discussed to verify data completeness. These included all input elements such as raw and ancillary material inputs, energy inputs, transportation, water consumption, and outputs such as products and coproducts, emissions to air, water, land, and final waste disposals. All input and output data were found to be complete and no data gaps were identified. The construction phases (transportation after manufacturing and installation) were not measured for this study, and a basic comparison of impacts from transportation was provided. Further research for the construction stages is necessary to reduce uncertainties in this area. Optional modules comparing end-of-life scenarios could be added into the cradle-to-gate analyses.

The consistency check process verifies that the assumptions, methods, and data are consistently applied throughout the study and are in accordance with the goal and scope of the LCA. A comprehensive review process was completed for the glulam LCA (Bowers et al., 2017) to ensure consistency was applied to the assumptions made, methods used, models, data quality including data sources, data accuracy, age, time-related coverage, technology, and geographical coverage. The data retrieved and utilized for the steel and concrete beams were from their respective EPDs and have gone through the appropriate review processes (Athena Sustainable Materials Institute, 2015; World Steel Association, 2011).

Sensitivity analysis can be applied to the LCA to determine changes in results due to variations in assumptions, methods, and data. All the LCAs performed utilized a mass allocation methodology to make comparisons with previous data sets when possible. The newest CORRIM LCI of glulam utilizes the current LCI of glued laminated timbers (Bowers et al., 2017), lumber (Milota, 2015), and forest management and harvest data (Puettmann et al., 2013). Below in Table 4-11 is a comparison of the data from the previous LCI to the most current LCI (Puettmann et al., 2013).

According to the sensitivity analyses, total primary energy went down slightly (-2.6%), but global warming potential went down significantly (-29.9%). This was a result of the significant increase in energy production from renewables, primarily energy from biomass, during the lamstock and glulam manufacturing stages. There were reductions for the other impact indicators except for smog potential, which was a result of this increased energy use. There was a decrease in non-renewables (-40.0%) which indicates the continued conversion of electricity away from coal and other non-renewables.

Table 4-11 Sensitivity of Data from Previous Glulam LCI Compared with Current Glulam LCA, Cradle-to-Gate, Functional Unit

Impact Indicator		Previous	Current	% Change
Global Warming	kg CO2 eq	27.55	19.32	-29.9%
Eutrophication	kg N eq	0.007	0.007	0.00%
Smog	kg O3	3.30	3.96	20.0%
Energy Use				
Total Primary Energy	MJ	854.18	832.23	-2.6%
Non-Renewable	MJ	457.15	274.08	-40.0%
Renewables	MJ	346.73	536.13	54.6%
Fresh Water	L	130.76	74.49	-43.0%

Additional sensitivity checks were performed by developing scenarios with beams of different lengths (22’ and 30’). Then comparisons that consider minimizing beam height (increasing floor to floor height) of glulam and steel beams were considered (W=wider but shallower beam) (Table 4-12). All the beam dimensions and specifications are listed in Appendix F. The glulam material requirements increased 103% for the 16’W beam compared to the baseline beam. For the longer lengths, the material requirements increased less dramatically at 45% and 41% when a wider beam was specified. The steel beam increased slightly for the 16’W scenario (28%) and increased slightly more at 22’ (36%) than 30’ (10%) accordingly. The concrete beam material dimensions did not change between the 16’ and 22’ lengths, but a deeper beam was required for the 30’ scenario. Wide beams were not provided for concrete for these sensitivity analyses since the minimal amount of material was already being utilized for each scenario and the environmental impacts for these beams far surpassed either of the other materials. The precast beam size at 16’ was the minimal-sized beam at that length and had additional loading capacity available, which resulted in no change in dimensions at a 22’ span.

When the length of the beam was extended to 22’ and 30’, there were increases in global warming potential by 166% and 375% for glulam, 116% and 315% for steel, and 38% and 134%

for concrete (Table 4-13). There were identical increases in the other indicators since only the dimensions of the beams were changing and the indicators increased at the same percentage.

When the width of the beam was changed to reduce beam height, there were increases in global warming potential by 103% (16'W), 285% (22'W), 568% (30') for glulam, and 29% (16'W), 195% (22'W), and 355% (30'W) for steel as shown in Table 4-13. The other indicators are shown in Appendix G.

Table 4-12 Sensitivity Check on Material Requirement Changes to Function Unit Beam Comparisons

Material Requirements	Beam Size	Unit	Value	% Change
Glulam Beam 16'	3 1/8 x 16 ½	m^3	0.1622	-
Glulam Beam 16' W	8 ¾ x 12	m^3	0.33	103.5%
Glulam Beam 22'.	5 1/8 x 19 ½	m^3	0.432	-
Glulam Beam 22' W	8 ¾ x 16 ½	m^3	0.625	44.7%
Glulam Beam 30'	5 1/8 x 25 ½	m^3	0.771	-
Glulam Beam 30' W	8 ¾ x 21	m^3	1.084	40.6%
Steel Beam 16'	W12x14	kg	101.6	-
Steel Beam 16' W	W8x18	kg	130.63	28.6%
Steel Beam 22'	W12x22	kg	219.54	-
Steel Beam 22' W	W10x30	kg	299.37	36.4%
Steel Beam 30'	W16x31	kg	421.84	-
Steel Beam 30' W	W14X34	kg	462.66	9.7%
Concrete Beam 16'	12RB16	ton	1.451	-
Concrete Beam 22'	12RB16	ton	1.996	37.6%
Concrete Beam 30'	12RB20	ton	3.402	134.5%

Table 4-13 Original Basement Beam Scenario Compared with Increased Beam Length 22’ and 30’ Spans, Extraction and Manufacturing Stages A1 through A3

		Beam Length and Wide Indicator					
Beam Material		16’	16’ Wide	22’	22’ Wide	30’	30’ Wide
Glulam	Global Warming	19.32	39.31	51.46	74.45	91.84	129.13
	Total Primary Energy	832.23	1693.19	2216.54	3206.80	3955.91	5561.87
	% Change		103%	166%	285%	375%	568%
Steel	Global Warming	162.56	209.01	351.26	478.99	674.94	740.26
	Total Primary Energy	1991.36	2560.35	4302.98	5867.65	8268.06	9068.14
	% Change		29%	116%	195%	315%	355%
Concrete	Global Warming	433.56		596.40		1016.52	
	Total Primary Energy	3801.91		5229.92		5229.92	
	% Change			38%		134%	

One comparison that will become more relevant as end-of-life scenarios become more commonplace in LCA research is the utilization of scrap steel as an input for the steel manufacturing stage. This reduces energy use during the extraction stage and decreases steel products’ embodied carbon from its cradle-to-installed LCA. Table 4-14 shows the comparison of using steel coming from 85% recycled content compared with the original 16’ wide beam scenario if the floor to floor height was the main consideration. In all of these scenarios, the steel beam is shallower than the wide scenario glulam. The results show that the recycled steel beam has less energy use (-2%) and a reduced impact on acidification (-5%). Global warming potential is higher because of the reliance on fossil fuels for energy. This is promising for steel in the future as its estimated 85% recycled content could improve. Coupling this with similar transportation energy used during the construction stage helps make the impact of a functional unit of steel much closer to the functional unit of glulam.

Table 4-14 Original Basement Beam Scenario Compared with Steel from Recycled Scrap Scenario, Extraction and Manufacturing Stages A1 through A3

		Glulam	Steel-R		Glulam	Steel-R		Glulam	Steel-R	
Impact category	Unit	16' Wide	16'	% Change	22' Wide	22'	% Change	30' Wide	30'	% Change
Global warming	kg CO2 equiv	39.31	121.92	210%	74.45	263.45	254%	129.13	506.21	292%
Acidification	kg SO2 equiv	0.397	0.376	-5%	0.752	0.812	8%	1.304	1.561	20%
Eutrophication	kg N equiv	0.015	0.035	128%	0.029	0.075	160%	0.050	0.143	188%
Ozone depletion	kg CFC-11equiv	4.39E-09			8.31E-09			1.44E-08		
Smog	kg O3 equiv	8.05	0.06	-99%	15.24	0.13	-99%	26.44	0.25	-99%
Energy Use	Unit	16' Wide	16'	% Change	22' Wide	22'	% Change	30' Wide	30'	% Change
Total Primary	MJ	1,693.19	1,666.24	-2%	3,206.80	3,600.46	12%	5,561.87	6,918.18	24%
Non-renewable	MJ	602.41	1,616.25	168%	1,140.93	3,492.44	206%	1,978.83	6,710.63	239%
Renewables	MJ	1,090.78	49.99	-95%	2,065.87	108.01	-95%	3,583.04	207.55	-94%
Dimensions		**8 3/4 x 12**	**W12x14**		**8 3/4 x 16 1/2**	**W12x22**		**8 3/4 x 21**	**W16x31**	

There is uncertainty within an LCA model when there is data missing or a process must be replaced with a dummy process (no data available). The processes analyzed for this research did utilize a dummy process for the installation of the beams and provided a transportation comparison during the construction stage. Additional research in these areas can help to minimize uncertainty by providing data inputs and outputs for these stages from their respective industries. Utilizing available sizing and span charts allow others to repeat these comparisons, which fosters consistency and transparency between the beam comparisons and reduces uncertainty with this comparative LCA.

4.12 Summary

In the past, evaluating building products based on their environmental friendliness was mostly based on perceptions or attempts to evaluate energy use during the manufacturing stages only. By conducting a cradle-to-construction LCA, there is a broader view of all the stages that compromise a product’s environmental impact from resource extraction to final installation within a building. Utilizing LCA as a tool for researchers, information can be more transparent for manufacturers who are looking to improve the environmental impact of their products by comparing their product to their industry’s average or to products with a similar function. Also, consumers and users of the product (builders or architects) can make more informed decisions when deciding between materials that might reduce a buildings impact on the environment. This data transparency is rewarded by the current generation of green building programs that award points for documentation related to EPDs for building materials and products contained within a finished building. Transparency with data inputs and outputs allows for less uncertainty in environmental impact calculations and LCA replication. Utilizing third parties to conduct independent LCAs helps minimize biases that might exist if manufacturers were allowed to conduct their own analyses.

Other useful studies would be to investigate changing the resin content from conventional urea-formaldehyde resins to ones with natural origins which could reduce CO_2 emissions by up to 16% in laminated wood products (Zabalza Bribián et al., 2011). Other studies implementing end-of-life scenarios like recycling of steel and reuse of wood-based glulam would bring a more complete picture of what the future of structural building materials could be where higher product recycling rates should lead to better results in the end-of-life phase (Rixrath & Wartha, 2016).

Providing LCA data to manufacturers and end-users has many marketing implications. Manufacturers can promote the environmental benefits of their materials as green if they meet certain EPD thresholds. They can also benefit from discovering where inefficiencies exist within their system to reduce costs as well as material and energy inputs. Manufacturers can reduce their impacts to the environment by utilizing energy from sustainable sources or purchasing materials from local suppliers to minimize transportation burdens. If manufacturers effectively manage their energy consumption, they can reduce their operating costs which can be passed on to the consumer. Marketers can help inform end-users of the benefits of products that use less energy and have a favorable environmental footprint from the minimization of process emissions. Most consumers are becoming aware of environmental problems and are seeking products that are less impactful to the environment. By highlighting products that have favorable end-of-life options, end-users such as architects, can incorporate the reuse and recycling of materials into their design process. This information is becoming more valuable as architects are looking to eliminate waste and are designing structures with the end-of-life scenarios from the onset.

5. Conclusions

5.1 Results

The 2011 survey included many research questions with links to the residential construction industry. Its main focus was to discern factors that contributed to the adoption of GBPs and ECWPs by architects who had designed residential homes in the U.S. Chapter 2 provided a comprehensive review of the survey and its results. The survey received 509 responses with 385 complete. There was almost complete awareness of the LEED for Homes program, with a large contingent of architects also aware of NGBS (85%). These numbers are attributed to only 24% of architects using LEED and only 7% using NGBS. When focusing on ECWPs awareness and use, 87% of architects were aware of FSC-certified wood while only 54% had used it. For SFI-certified wood, 76% of architects were aware while considerably less had used (26%). These results led to an investigation the drivers for adopting GBPs and ECWPs and discovering if there were different market segments of architects who were more likely to use them.

Chapter 3 analyzed architect segments and the factors that influenced adoption of GBPs and ECWPs. In reference to the research questions in Chapter 1, architects revealed significantly different market orientations that helped segment them into distinct market segments (enviro-centric, conventional, and market-driven). Table 5-1 shows how these segments were different in their use of GBPs and ECWPs. H1 and H2 both suggested that market segments were predictors of GBP (LEED only) and ECWP use (both FSC and SFI) and these hypotheses were supported. Members of the enviro-centric segment were more frequent users of LEED for Homes and both FSC- and SFI-certified wood than the other segments. The enviro-centric segment did not use NGBS at a higher rate than the other segments; this was a result of the market-driven segment having builders as their main client. The market-driven segment were the most frequent users of NGBS, which was heavily promoted to homebuilders; this was not significant, and this hypothesis was not supported. The enviro-centric segment was more likely to use FSC wood and had a comparable frequency of SFI-wood use to the market-driven segment. Conventional architects had the lowest use of ECWPs and LEED, but slightly higher use of NGBS than the enviro-centric segment, but again this proved to be not significant.

Table 5-1 Summary Results of Architect Segmentation

Hypotheses	**Results**	**Interpretations**
H1: Orientation on GBP Use (LEED)	Supported	Enviro-Centric Segments Used LEED
H1: Orientation on GBP Use (NGBS)	Not Supported	Higher Rate of Homebuilder Clients
H2: Orientation on ECWP Use (FSC)	Supported	Enviro-Centric Segments Used FSC
H2: Orientation on ECWP Use (SFI)	Supported	Enviro-Centric Segments Used SFI

For GBP adoption models, Table 5-2 shows that H3a (*employment type*), H3c (*years in business*), and H3d (*area of business*) were not significant and not supported. H3b (*client type*) was not supported based on a homeowner client type; however, architects that worked with homebuilders were more likely to use the NGBS program. For H3e (*region*), being in the South did somewhat influence NGBS adoption (partially supported) but did not influence LEED use. H3f (*other GBP*) predicted LEED use but not NGBS use, partially supporting the theory that familiarity with one program eases further adoption. H6a (*environmental orientation*) was significant ($p<0.1$) and H6b (*innovation s*core) was a highly significant predictor of LEED use ($p<0.001$), but neither was significant in predicting NGBS use. Thus, H6a and H6b were partially supported. This was not a tested hypothesis, but the use of NGBS had a positive and significant effect on LEED use. Whereas the use of LEED had a lesser but significant negative effect on NGBS use.

Table 5-2 Summary Results of Adoption of GBPs

Hypotheses	Results	Interpretations
H3a: Firm Type	Not Supported	No Effect on Adoption
H3b: Client Type	Not Supported	Homebuilder as Clients Indicated NGBS Use
H3c: Years in Business	Not Supported	No Effect on Adoption
H3d: Area of Business	Not Supported	No Effect on Adoption
H3e: Region	Partially Supported	South (+) on NGBS
H3f: Other GBPs	Partially Supported	Familiarity Leads to Additional Adoption of LEED
H6a: Environmentally Oriented	Partially Supported	Slightly Significant for LEED
H6b: Innovative Technology	Partially Supported	Might Be GBP Driving Innovative Product Adoption

For the ECWP adoption model, Table 5-3 shows that H4a (*employment type*) was not supported by the model. H4b (*client type*) was not supported based on homeowner client type; however, architects that worked for homebuilders were more likely to use SFI wood. H4c (*years in business*) did not influence SFI, but had a negative influence on FSC adoption and thus was not supported. H4d (*area of business*) was partially supported for FSC adoption. For H4e (*region*), there was a regional influence on FSC and SFI adoption: being from the West had a negative effect on SFI use while being from the Midwest was significant at the $p<0.1$ level for FSC use (supported). H5a (*other GBP*) predicted FSC adoption but not SFI adoption, thus this hypothesis is partially supported. For H5b (*LEED or NGBS use)*, LEED use predicted FSC adoption and NGBS use predicted SFI use; these ECWPs align with the programs that reward them points in a certified home (supported). H7a (*environmental orientation*) and H7b (*innovation score*) predicted FSC use ($p<0.001$), but only *innovation score* predicted SFI use, thus H7a was partially supported and H7b was fully supported. H7c (*material perceptions*) utilized clusters to determine if higher environmental perceptions of wood influenced ECWP adoption. This was not significant and was not supported. H8 (*willingness to pay)* tested whether architects were willing to pay a price premium for ECWPs; the results indicated that WTP did not have a significant effect on adoption (not supported). It did show a negative coefficient in the full model for FSC, but WTP was not significant in the reduced model. For users of ECWPs, H9 sought to discern if light and heavy users were different based on the significant variables of the ECWP adoption models. H9 was supported; *innovation score, environmental orientation,* and *LEED use* were indicators of heavy users.

Table 5-3 Results of Adoption of ECWPs

Hypotheses	**Results**	**Interpretations**
H4a: Firm Type	Not Supported	No effect on adoption
H4b: Client Type	Not Supported	Homebuilder clients indicated SFI use
H4c: Years in Business	Not Supported	Age with a negative effect on adoption
H4d: Area of Business	Partially Supported	Urban and small city
H4e: Region	Supported	Midwest for LEED, NEast, Midwest, and South for SFI
H5a: Other GBPs	Partially Supported	Slightly significant in predicting FSC adoption
H5b: LEED or NGBS Use	Supported	LEED for FSC and NGBS for SFI
H7a: Environmentally Oriented	Partially Supported	Highly significant for LEED, Economic (-) effect on LEED
H7b: Innovative Technology	Supported	Familiarity with products leads to additional adoption
H7c: Pro-Wood	Not Supported	Material perceptions were not significantly different for wood
H8: Willingness to Pay	Not Supported	Architects not involved with purchasing
H9: Heavy vs. Light Users	Supported	Innovation Score, Environmental Orientation, and LEED Use are indicative of Heavy User of ECWPs

Chapter 4 took architects' perceptions of the environmental attributes of wood, steel, and concrete during their manufacture and compared them to these materials' actual environmental impacts. Low CO2 emissions ($p<0.01$) and low energy use ($p <0.001$) were the only two attributes whose cluster means were significantly different from each other when rating wood in from the Chapter 3 analyses. Architects that have a deeper understanding of these attributes of wood may have some experience with LCA since this data is becoming more available from their respective industries. Table 5-4 summarizes the results of Chapter 4 with both hypotheses supported. The results showed a cluster of architects that perceived wood-based building materials as better for the environment during their cradle-to-gate stages than concrete and steel. These architects also rated steel and concrete significantly lower than the other cluster (pro-steel and concrete) with the mean rating less than 2 (*strongly disagree*). It was found that the actual environmental impacts generally align with architects' common perceptions of wood products regarding energy use and emissions, which supports H10. By looking at demographic variables that were significant in describing these clusters, architects that work for homeowners are more likely to perceive wood as better for the environment based on those two environmental attributes. Providing architects who work for home builders with information on the environmental impacts of wood products could help solve misperceptions and strengthen their knowledge when specifying materials for their designs.

Based on the comparative LCA, wood-based glulam used in a floor beam application had less of an impact on the environment based on the measured impact indicators and energy use during the cradle-to-installed life cycle. H11 is supported based on these LCIA results. During the construction stage, steel and glulam had similar impacts when transportation distances were equal. There will be differences in energy use and installation techniques at the construction site, but those inputs were assumed to be small compared to the overall energy use and impacts for the entire cradle-to-installed cycle. The results showed glulam used significantly less energy (-357% and -139%) than similarly functioning beams of concrete and steel, respectively. There was a larger difference in global warming potential than steel (-741%) and concrete (-2,144%) since most of the energy used in the manufacture of glulam was from renewable biomass and those emissions are considered carbon-neutral and do not contribute to that factor. The steel beam did use less energy (-2%) and have lower impacts in smog and acidification factors when a steel beam from 85% recycled content was compared to the wider glulam at a 16’ span. The natural extension of these analyses would be to collect data for the end-of life-scenarios of all three materials. This could provide crucial data on how impacts change when recycled content from steel or concrete is used during the manufacture stages and other end-of-life scenarios where wood was not incinerated or landfilled. With quantitative data from the functional unit comparisons of other building materials, the perceptions of environmental friendliness can either be supported or opposed.

Table 5-4 Results of Perception vs. Reality Comparative LCA

Hypotheses	Results	Interpretations
H10: Material Perceptions	Supported	Different perceptions with client type being indicator of cluster membership
H11: Beam Comparative Analyses	Supported	Wood showed reduced environmental impact overall than steel and concrete, but worse than steel in smog and eutrophication. All three materials showed significant differences in energy use and environmental impacts

5.2 Discussion

Based on the study’s results, it is appropriate to state that architects will have an influential role in the adoption and use of environmentally friendly building materials. There has been a slow pace of participation in residential green building programs, but this frequency should increase as more architects become aware of the energy-saving and sustainable characteristics of certified homes. These highly marketable attributes can be used to their advantage when trying to attract environmentally conscious homeowners. Many links were found between green building programs and the use of environmentally certified wood products. First, it was shown that LEED for Homes was an indicator of FSC-wood use. This link is significant since, during the time of the survey, FSC wood was the only forest certification program that could receive points toward a LEED-certified home. FSC wood continues to be the primary ECWP used in LEED for Homes, but the rules have softened slightly to be more accepting of other forest certification programs. A similar situation arose with NGBS use influencing SFI wood use. Under NGBS, most certified wood programs are accepted for points toward a certified home, and previous research reported issues with FSC-certified wood availability. More forest lands in the U.S. are SFI certified, resulting in less issues reported with SFI-certified wood availability.

The primary reasons given for not using GBPs by architects who had not participated in LEED for Homes or NGBS were *customers not willing to pay*, *no market demand*, and *documentation difficult*. While 74% of architects reported they have not used one of the two main GBPs, it appears there is good opportunity for growth in this sector as almost 30% of architects indicated that they were planning to use LEED for Homes and 20% were planning on using NGBS in the future. Of architects who had used another regional GBP (27%), only slightly over half had not used either LEED for Homes or NGBS. If these issues were addressed by their respective programs, there is a high likelihood that participation rates would grow. With low numbers of NGBS use by architects, it would be prudent for the National Association of Home Builders (NAHB) to increase its marketing efforts toward architects and designers.

One of the benefits of GBPs is the increased awareness of the environmental issues during the construction and operation of a building. Also, participation in a GBP could lead to additional exposure and experience with innovative green building products and technologies. As discussed before, GBPs could be the driver for use of these materials and not the other way around. These programs are voluntary, but some of their elements are being slowly adopted into local and regional building codes. With the increased initiative of architects to push carbon neutral construction, there is incredible room for growth for products and technologies that reduce the environmental footprint of a structure.

The market segmentation of architects provides insight into latent characteristic factors. Segmenting architects into groupings with similar identifying characteristics makes market research more efficient when promoting green products and programs to the architects most likely to implement them. Further development of the orientation measurement scale is necessary to accurately measure the customer (social) orientation. This factor was only measured by two loading variables and the reliability was the lowest of the three factors (Cronbach's Alpha .574). Developing an adoption model of architects discerns factors that heavily impact the likelihood of adoption of either GBPs or ECWPs. This model considers demographic, psychographic, and other statistical groupings to determine which independent variables contribute significantly to the adoption outcome. These measurement tools are a few of the statistical methodologies that can help marketers discern a segment or attribute, but are not an exhaustive list for dividing this group of U.S. architects.

The comparative LCA results supported the perception of environmental friendliness of wood-based building products. This was one specific comparison; similar studies could verify this statement beyond a generalization. Adding in end-of-life scenarios or technology changes could make these comparisons more equivalent, as was shown when steel with recycled content was compared with glulam in a height restricted scenario. While this was a comparison of one specific building product (floor beam), a building system approach or environmental building declaration are more comprehensive ways of looking at the entire environmental profile of building or system (e.g., entire wall or floor, etc.). As more industries are compliant with and supportive of data transparency, similar studies in all sectors will change how environmental friendliness is presented. Industries can either improve their environmental impacts or be perceived as laggards.

The following are notable points from this research:

a. There are different market segments of architects, with enviro-centric architects more likely to use LEED for Homes and ECWPs.
b. Architects whose main client type is homebuilders and who are from the South are more likely to use the NGBS program and SFI-certified wood.
c. Architects that are environmentally oriented are more likely to use LEED and FSC wood, and economically oriented architects that have been in business longer are less likely to use FSC wood.
d. Use of LEED for Homes is a factor on FSC wood use and the use of NGBS is a factor on SFI wood use.
e. Architects that use other innovative green products and technologies are more likely to use LEED and ECWPs.
f. Architects are relatively homogenous in their environmental perceptions of wood as a building material but have significantly different perceptions on steel and concrete.
g. Almost all architects have used some innovative green building product or technologies, but less than 25% have heavily used products that are still in the growth phase of their life cycle.
h. Architects that are heavy users (>50%) of ECWPs are most likely users of LEED, environmentally oriented, and heavy users of other innovative green products and technologies.

i. Environmental impacts from the functional unit of glulam is less than steel (except for smog) and concrete, but when recycled steel is considered its total energy use is less when height restriction is the primary criteria.

5.3 Recommendations

Based on the results of this study, there are some recommendations for marketers of GBPs and ECWPs, researchers in forest products marketing, and the wood industry overall.

First, there is room for growth in the green building sector for multi-family and multi-story structures. This area of residential construction has been the quickest to recover since the housing bubble and additional support and focus in this market is crucial. There is a growing need for homes in urban areas, and the most realistic solution to the growth in the renter segment will be multi-unit buildings. Costs for green materials and technologies get scaled over multiple units and the payback time is shorter on average.

Second, the low use of NGBS by architects suggests it would be prudent for the NAHB to increase its marketing efforts toward architects and designers. Since architects initiate design and material selection it would be easier to incorporate green materials and technologies from the onset and a better way to achieve higher rated structures.

Third, as more forests receive third-party certification, green building programs should require all wood-based materials to come from sustainably managed forests. Housing starts have been staying at more sustainable levels so availability of certified products should be less of an issue. New certification labels with mixed FSC and SFI material are making it easier for forest products suppliers to provide qualifying materials for GBPs.

Fourth, LCI databases need to be updated more frequently. Frequent changes to the energy grid and an increasing reliance on renewable energy sources make previous LCI's less reliable. With greater cooperation from the involved industries, updating crucial inputs to products' LCIs could significantly change the resulting environmental impacts.

Fifth, wood products manufacturers need to utilize LCA results from environmental product declarations to promote their products. Customers' awareness of global warming is growing as initiatives are developed to combat climate change, and their enthusiasm to do the right thing for the environment impacts their purchasing decisions. This is highly advantageous for industries that make their products locally and are already minimizing the environmental impacts from transportation.

Sixth, future LCA studies need to collect data on the material inputs, transportation, on-site energy, and waste generated by the installation of building materials on an actual home site. This stage of LCA has little available data and best estimates are being used to fill the gap. Actual data for these inputs would provide a more complete analysis and continue to reduce uncertainty.

5.4 Contribution to Literature

Only a few studies in the forest products marketing literature have involved architects, and these mainly focused on their material and design preferences. Also, these studies rarely had their sole focus on the residential construction market. This research attempts to fill gaps in the literature by providing an exploratory overview of the demographics of U.S. architects. By also measuring psychographic variables, a market segmentation was performed to provide insight into different market orientations that could influence architects' decision making. There have been few studies examining architects and their decision making regarding wood-based building materials, but this research takes a descriptive approach by modeling architects based on factors that influence whether or not they adopt GBPs and ECWPs. Building a statistical model measuring architect adoption can be replicated for other studies of homebuilders and homeowners to provide more insight into the residential construction sector.

There have been many areas of LCA research, but there has been a lack of functional unit analyses. These are built upon individual product LCAs and are meant to provide realistic comparative scenarios. For a more comprehensive collection of literature in the building products field, this comparative analysis will help develop a methodology for conducting these analyses, which are not defined by ISO protocols. This study provides another way to develop a framework for a comparative analysis and will help LCA practitioners develop their scenarios.

These comparisons are essential for the design and construction community as transparency of materials and their environmental impacts become a greater factor of implementation in future homes. This data builds on previous studies of the environmental impacts of building materials and adds to the comparative literature with the functional unit of a floor beam. More of this data is being requested by design professionals and the Carbon Leadership Forum is developing a tool to measure the embodied carbon within a building (Carbon Leadership Forum, 2019). Additional research in this area will produce a foundation from which updated technologies and energy sources can be easily and quickly built into existing LCI databases. This initiative will provide the resources that practitioners need to make material decisions for continual improvement in building and home design.

5.5 Limitations

Despite a thorough analysis of the factors driving the adoption of GBPs and ECWPs, there were some limitations to this study. The survey was limited in its scope (residential construction) and focused on one target population (architects). Other studies analyzing builders/remodelers and homeowners would add differing perspectives to this research, which is invaluable to a holistic view of the residential construction industry. Another limitation was that the 2011 survey was conducted during the bottom of the housing market, however, the industry has slowly recovered and evolved to adhere to stricter regulations. It would be prudent to conduct a new survey to assess how architect's sentiments toward building green and their use of innovative products has changed since 2011.

The survey had some inherent flaws, but these did not dramatically affect data quality. The survey data is cross-sectional in nature, but more information would be provided by comparisons from a longitudinal study. Tracking architects' adoption of residential GBPs and ECWPs over time would strengthen the argument for why architects used a particular program or specified wood from certified forests. All responses to the survey were collected within a few days, so a comparison of early to late respondents was not available. There was a high frequency of non-respondents to some questions; forced responses would have helped minimize this. More responses were received than required by the design, but this actually helped overcome the non-response later in the survey, which met the research design thresholds for proper analyses.

Some issues were encountered due to the non-response. Even if a respondent selected they had used a GBP, they did not always rank the top reasons why they had used it. Also, many architects responded that they had participated in one of the GBPs, but only a few answered the number of each certifications received. Architects may design a building to meet a certain certification standard, but during construction costs may become a more relevant factor and the building may not achieve the level for which it was designed. Many architects do not sell the homes they design, so the level a home attains may be irrelevant; whereas a homebuilder could be more invested or concerned with a home’s rating level because there may be an additional price premium for a higher-rated home (i.e., Platinum, Emerald, etc.). The survey was distributed and collected by the AIA; therefore, limited control existed on survey distribution.

The LCA results in this research add some justification to the promotion of comparative LCAs. However, future research will need to complete the life cycle and include end-of-life scenarios. This study was limited by acquiring data from the respective steel and concrete LCAs, which do not provide data on the construction stages of their respective LCIs. This data contributes some uncertainty to the results, but this was addressed by providing a transportation scenario with equal distances from gate-to-installed. Installation energy use and impacts should be measured in the future to eliminate gaps within this stage of the life cycle. The environmental impacts from steel-based building products could be more equivalent to wood-based products if the scenario of utilizing scrap steel and concrete from recycled aggregate was included. Thus far, concrete does not have the benefit of reuse when calculating its end-of-life impacts.

Another limitation was that only the updated cradle-to-gate glulam LCA was utilized and the steel and concrete LCAs were from their relevant but older EPDs. Updated LCAs for the other two materials would be important to represent updates to the energy grid and could result in changes in energy use and the relevant impact indicators. Utilizing primary data and measuring the energy use and inputs for all three materials would reduce statistical uncertainty. However, every individual LCA is a large-scale endeavor and may not provide statistically different results.

Future studies can build on this data and explore the integration of LCIs when architects seek to evaluate the environmental impacts of the building materials they choose. Whole building LCIs are in their infancy but are becoming more common as software and databases are more readily available, training is provided, and costs are less prohibitive. The next generation of construction will have an integrated and systems approach and should contribute to better homes that are more resource efficient, recyclable, and longer lasting.

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7. Appendix

7.1 Appendix A: Architect Survey

CINTRAFOR/NAHB Architect Survey 2011

Screening question:

1. **Please choose your main business type:**
    a. Designer
    b. Engineer
    c. Architect
    d. Other: specify ___________ (if this category terminate the survey)

2. **How many home design projects (new and/or home improvement) did you partake in 2010?** _________
    (if less than 2 terminate the survey)

3. **In which state did your company design the greatest number of homes?** _____ (used for ensuring geographical coverage)

Basic Demographic questions for Architects (Respondents a, b or c on the basic screening question):

4.1 Approximately what percentage of your company's 2010 sales revenue was generated from the following activities?

Single Family Spec Homes	_______%
Single Family Custom Homes	_______%
Multi-family Construction	_______%
HomeDesign/ Additions	_______%
Nonresidential Construction	_______%
Other: please specify_______	_______%
Total =	**100%**

4.2 Which of the following best describes the area where your company conducts most of its business? (Check One)

☐ URBAN/SUBURBAN: A city or group of contiguous communities with a population greater than 50,000.

☐ SMALL TOWN: A city or town that is generally isolated from a major urban area and with a population less than 50,000.

☐ RURAL: Low density population scattered over a wide area

4.3 Approximately how many years has your company been in the architecture/designing business? __ years

4.4 How would you describe your employment?
a. Single home builder
b. Architectural firm
c. Independent consultant
d. Other: specify________

4.5 Which describes your client type?
a. Large homebuilders
b. Medium and small homebuilders
c. Homeowners
d. Architects, designers, or engineers
e. Other: specify________

Basic and psychographic questions for all respondents:

5.1 How important are each of the following attributes in influencing your specification of building materials (1=not important, 5=extremely important)

Attributes	**Not at all important**	**Not Important**	**Neutral**	**Important**	**Extremely Important**
Overall price	1	2	3	4	5
CO2 emission during manufacture and transportation	1	2	3	4	5
Availability	1	2	3	4	5
Homeowner Demand	1	2	3	4	5
Homebuilder Demand	1	2	3	4	5
Low maintenance	1	2	3	4	5
Made with recycled materials	1	2	3	4	5
Recyclability of the material	1	2	3	4	5
Energy efficiency	1	2	3	4	5
Ease of Installation	1	2	3	4	5
Made with renewable raw materials (e.g., wood, etc...)	1	2	3	4	5
Locally produced material	1	2	3	4	5
Longevity and Durability	1	2	3	4	5
Energy usage during manufacturing process	1	2	3	4	5

5.2 Rank following building materials with respect to each of the following attributes

Environmental Attributes	**Structural and non-structural building materials**		
	Wood	**Concrete**	**Steel**
Low energy use during the manufacturing process	Dropdown box	Dropdown box	Dropdown box
Contributes to high energy efficiency of the completed house	Dropdown box	Dropdown box	Dropdown box
Low CO2 emission during manufacture and transportation	Dropdown box	Dropdown box	Dropdown box
The resource is renewable	Dropdown box	Dropdown box	Dropdown box
Longevity of the material	Dropdown box	Dropdown box	Dropdown box
Recyclability of the material	Dropdown box	Dropdown box	Dropdown box

Options in the dropdown box:
1: Strongly Disagree
2: Disagree
3: Neutral
4: Agree
5: Strongly Agree

Green products (including certified wood) related questions:

6.1. Indicate your level of familiarity with the following building materials:

Green Building Materials	Options
Heat recovery or energy recovery ventilators	■ **(0)** Haven't heard about it ■ **(1)** Aware of the product/technology, but never specified it ■ **(2)** I have occasionally specified the product/technology ■ **(3)** I am a frequent specifier of the product/technology
Energy efficient windows	
Solar Water Heating	
Structural insulated panels	
Radiant barriers	
Solar Power Generation	
Engineered wood (e.g., I-joist, OSB, LVL, etc)	
Water conserving fixtures	
Energy efficient appliances	
Concrete with reduced cement (via fly ash or slag replacement)	
Low VOC/Low toxic paints	
Tankless water heater	

6.2. In your opinion, how important is each of the following in reducing the environmental footprint of a house?

Green Building Materials	**Not at all important**	**Not Important**	**Neutral**	**Important**	**Extremely Important**
the items from 6.1 with the response code '1', '2' or '3'	1	2	3	4	5
	1	2	3	4	5
	1	2	3	4	5
	1	2	3	4	5
	1	2	3	4	5

7. Certified wood related questions: (respondents who have indicated ‘0’ for ‘both FSC and SFI certified wood’ in 7.1 will not receive any questions from this series)

7.1. Indicate your knowledge of the following building materials

	Options
FSC certified wood	**(0)** Haven’t heard about it **(1)** Aware of cert wood, but never required or specified it **(2)** I have occasionally required or specified it **(3)** I have frequently specified it
SFI certified wood	

7.2a. Indicate the price premium associated with the certified wood in your locality.

	Options
the items from 7.1 with the response code ‘1’, ‘2’ and ‘3’	0% (no price premium for certified wood) 1% to 5% (a small price premium for certified wood) 5% to 10% (substantial price premium for certified wood) Above 10% (very high price premium for certified wood)

7.3. Approximately what percentage of your homes designed in 2010 were specified with environmentally certified lumber? **(only for respondents who have indicated options coded ‘2’ or ‘3’ for at least one of the certified wood options in 7.1)**

- Less than 10%
- 11% to 30%
- 31% to 50%
- 51% to 70%
- More than 70%

7.4a. Over the past 2 years my usage of FSC certified wood has (only for respondents who have indicated options coded ‘2’ or ‘3’ for FSC certified wood options in 7.1)

- ○ Increased
- ○ Stayed the Same
- ○ Decreased

7.4a1. During the next two years I think my usage of FSC certified wood will (only for respondents who have indicated options coded ‘1’, ‘2’ or ‘3’ for FSC certified wood options in 7.1)

- ○ Increase
- ○ Stay the Same
- ○ Decrease

7.4b. Over the past 2 years my usage of SFI certified wood has (only for respondents who have indicated options coded ‘2’ or ‘3’ for SFI certified wood options in 7.1)

- ○ Increased
- ○ Stayed the Same
- ○ Decreased

7.4b1. During the next two years I think my usage of SFI certified wood will (only for respondents who have indicated options coded 1, ‘2’ or ‘3’ for SFI certified wood options in 7.1)

- ○ Increase
- ○ Stay the Same
- ○ Decrease

.

7.5. In your opinion how do the FSC & SFI forest certification programs compare with respect to the following attributes: (only for respondents who have indicated options coded 1, '2' or '3' for both FSC and SFI certified wood options in 7.1)

Attributes	**FSC is better ← ← FSC v/s SFI → → SFI is better**					**I don't know**
	FSC is significantly better	**FSC is somewhat better**	**Both are Same**	**SFI is somewhat better**	**SFI is significantly better**	
Better for the environment	☐	☐	☐	☐	☐	☐
Ready Availability	☐	☐	☐	☐	☐	☐
Homeowner awareness	☐	☐	☐	☐	☐	☐
Homebuilder awareness	☐	☐	☐	☐	☐	☐
Sustainable forest mgmt.	☐	☐	☐	☐	☐	☐

7.6. The main reasons why I have not specified FSC or SFI certified wood are: (only the items from 7.1 with the response code '1' will be in this list) – select up to 3 options

	Options
the items from 7.1 with the response code '1'	■ Never felt the need ■ Not readily available ■ Cost not justified from business standpoint ■ No customer demand ■ Not enough green building points ■ I have plans to start using it in near future ■ I do not believe the environmental benefits are substantial ■ Other (specify) ______________

7.7. The main reasons why I have specified SFI or FSC certified wood are: (only the items from 7.1 with the response code '2' or '3'will be in this list) – select up to 3 options

	Options
the items from 7.1 with the response code '2' or '3'	■ Customer demand ■ Reliable availability ■ It is an integral part of my construction design/practice ■ Contributes significantly to green building points ■ I believe the environmental benefits are substantial ■ Helps differentiate my homes from competitors ■ Increases profitability of my homes ■ Increases greener image of my company ■ Other (specify) ______________

8. Green Building related questions: (respondents who have indicated ‘0’ for ‘both LEED and NGBS’ in 8.1 will not receive any questions from this series)

8.1. Please indicate your familiarity with these national green building programs

Third Party Certification programs	Level of Familiarity
LEED for homes (Leadership in Energy and Environmental Design by USGBC)	• **(0) Haven’t heard about it** • **(1) Heard about it but never used it** • **(2) Heard about it and am planning to use it in the future** • **(3) Have used it**
NGBS (National Green Building Standards Certification by NAHB)	

8.2. Have you ever used any other regional green building programs? No ☐ Yes Specify: ______________

Options in the dropdown box:

- Built Green
- Earth Advantage
- Building Design Energy (Living Building)
- Other: Specify: ________

8.3. How many residential projects under the following certification programs did you complete in last 2 years?

National Third Party Certification programs	
LEED for homes (Leadership in Energy and Environmental Design by USGBC) (if response code ‘3’ in 8.1 for LEED)	Platinum ______________ Gold ______________ Silver ______________ Bronze ______________ Certified ______________
NGBS (National Green Building Standards Certification by NAHB) (if response code ‘3’ in 8.1 for NGBS)	Emerald ______________ Gold ______________ Silver ______________ Bronze ______________

8.4. Reasons for not using the green building program/s

Third Party Certification programs	Reasons (check the most important reason/s -- max. 3 reasons)
Third Party Certification programs from 8.1 with the response code ‘1’	■ No market demand for certified houses under this program ■ Homebuyers are not willing to pay a premium for a green house ■ It is too expensive to get homes certified under this program ■ We do not have the necessary training to get certified under this program ■ The documentation process is too complicated ■ Green building products are too difficult to obtain ■ Other: Specify ______________________

8.5. Reasons for using or considering the green building program/s

Third Party Certification programs	Reasons (check the most important reason/s -- max. 3 reasons)
Third Party Certification programs from 8.1 with the response codes ‘2’ or ‘3’	■ Strong demand for green houses certified under this program ■ It helps differentiate my homes in the market ■ Increases profitability of my homes ■ Documentation process is straight forward ■ Homeowner specified the program ■ Builder specified the program ■ Other: Specify ______________________

8.6. Please indicate the top three reasons you have gotten involved with ‘green’ certified residential building program/s. (only for respondents who have indicated options coded ‘2’ or ‘3’ in 8.1)

OPTIONS

- Customer demand
- Lower energy costs is a good selling point
- It helps me differentiates my homes from the competitors
- Increased profitability from selling a green house
- Increases the greener image of my company
- Local tax incentives for certified ‘green’ houses make it easier to sell.
- Green homes are better for the environment
- Subsidies on green construction materials and technologies helps offset higher costs
- Staying ahead of the curve – I think this will be required by law in the near future
- It is a viable marketing strategy in tough market conditions

8.7. In your opinion how do the LEED and NGBS programs compare along the following factors: (for respondents who have indicated options coded ‘1’, ‘2’ or ‘3’ for both LEED and NGBS in 8.1, i.e., architects who are aware of both)

Attributes	**LEED is better ← ← LEED v/s NGBS → → NGBS is better**				
	LEED is significantly better	**LEED is somewhat better**	**Both are Same**	**NGBS is somewhat better**	**NGBS is significantly better**
Effectiveness in reducing the environmental footprint of the house	☐	☐	☐	☐	☐
Easily understood rules	☐	☐	☐	☐	☐
Cost of certification	☐	☐	☐	☐	☐
Documentation requirements	☐	☐	☐	☐	☐
Influence on home sales	☐	☐	☐	☐	☐
Brand recognition by customers	☐	☐	☐	☐	☐
Price premium customers willingness to pay	☐	☐	☐	☐	☐

Please provide the following information so we can send you a gift:

a. Email:

b. First Name:

c. Last Name:

d. Title:

e. Company:

f. Street:

g. Suite/Unit:

h. City:

i. State/postal code:

j. Zip Code:

k. Phone Number:

l. Ext

7.2 Appendix B: Correlation of Orientation Factors

Correlations

	CO2	EnergyUse	MadeRecy	Renew	Recycle	Local	OwnDem	BuildDem	EnEff	Price	Avail	Low Main	Install	Long Life
C02		0.699**	0.503**	0.562**	0.541**	0.460**	0.016	0.035	0.312**	0.03	0.139**	0.143**	0.128**	0.185**
EnergyUse	0.757**		0.506**	0.576**	0.531**	0.499**	0.086	0.056	0.342**	0.013	0.094*	0.153**	0.121**	0.185**
MadeRecy	0.556**	0.554**		0.664**	0.586**	0.505**	0.088*	0.074	0.383**	0.04	0.137**	0.244**	0.158**	0.231**
Renew	0.618**	0.623**	0.707**		0.644**	0.512**	0.088*	0.028	0.381**	0.029	0.199**	0.210**	0.165**	0.266**
Recycle	0.600**	0.585**	0.634**	0.690**		0.479**	0.03	0.028	0.323**	-0.014	0.163**	0.224**	0.150**	0.252**
Local	0.513**	0.547**	0.552**	0.558**	0.527**		0.095*	0.046	0.378**	0.045	0.116*	0.231**	0.109*	0.275**
OwnDem	0.019	0.098	0.099	0.099	0.034	0.107*		0.267**	0.105*	0.225**	0.206**	0.218**	0.135**	0.168**
BuildDem	0.042	0.068	0.087	0.033	0.034	0.055	0.295**		0.005	0.175**	0.177**	0.132**	0.207**	0.006
EnEff	0.345**	0.373**	0.413**	0.412**	0.349**	0.409**	0.114*	0.006		0.146**	0.153**	0.311**	0.231**	0.388**
Price	0.034	0.015	0.045	0.033	-0.015	0.05	0.244**	0.200**	0.155**		0.312**	0.254**	0.327**	0.115*
Avail	0.155**	0.104*	0.151**	0.219**	0.179**	0.128*	0.226**	0.203**	0.162**	0.331**		0.286**	0.378**	0.223**
LowMain	0.161**	0.170**	0.267**	0.230**	0.246**	0.253**	0.237**	0.149**	0.328**	0.270**	0.303**		0.385**	0.392**
Install	0.147**	0.138**	0.176**	0.185**	0.168**	0.123*	0.150**	0.239**	0.248**	0.353**	0.409**	0.413**		0.260**
LongLife	0.204**	0.202**	0.251**	0.290**	0.274**	0.299**	0.182**	0.007	0.405**	0.122*	0.235**	0.407**	0.279**	

Upper right is Kendall Tau and Lower left is Spearman's Rho

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

7.3 Appendix C: Cluster Dendrogram

Figure 7-1 Dendrogram of Ward Linkages for Architect Segmentation

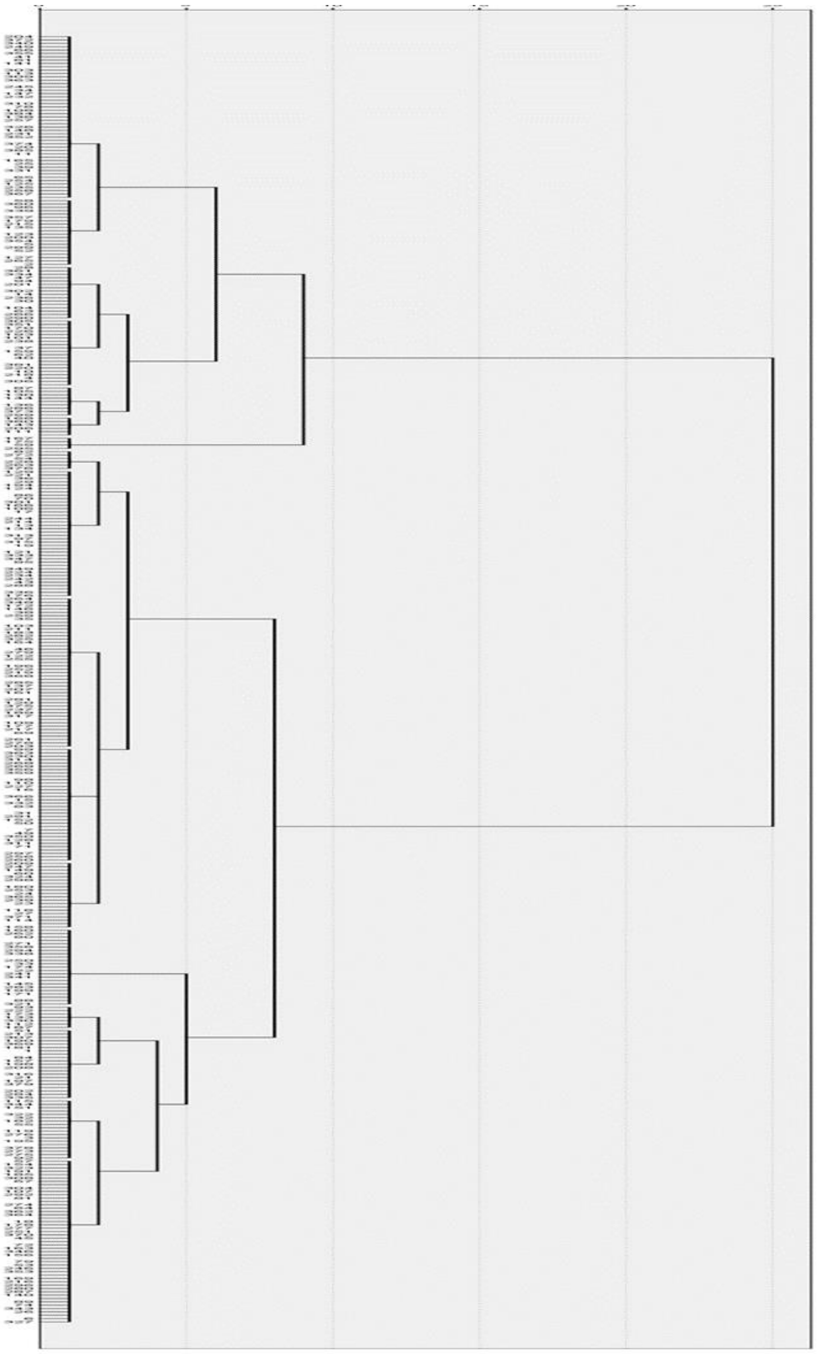
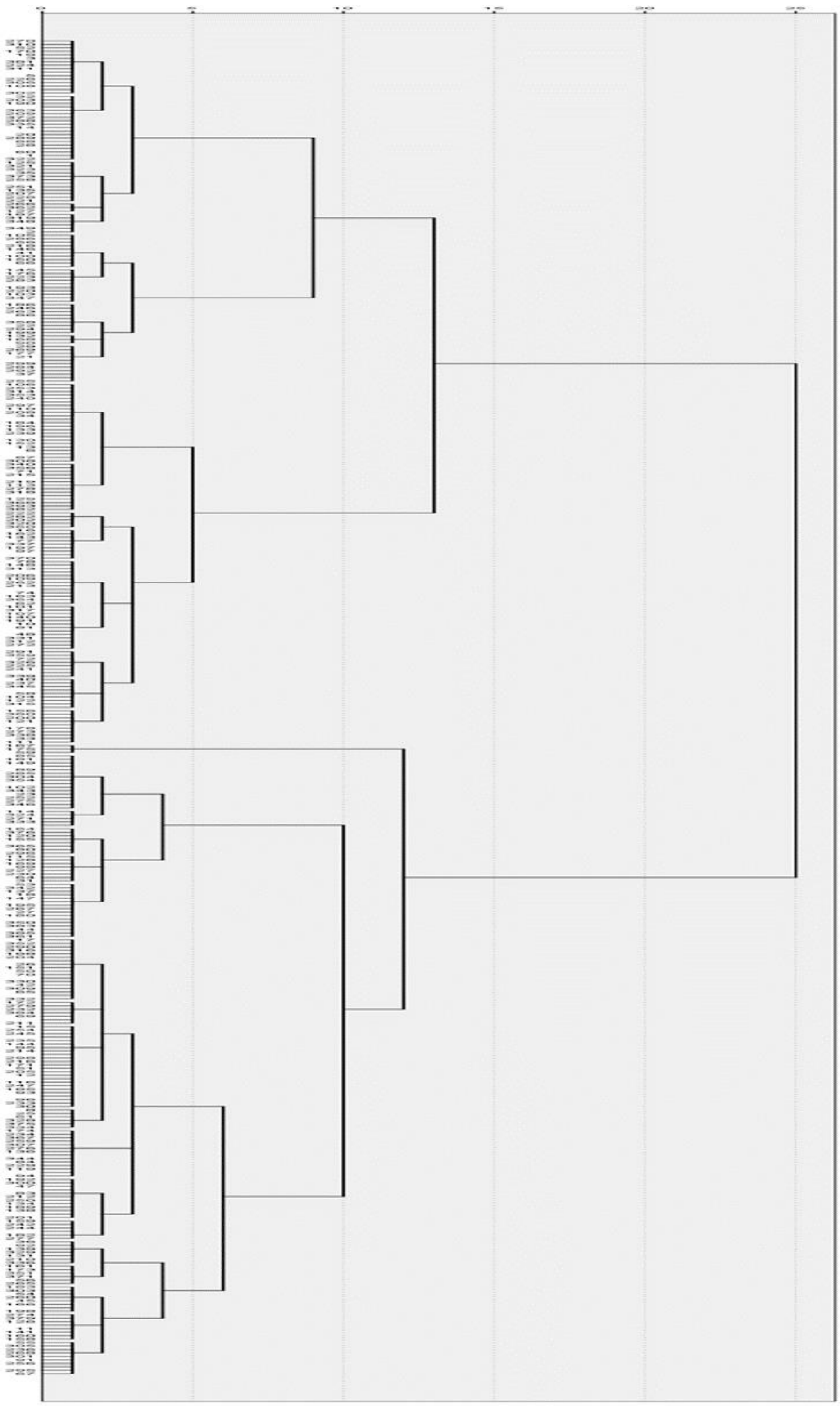
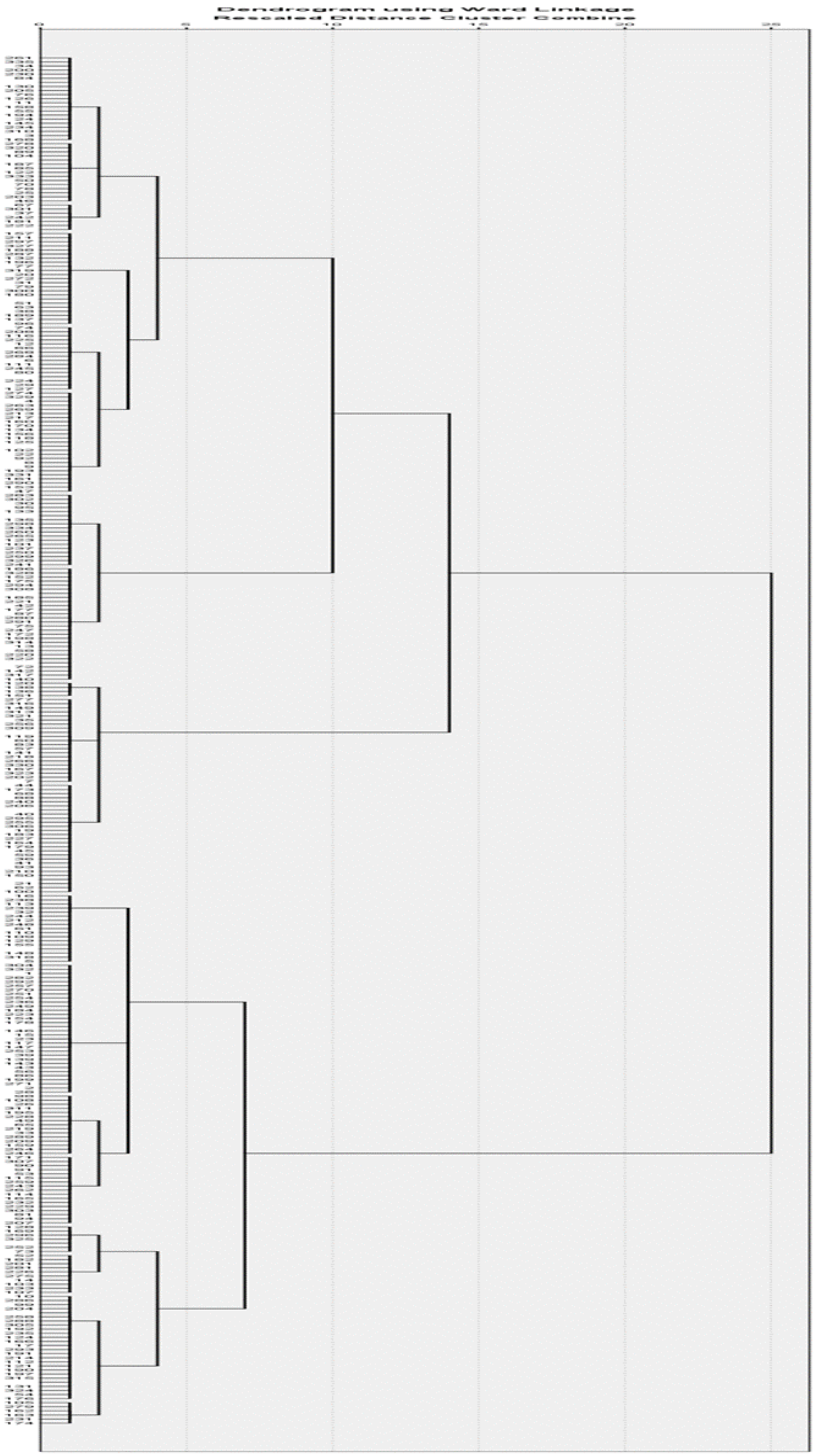


Figure 7-2 Dendrogram of Ward Linkages for Material Environmental Attributes



7.4 Appendix D: Cluster Dendrogram (LCA)

Figure 7-3 Dendrogram of Ward Linkages for Material Environmental Attributes (2-Question)



7.5 Appendix E: Secondary Data Sources for Glulam LCI

Process	LCI data Source	Publication date
Diesel truck	USLCI data for “Transport, combination truck, diesel powered/US”	2008
Diesel locomotive	USLCI data for “Transport, train, diesel powered/US”	2008
Electricity	USLCI data for “Electricity, at Grid, WECC, 2008/RNA U”	2008
Forestry and Harvesting	CORRIM data for PNW softwood forestry operation;	2005, updated 2013
Wood residue production	CORRIM data for PNW softwood lumber production modified for Canada electricity	2015
Lamstock production	CORRIM data for PNW softwood lumber	2015
Hydraulic fluid, Lubricants, motor oil, thermal fluid	USLCI data for “Gasoline, at refinery/l/US” without combustion emissions.	2008
Propane	USLCI data for “Liquefied petroleum gas, combusted in industrial boiler/US”. Combustion emission removed if mill reported emissions	2008
Gasoline	USLCI data for “Gasoline, combusted in equipment/US”. Combustion emission removed if mill reported emissions	2008
Diesel	USLCI data for “Diesel, combusted in industrial equipment/US.” Combustion emission removed if mill reported emissions	2008
Natural gas	USLCI data for “Natural gas, processed, at plant/US.” Combustion emission removed if mill reported emissions	2008
Plastic strapping/wrapping material	USLCI data for “Low density polyethylene resin, at plant/RNA”	2008
Metal strapping	USLCI data for “Hot rolled sheet, steel, at plant/RNA”	2008
Resins	USLCI data for “Phenol-resorcinol-formaldehyde Melamine-urea-formaldehyde Resins” at plant, US 1.0 kg neat resin”	2009
Wood Boiler	CORRIM data for Wood combusted from self-generated waste.	2015

7.6 Appendix F: Beam Dimensions and Specifications

Beam Dimensions	Scenario	Width in	Depth in	Length ft	Volume ft^3	Volume m^3	Weight lbs/ft	Total lbs	Total kgs	Total tons
3 1/8 x 16 1/2		3.125	16.5	16	5.73	0.1622	12.5	200	90.72	0.091
8 3/4 x 12	Wide	8.75	12	16	11.67	0.330	25.5	408	185.07	0.185
W12x14		3.97	11.91	16	5.25	0.149	14	224	101.60	0.102
W8x18	Wide	5.25	8.14	16	4.75	0.134	18	288	130.63	0.131
12RB16		12	16	16	21.33	0.604	200	3200	1451.49	1.451
5 1/8 x 19 1/2		5.125	19.5	22	15.27	0.432	24.3	534.6	242.49	0.242
8 3/4 x 16 1/2	Wide	8.75	16.5	22	22.06	0.625	35.1	772.2	350.26	0.350
W12x22		4.03	12.31	22	7.58	0.215	22	484	219.54	0.220
W10x30	Wide	5.81	10.47	22	9.29	0.263	30	660	299.37	0.299
12RB16		12	16	22	29.33	0.831	200	4400	1995.80	1.996
5 1/8 x 25 1/2		5.125	25.5	30	27.23	0.771	31.8	954	432.73	0.433
8 3/4 x 21	Wide	8.75	21	30	38.28	1.084	44.7	1341	608.27	0.608
W16x31		5.525	15.88	30	18.28	0.518	31	930	421.84	0.422
W14X34	Wide	6.745	13.98	30	19.64	0.556	34	1020	462.66	0.463
12RB20		12	20	30	50.00	1.416	250	7500	3401.94	3.402

7.7 Appendix G: Beam Scenarios - LCIA and Energy Use Data

		Glulam Beam Length Scenarios					
Impact category	Unit	16'	16' Wide	22'	22' Wide	30'	30' Wide
Global warming	kg CO2 equiv	19.32	39.31	51.46	74.45	91.84	129.13
Acidification	kg SO2 equiv	0.195	0.397	0.520	0.752	0.928	1.304
Eutrophication	kg N equiv	0.007	0.015	0.020	0.029	0.035	0.050
Ozone depletion	kg CFC-11 equiv	2.16E-09	4.389E-09	5.7456E-09	8.31E-09	1.03E-08	1.44172E-08
Smog	kg O3 equiv	3.96	8.05	10.54	15.24	18.80	26.44
Energy Use	Unit	16'	16' Wide	22'	22' Wide	30'	30' Wide
Total Primary Energy	MJ	832.23	1,693.19	2,216.54	3,206.80	3,955.91	5,561.87
Non-renewable	MJ	296.09	602.41	788.61	1,140.93	1,407.45	1,978.83
Renewables	MJ	536.13	1,090.78	1,427.93	2,065.87	2,548.46	3,583.04

		Steel Beam Length Scenarios					
Impact category	Unit	16'	16' Wide	22'	22' Wide	30'	30' Wide
Global warming	kg CO2 equiv	162.56	209.01	351.26	478.99	674.94	740.26
Acidification	kg SO2 equiv	0.457	0.588	0.988	1.347	1.898	2.082
Eutrophication	kg N equiv	0.037	0.047	0.079	0.108	0.152	0.167
Ozone depletion	kg CFC-11 equiv						
Smog	kg O3 equiv	0.08	0.10	0.18	0.24	0.34	0.37
Energy Use	Unit	16'	16' Wide	22'	22' Wide	30'	30' Wide
Total Primary Energy	MJ	1,991.36	2,560.35	4,302.98	5,867.65	8,268.06	9,068.14
Non-renewable	MJ	1,931.62	2,483.54	4,173.89	5,691.62	8,020.02	8,796.09
Renewables	MJ	59.74	76.81	129.09	176.03	248.04	272.04

		Concrete Beam Length Scenarios		
Impact category	Unit	16'	22'	30'
Global warming	kg CO2 equiv	433.56	596.40	1,016.52
Acidification	kg SO2 equiv	7.255	9.980	17.010
Eutrophication	kg N equiv	0.435	0.599	1.021
Ozone depletion	kg CFC-11 equiv	2.76E-03	3.79E-03	6.46E-03
Smog	kg O3 equiv	85.03	116.97	199.36
Energy Use	Unit	16'	22'	30'
Total Primary Energy	MJ	3,801.91	5,229.92	8,913.92
Non-renewable	MJ	3,730.67	5,131.92	8,746.88
Renewables	MJ	66.89	92.02	156.83