RESIDENTIAL LIFE CYCLE ASSESSMENT MODELING FOR GREEN BUILDINGS AND BUILDING PRODUCTS

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This research created a residential life cycle assessment (LCA) framework by comparing traditional wood home and a home built of a new building product called insulating concrete forms (ICF). This framework was utilized in analyzing the green building product labeling system and recommendations provided for improving the use of LCA in labeling of products. The framework case study results were evaluated for their potential for energy savings in the US. The national implications of using emerging and existing energy saving building products were quantitatively examined.

This study quantitatively measured ICFs' performance through a comparative LCA of wall sections comprised of ICF and traditional wood-frame. The life cycle stages included raw materials extraction and manufacturing, construction, use and end of life for a 2,450 square foot house in Pittsburgh, Pennsylvania.

Results showed that although building products such as ICFs are energy intensive to produce and thus have higher environmental impacts in the raw materials extraction and manufacturing phase, the use phase dominated in the life cycle. A residential LCA framework was created as part of this study and was utilized in evaluating the green product labeling system for building products.

This study compared generic and green-labeled carpets, paints and linoleum flooring using the Building for Environmental and Economic Sustainability (BEES) LCA database.

The results from these comparisons were not intuitive and were contradictory in several impact categories with respect to the greenness of the product. Life cycle thinking, in theory, has the potential to improve the environmental impacts of labeling systems but databases currently are lacking in detailed information about products or sometimes provide conflicting information.

The residential LCA case study showed the energy saving potential of an ICF home. The energy savings achieved when building products such as ICFs, windows and doors were used in projected new residential constructions was evaluated. A combination of strategies involving the use of ICFs, windows and doors were studied and the results compared with targets set by the McKinsey and Company and Architecture 2030.

When ICFs, windows and doors were used as energy saving building products, the results showed that they might not be saving as much energy as expected and implementing each energy saving strategy on its own was not a solution to achieve the energy goals of the McKinsey report and Architecture 2030. A combination of strategies was the key to reaching end points set by the standards.

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PREFACE

This project was funded by the Green Building Alliance (GBA) Project Innovation Grant. I would like to thank Dr. Aurora Sharrard of the GBA for all her help in this project.

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1.0 INTRODUCTION

Buildings are complex structures with various building products and processes involved. The advent of new building products addressing major environmental concerns of buildings such as energy and indoor air quality necessitates a scientific approach in analyzing these new building products. Life cycle assessment (LCA) is one approach that can examine the products and processes from cradle to grave. Building and building product LCAs have been conducted in the past with the aim to understand the most energy intensive phase or to identify the maximum environmental impact. However, a holistic approach addressing all the phases of a building or combining the use of the building product in a building is required instead of a case study approach for buildings or a gate-to-gate approach analyzing only the product.

This research contributed to three major directions. The first contribution was a developed residential LCA framework. The framework can be used to analyze residential buildings in any location, using standard construction practices. The second contribution was in explaining the inconsistencies in the LCA databases used for green labeling of products. The LCA framework created was also used to highlight how the building products manufacturing impacts are minimal compared to the use phase of a building. The third contribution was in extrapolating the use of energy saving building products from a single home to all projected new homes constructions in the US and weighing each strategy's energy saving potential against future energy goals.

The motivation behind the research is first presented followed by the research area of interest and the research questions this study has examined. Background information about LCA and different LCA studies about residential structures and the use of new building products in residential homes is provided in Chapter 2. The approach for creating the LCA model is presented and results are presented in Chapter 3 followed by application of LCA in labeling and surveying the national impacts of green building products in Chapters 4 and 5, respectively.

1.1 MOTIVATION

The main motivation for this research is the impacts of buildings on resources and the consumption of energy, electricity, and water (USGBC 2009). Buildings account for 30-40 percent of the world's energy use (IPCC 2007). In the United States, buildings annually use 70 percent of the nation's electricity (USDOE 2005) and emit about 40 percent of the country's greenhouse gas emissions (USDOE 2009). The use phase of buildings is the most energy intensive phase (Blanchard and Reppe 1998; Angela Acree and Arpad 2005; Junnila, Horvath et al. 2006). Innovative building products are emerging that have the potential to reduce environmental impacts specifically for the use phase and contribute towards sustainable development.

Life cycle assessment (LCA) is a tool useful in assessing the environmental impacts of any product, process or service and can be effectively utilized in evaluating complex systems such as buildings. Previous LCA studies on buildings have performed an LCA based on data available from existing projects (Keoleian, Blanchard et al. 2000; Angela Acree and Arpad 2005; Junnila, Horvath et al. 2006). Although these studies have shown which phases of the life cycle is energy intensive, they sometimes neglect the importance of other phases such as construction that are equally important (Bilec, Ries et al. 2006; Sharrard, Matthews et al. 2008). The results from the previous studies often cannot be replicated in residences in a diverse geographic location with varied square footage and construction methods and using different materials. The studies are too case specific or focus on only one phase of the life cycle. This leads to different results because each LCA uses various methods for assessing the environmental impacts from the structure. Although there is consensus among the results about the use phase being the most energy intensive phase, there is no residential framework to address the problems when different materials or construction method are used for the structure.

Green building materials research has evolved to help reduce the impacts of the use phase. Building products that help in reducing energy consumption in the use phase of buildings are being introduced in the building sector. Many certification programs are available for various products used in buildings. The Building for Environmental and Economic Sustainability

(BEES) tool is a database of 280 building products (Lippiatt and Boyles 2001) that provides an LCA approach to selecting products. The tool is useful for selection of products having a lower environmental impact in the manufacturing stage. However, the use phase of the products in the structure is often not assessed by this tool.

The general perception for selection of a product is that any product manufactured using naturally growing raw materials may be green and other products made using fossil fuels might be harmful to the environment. Innovative building products that enter the market may not be received well because of this perception. Another hindrance to promotion of green products is the assumption about cost and quality of the alternatives as opposed to traditional materials (EBN 2009).

The motivation of this research is to dispel some of the perceptions associated with green products. Green labels are one way to erase such misconceptions from the minds of the public, but many labels are available in the market labeling products based on single criteria leading to a lot of confusion on their validity and sometimes creating a negative impression about the product itself. Green washing is a concept where a company might falsely make claims about their product and advertises as such in order to attract the consumers to their product. Moreover, labeling a product green requires a holistic approach studying the entire life cycle including the use phase, which is ignored by many labeling programs.

Many of the green products such as innovative wall products, and windows help in conserving energy in homes. Another motivation of this research is to identify if implementation of the strategies mentioned above conserve energy nationally and help in achieving energy and greenhouse gases (GHG) goals set by various agencies.

1.2 RESEARCH QUESTIONS

The research questions answered by this study are provided below in Table 1: Proposed research questions.

Table 1: Proposed research questions

1	How can a residential LCA framework be created to overcome shortcomings of previous LCAs?
2	How can the framework created be validated?
3	How can the LCA framework created be used for labeling of products?
4	How can the impacts of the products labeled green be evaluated at a national scale?

1.2.1 Question 1: How can a residential LCA framework be created to overcome shortcomings of previous LCAs

This first question is the basis of the research and involves the residential LCA division of life cycle into broad phases, database identification, combining databases, identifying hotspots and conducting impact and improvement analysis. An attempt was made to move away from case specific residential LCAs towards conducting LCA of homes without access to any data.

Research questions 1 and 2 were coupled together and a framework was created to conduct residential LCAs using different building products used in homes.

Outcome: A framework was created and illustrated by comparing a home constructed using a new building product called insulating concrete forms (ICF) and a traditional wood home. This study has been published at the Journal of Green Building (Rajagopalan, Bilec et al. 2010).

1.2.2 Question 2: How can the framework created be validated

The residential framework created using the case study approach was validated by comparison with other published literature and the Department of Energy (DOE) data on homes. The previous literature on LCA of homes used a specific case study results. For example (Blanchard and Reppe 1998; Keoleian, Blanchard et al. 2000) studied a home in Michigan or focused on specific phases in the life cycle, while (Marceau, Gajda et al. 2002) calculated the manufacturing emissions of building products used in a home. The residential framework was created as a response to the data gaps in the previous literature. The results from previous studies were compared with this study and the reasons for lower or higher results in this study and their accuracy were discussed.

Outcome: Published in Journal of Green Building (Rajagopalan, Bilec et al. 2010).

1.2.3 Question 3: How can the LCA framework created be used for green labeling of building products?

The residential LCA was used as a framework for comparing green building products. Green products used for validation include floor coverings like carpets certified green by the Carpet and Rug Institute (CRI 2009), wall paints certified by the Green Seal standard (GreenSeal 2008), and linoleum flooring. The materials and products selected were compared through an LCA approach and the results compared with the green label requirements. The results showed the inconsistencies in the LCA databases used for labeling of products and how multi-attribute labels are a solution to improving the labeling system. Incorporating an LCA based multi-attribute labeling system can identify the impacts of a building product in specific impact categories.

Outcome: This research was submitted to International Journal of Life Cycle Assessment.

1.2.4 Question 4: How can the impacts of green labeled building products be evaluated at a national level?

This research question extrapolated the energy savings achieved by using ICFs in a single 2,450 square foot home to all the projected new home constructions in the US. Additionally, other strategies such as energy saving windows and doors were also employed in homes in combination with ICFs and the energy savings were compared with goals set by McKinsey and company and Architecture 2030 (Architecture2030 2009). The results showed that reaching the energy targets required a combination of energy saving strategies such as use of ICFs, windows and doors.

Outcome: This study is to be submitted at Energy and Buildings.

1.3 RESEARCH CONTEXT AND CONTRIBUTIONS

1.3.1 Context

The growth of the green building products market drives the need to assess the sustainability of these products. Analyzing the use of building products in structures along with other life cycle phases (manufacturing, transportation and end of life) are vital to understanding their environmental implications.

This research is of exterior wall sections for a single house in Pittsburgh and the energy consumption is modeled for a newly constructed single family home. To understand how the use of ICF in wall sections in houses all over the US would affect the energy consumption in the country, a study involving the penetration of ICF completely in the residential market was conducted. Based on the projections of construction of residential structures in the future and the increasing use of green building products for construction, a study showing the potential for energy savings in the residential structures construction market was conducted.

The current rating system for buildings, Leadership in Energy and Environmental Design (LEED) rates buildings on four levels- Certified (40-49 points), Silver (50-59 points), Gold (60-79 points) and Platinum (80-100 points). The points are distributed between the categories- Sustainable Sites, Water Efficiency, Energy and Atmosphere, Materials and Resources, Indoor Environmental Quality and Innovation in Design (USGBC 2009). The use of green building products can earn points in Indoor Environmental Quality, Materials and Resources, Energy and Atmosphere and Innovation in Design categories. Since the labeling of products is heavily dependent on single criteria labeling systems, understanding if a product is green based on life cycle principles will help in refining the green building rating of a building. This research evaluated the labeling systems of carpets, paints and linoleum flooring and compared LCA results of the products using various databases. The developed residential framework was then used to evaluate the environmental impacts of products used in homes. Product level LCA of carpets, paints and linoleum flooring were scaled up to a two story, 2,450 square foot home and the case study results were added to the product level LCA results. Since, the case study is the most robust LCA; the method used to create the framework is representative of the life cycle approach proposed for a green labeling system of other building products.

1.3.2 Contribution

This research contributed towards advancing knowledge in two directions. The first area created a residential life cycle framework useful in the LCA community to input different materials, construction practices and manufacturing techniques for residential structures and obtain environmental impacts of residential homes. The framework developed in this research was validated with a case study using the building product, ICF, as an exterior wall section in a home and compared with a house traditionally made of wood. Each life cycle phase was analyzed in detail, and phases having higher environmental impact were identified when the LCA framework proposed in this research was used.

Another aspect of this research is its utility in improving the labeling of building products. For example, the results showed that ICF had lower impacts in all life cycle phases except manufacturing of raw materials phase. Modifications were suggested for improving the manufacturing of raw materials process such that the impacts were reduced. If deconstruction and demolition occur in the best manner, meaning that all materials are separated, reused and recycled when possible, the impacts of the end of buildings' lives can be minimized. Specifically, the impacts of the end of a building constructed with ICF are minimal, when compared to the impacts of traditionally constructed homes. This study showed that end of life impacts of ICF are relatively low and its overall chances of being considered a green building material can be increased if manufacturing improvements can be made in the raw materials extraction and manufacturing phase.

Product labeling analysis was conducted with respect to carpets, paints and linoleum flooring. The functional unit for these analyses was the single-family residential structure. With so many new building products in the construction market, the residential framework created in this research will help in analyzing the benefits of using one product over the other. Improving databases and increasing transparency in the LCA procedure will help identify the highest impacts a product has in any impact category.

The energy potential of new and existing energy saving building products was analyzed. Products such as ICFs, windows and doors were analyzed for their energy saving qualities in new residential constructions in the US. The results showed that a combination of ICF, windows and doors achieved maximum energy savings. But the payback periods for such energy saving strategies was high. Thus a tradeoff exists between energy savings and initial costs.

2.0 BACKGROUND AND LITERATURE REVIEW

This chapter provides the literature surveyed with respect to buildings and LCAs. A justification of why residential buildings were chosen specifically for this research is provided. The basic premise for conducting this research is that although residential LCAs have been previously conducted the results might not necessarily apply for other geographical locations and homes. The literature surveyed is discussed and the associated problems with previous studies are also illustrated.

After establishing that LCA of buildings is very case specific and a residential framework is required to analyze environmental impacts of homes, the framework will be used as a guide to evaluate building product labels. This chapter will also focus on studies which have been previously conducted on green product labels and including LCA as a tool for green labeling.

Green building products that have the potential to reduce energy and studies focusing on energy reductions achieved by the products was also be reviewed.

2.1 WHY RESIDENTIAL BUILDINGS

Homeowners are key players in the residential building sector as they engage in a greater role in the decision making process regarding the location of project, type of construction, selection of building products and in the ultimate use of their homes (Martin, Swett et al. 2007). Adoption of emerging and novel products is higher amongst single family custom home builders, multifamily builders and national and regional builders when compared with other industries such as commercial builders (Koebel, Papadakis et al. 2004). Buildings provide an opportunity for reduction of greenhouse gases. Of the 300 billion square feet building stock, every year 1.75 billion square feet is demolished and 5 billion square feet is renovated and another 5 billion is constructed new (Architecture2030 2009). Sustainable tools such as LCA can potentially assist overcoming some of the problems created due to the increased construction activities of buildings.

2.2 LIFE CYCLE ASSESSMENT

LCA is a cradle-to-grave method to analyze all impacts from the manufacturing of any product or process to the final disposal or end of life. Growing concerns about environmental impacts of various products and services has spurred the growth of LCA as a tool used specifically for identifying the negative environmental components in any process or product.

LCA can be used as a tool for policy-making where after identification of the environmental impacts, policies can be made to revert or correct a situation.

Based on the International Organization for Standardization (ISO) 14040 series (ISO 1997), LCA essentially has four steps: (1) Goal and Scope Identification, (2) Life Cycle Inventory Assessment (LCI), (3) Life Cycle Impact Assessment (LCIA), and (4) Improvement Assessment. For any LCA, the results are valuable only if they are consistent with the goal definition and scope of the project. The boundary has to be defined including all the important phases leading to a complete product, but at the same time making assumptions on certain functions and data used for an LCA. A functional unit describes a unit process or scale of the base case and is defined depending on the product or process. Based on the boundaries set for an LCA and the functional unit selected, relevant data for the LCI is assembled. Data can be obtained from various government and private sources as well as from previously published scientific work. Databases like the Franklin database are often used to obtain data for an LCI. The data obtained from databases or private sources is converted to the functional unit for analysis of the product or process. The inventory phase essentially quantifies the environmental emissions to air, water, soil and various other media from the data. An inventory assessment can be conducted using the conventional process-based method looking at mass and energy balances and the economic input-output method, which quantifies emissions based on dollar value of the product or service (Hendrickson, Horvath et al. 1998; Cicas, Matthews et al. 2005). Both procedures have inherent advantages and drawbacks and a hybrid approach tries to capture the advantages of both systems is also used (Treloar, Love et al. 2000; Suh, Lenzen et al. 2004; Bilec, Ries et al. 2006; Sharrard, Matthews et al. 2008). Based on the inventory, an LCIA is conducted. The LCIA classifies the LCI data into categories in which they have an impact. LCIA results can be presented at four different levels: midpoint, endpoint, damage and weighting factors. Some major LCIA midpoint categories include: global warming, ozone depletion, human health, energy consumption, acidification, eutrophication and smog formation. The final stage of an LCA suggests strategies to improve a product or process. Based on the results of the impact assessment, some strategies to improve a product or process can be suggested. No specific method for the improvement assessment has been established, and is often not included as a component of LCA.

A variety of LCA databases and software are available and a brief description of some of the databases and software programs used in this research is provided.

2.2.1 Building for Environmental and Economic Sustainability

Building for Environmental and Economic Sustainability (BEES) is software developed by National Institute of Standards and Technology (NIST) useful for making purchasing decisions for “green” product selection. Actual environmental and economic performance data is available for more than 230 building products. An LCA approach is used to measure the environmental performance of the products. All phases including acquisition of raw materials, manufacturing, transportation, recycling and the environmental impacts associated with the phases are analyzed using the LCA approach for most products. The economic performance is measured using the life cycle cost method that covers initial investment, operation and maintenance, replacement and disposal. To combine both these variables, American Society for Testing and Materials (ASTM) Multivariate Decision Analysis is used.

The user provides relative weights for each of the parameters and sensitivity of the results to changes in weights can be analyzed. Combining the economic and environmental performance into a single score is a default option. If the user does not require a combined score, a ‘No Weighting’ option can be specified. If equal preference is to be given to both economic and environmental parameters, a weighting option of 50 percent can be provided. User-defined weights for the environmental impact categories can also be provided or the default options provided in BEES can be selected. For the economic performance, a discount value, which provides the present value for any future building costs, can be applied. A default value of 3 percent as mandated for any federal projects can be used if the user does not specify a discount rate. The user selects the product for analysis or comparison from the database and provides the transportation distance from manufacturer to use. Tables and graphs showing the overall performance scores and the individual environmental and economic performance scores are available in the results section of BEES (Lippiatt and Boyles 2001).

2.2.2 ATHENA^{TM}

ATHENA is a software tool using the LCA method to assess whole buildings and assemblies (Athena 2009). The tool is geared towards architects, engineers and others to assess environmental implications of industrial, residential and commercial buildings both new buildings and major renovations. It is in an easy to use tool providing cradle-to-grave environmental impacts in terms of embodied energy, global warming potential, emissions to air, water and solid waste emissions and the weighted resource use. The environmental impacts of material manufacturing, transportation, on-site construction, regional variations in energy and transportation, building type and its impacts throughout its lifetime, building maintenance and repair and demolition and disposal are included. Energy simulation is not a component of ATHENA but the results of the simulation from other energy modeling tools can be applied to ATHENA results.

The database used to conduct LCA is based on North American data and is provided by industry experts. Though ATHENA is an LCA tool, the user cannot modify the data in the database to suit their specific requirements. The LCA results are based on the set of criteria available in the tool and decisions are based on the performance of the structure in these criteria. For example, when comparing two residential buildings, comparisons can be made on which structure has the highest global warming potential.

2.2.3 SimaPro 7

This software program is primarily a collection of databases including a variety of processes such as construction materials, transportation, energy, chemicals and many others. The databases available in version 7 include: Ecoinvent v2 (Frischknecht and Jungbluth 2007); US, Japanese, Dutch and Danish Input Output database (MCA 1999; BEA 2002; Statistics Denmark 2010); Industry data; LCA Food database (Nielsen, Nielsen et al. 2003); ETH-ESU 96 (Frischknecht and Jungbluth 2001); BUWAL 250 (Spriensma 2004); IDEMAT 2001 (Delft 2001); Franklin database (Norris 2003); Data archives; and the IVAM database (Lindeijer and Ewinjk 1998). In addition to the variety of databases, the software also has the capability to perform impact assessment using different methods available such as: Eco-indicator 99 and 95 (Goedkoop, Demmeers et al. 1995; Goedkoop and Spriensma 1999), CML 92 and 2002 (Heijungs, GuinÈe et al. 1992; GuinÈe, Gorree et al. 2002), IMPACT 2002+ (Jolliet, Margni et al. 2003) and TRACI (Bare, Norris et al. 2003) among others. The major drawback for US users is the majority of data is Europe-centric except the Franklin and the US input-output database which provide data for the US. This leads to varied results due to differences in manufacturing processes in separate regions, energy mixes and assumptions in the collection of data.

2.3 PRIOR WORK ON BUILDINGS AND BUILDING PRODUCTS

Previous LCAs showed that the use phase is the most energy intensive life cycle stage for residential buildings. One process-based LCA of a 2,450 square foot traditional wood house built in Ann Arbor, Michigan showed that the heating and cooling of the house whose use phase was assumed to be 50 years, accounted for 96 percent of energy consumption, as compared to 4 percent of embodied energy from maintenance and renovations (Blanchard and Reppe 1998). Other studies also looked at the energy use during the lifetime of homes by dividing the life cycle into phases such as production, construction, operation, maintenance and demolition. The operation phase accounted for most of the energy consumption, while the production phase only accounted for 10-15 percent of the energy use (Adalberth 1997; Winther and Hestnes 1999; Peuportier 2001). Another study on residential LCA using Economic Input Output-Life Cycle Assessment (EIO-LCA) showed that the construction phase is the largest contributor to economic activity and hazardous waste and air emissions while the use phase resulted in significant energy consumption and greenhouse gases (Ochoa, Hendrickson et al. 2002).

Asif et al. (2007) studied dwellings in Scotland using an LCA by varying the construction materials. The materials studied were timber, concrete, glass, aluminum, slate, ceramic tiles, plasterboard, damp course and mortar. The study concluded that concrete had the highest level of embodied energy as compared to other materials and was responsible for 99 percent of the total CO_2 emissions for home construction as against timber which had lower CO_2 emissions.

Lippke et al. (2004) compared homes constructed of steel, wood and concrete in different locations such as Minneapolis, MN and Atlanta, GA. The authors found that the Minneapolis home consumed 60 percent more energy than the Atlanta home and the steel framed home consumed 17 percent more fuel than the wood framed home in Minneapolis. The homes compared in Atlanta were made of concrete and wood and concrete consumed 15 percent more energy than the wood home.

Other studies such as Adalberth (1997) and Peuportier (2001) also showed that the global warming potential (GWP) and acidification impacts were higher when the construction material was concrete. Both the studies conducted LCAs of dwellings but the functional unit used was one square meter of usable floor area or living area. These studies show that comparing the use phase with one square meter of usable area functional units does not provide reliable results and most of the impacts in the use phase tend to be ignored.

A study analyzed the building sector to judge the possibility of including the use phase in LCA studies (Paulsen and Borg 2003). The authors found that first the relevance of the use phase in building product comparisons needs to be assessed. Then the possibility of estimating environmental emissions from use phase should be considered. This study showed a procedure which could be used to estimate if the building product use phase could be included in the LCA based on the impacts to indoor air quality, leaching of hazardous substances to outdoor environment, impact on relative flows due to choice of the product and the maintenance schedule for the product. The next step was to check for availability of data at product and building level.

If the two conditions were satisfied, the use phase could be included by quantifying the environmental loads. This is a procedure for evaluating existing building products used in homes as product and building level data is easily available but for new building products, obtaining building data and sometimes even product data can be complex.

Few studies have focused on conducting LCAs of buildings made of new building products such as ICFs by including relevant phases in the life cycle. LCA studies researched houses constructed of ICFs through a partial life cycle inventory assessment (Marceau, Gajda et al. 2002) and by modeling the energy use of the houses (Gajda and VanGeem 2000). The houses in both studies were in five different locations: Phoenix, AZ (hot, dry climate); Miami, FL (hot, humid climate); Seattle, WA and Washington, DC (moderate, wet); and Chicago, IL (variable with cold climate). The results of the partial inventory assessment showed that the embodied energy for an ICF home was higher than a traditional wood frame house initially, but the cumulative energy for the wood frame house was much higher than ICFs after a period of five years. The energy use study results showed that the ICF walls had an inherent capacity of higher insulation in comparison to wood frame walls in all locations modeled. Another study (Trusty and Meil 2000) also conducted a comparative LCA of a 2,400 square foot ICF house using the LCA tool ATHENA. The results of the study also showed that the ICF system had higher embodied energy than both the wood frame and the steel structures.

Three studies (Gajda and VanGeem 2000; Trusty and Meil 2000; Marceau, Gajda et al. 2002) showed that even though ICF has a higher embodied energy, the advantages in the use phase of the building product needed further investigation. The partial LCI attempted to identify the hotspots associated with the ICF life cycle. ICF manufacturing had high environmental impacts, but hotspot analysis was difficult when the entire house is used as a functional unit since many products were used in the analysis.

The National Association of Home Builders (NAHB) (1997) constructed four demonstration homes made of ICF to gauge the response of using such a building product in homes. The study showed that ICF is increasingly becoming popular and the major drawback, the increased price, can be overcome by focusing on the desirable qualities of ICF such as durability, serviceability and energy conservation properties. The study identified where more research is needed for people to accept ICF homes.

Prior research related to LCA and ICFs has focused mainly on disparate life cycle phases, leading to incomplete life cycle results. Table 2 shows the residential LCA literature surveyed and their major findings. Through this research, some of the problems associated with previous LCA studies such as case specific results or partial LCI were addressed. A detailed comparison of ICFs to traditional materials was performed throughout the entire life cycle of an ICF home and elucidates the environmental advantages and disadvantages. This research conducted a comparative LCA of an ICF and wood-frame house and identified areas in the life cycle where improvements for a building product such as ICF can be made. Through this comparative research, a framework used to assess any emerging building product without a case specific data burden was created.

Table 2: Background information on literature

Type of Study	Authors	Findings
Process-based LCA	Blanchard et al. 1998	Use phase of 50 years most energy intensive phase. Case specific results
EIO-based LCA	Ochoa et al. 2002	Use phase most energy intensive. An EIO-study performed on residential homes. 1-year life cycle. Purely EIO study
Partial LCI	Marceau et al. 2002	Analyze building product called ICF. Manufacturing phase has high energy consumption but use phase, ICF performs better than wood framed homes. Partial LCI. Not all major material inputs analyzed
Energy modeling	Gajda & Vangeem 2000	Use phase of ICF homes modeled and compared with traditionally built homes. ICFs consume lower energy than traditional materials in homes. Only use phase of ICF home addressed
Process-based LCA	Kahhat et al. 2009	LCA study on several wall sections using ATHENA. ICFs found to have higher embodied energy but lower energy consumption in use phase. Case study data used for LCA software.
Process-based LCA	Blanchard et al. 1998	Use phase of 50 years most energy intensive phase. Case specific results
EIO-based LCA	Ochoa et al. 2002	Use phase most energy intensive. An EIO-study performed on residential homes. 1 year life cycle. Purely EIO study

Other building material specific LCA studies were also reviewed in the literature survey. Wood is a building material commonly used in homes and research evaluating the environmental impact of wood and comparison of wood impacts with other materials such as concrete was studied (Buchanan and Levine 1999; Borjesson and Gustavsson 2000; Lenzen and Treloar 2002; Lippke, Wilson et al. 2004). Wood consistently has lower impacts than concrete in global warming in all literature. Most studies focus on a small boundary or compare only global warming impacts. Detailed research in comparing wood when used in a building with other building products are required to understand all the environmental impacts of wood over its life cycle.

Building product LCAs focusing on impacts of the life cycle of the product have been previously conducted. Flooring material LCAs were performed by several researchers, some focusing on the life cycle of the product while some focused on specifically the maintenance phase (Günther and Langowski 1997; Jönsson, Tillman et al. 1997; Gorrée, Guinée et al. 2002; Paulsen 2003; Thabrew, Lloyd et al. 2008). The building in which these flooring materials were used was not considered in any of these studies and case-specific results were provided in all the aforementioned studies. Figure 1 shows the objective of this research, using LCAs to evaluate buildings and building products based on the literature survey conducted. The literature relevant to LCA and buildings is shown between the two circles while studies pertaining to LCA and building products are shown in between the relevant circles. A systems approach investigating all components of a residential building is required instead of focusing on single elements such as only building products or buildings.

Studies detailing the national impacts of rebuilding and potential performance improvements were also reviewed. An LCA based case study evaluated the impacts of rebuilding versus constructing new homes in Sweden (Hendrickson, Horvath et al. 1998). The study concluded that rebuilding is a better option if the same functionality can be achieved in homes instead of constructing new homes.

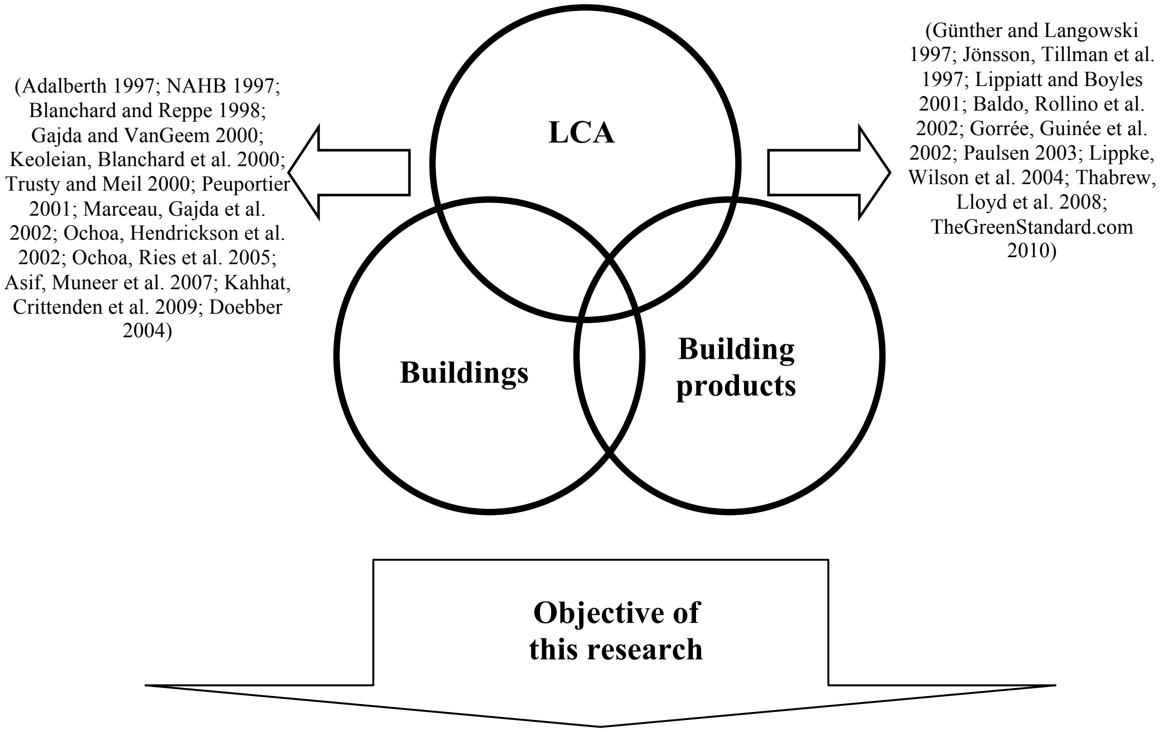


Figure 1: Literature review showing the areas of interest with respect to this research

Another study investigated the potential for profit from energy savings in the residential homes with a market-based residential energy services company (RESCO) (Soratana and Marriott 2010). The hypothesis was that there is a market failure in the residential efficiency improvement market due to lack of customer knowledge and reduced investments. The study showed that RESCO needs to be in a contract for 35 years to recover the profits from energy savings but the experience plays a big role in reducing the contract length.

The opportunities for reducing energy emissions and thus the greenhouse gas effect exist in all countries, but the feasibility of abatement policies, the extent to which they can be implemented and their likely impacts vary (Frischknecht and Jungbluth 2001).

The literature surveyed shows the need for a residential framework and the case study approach can identify hotspots in the life cycle of the building product. The use of ICF as an energy saving product has been established in previous literature. But this study is a holistic LCA of the product that can be utilized in promoting energy savings in homes.

3.0 RESIDENTIAL LIFE CYCLE MODELING: COMPARATIVE CASE STUDY OF INSULATING CONCRETE FORMS AND TRADITIONAL BUILDING MATERIALS

3.1 MOTIVATION

The previous chapters discuss *general* motivation and background; this chapter *more specifically* delves into the background and motivation related to research question one.

Buildings account for 30-40 percent of the world's energy use (Heijungs and Frischknecht 1998). In the United States, buildings annually use 70 percent of the nation's electricity (USDOE 2005) and emit around 40 percent of the country's greenhouse gas emissions (USDOE 2009). The construction industry has a significant impact on resource use. The average American in their lifetime accounts for 540 tons of construction materials (Young and Sachs 1994), while buildings use 40 percent of raw materials globally, equating to 3 billion tons annually (Roodman and Lenssen 1995). Innovative building products are emerging that have the potential to reduce environmental impacts and contribute to sustainable development.

Based on the four principles of green buildings: reducing energy use; minimizing external pollution and environmental damage; reducing embodied energy and resource depletion; and minimizing internal pollution and damage to health- it is clear that the entire life cycle of buildings has a huge impact on the environment (Woolley 1997). As the construction industry accounts for 4 percent of the $13.2 trillion United States Gross Domestic Product (GDP) in 2007, it makes sense to market construction technologies that have lower environmental impacts, better efficiency, higher energy-savings and produce less waste (U.S. Department of Commerce 2009).

Previous research has identified the use phase of residential buildings as the energy intensive phase and emerging innovative building products such as Insulating Concrete Forms (ICFs) can reduce the energy consumption in the use phase (Blanchard and Reppe 1998; Keoleian, Blanchard et al. 2000; Ochoa, Hendrickson et al. 2002; Ochoa, Ries et al. 2005). But most of the previous studies on ICFs focus on a single phase (Gajda and VanGeem 2000) or have only partial life cycle assessment (Marceau, Gajda et al. 2002) which provide incomplete results.

The aim of this research was two-fold: (i) develop a life cycle assessment model to systematically analyze all life cycle phases of a residential building, and (ii) analyze the sustainability of innovative building products in comparison to conventional building materials. This work provided insight into the energy intensive phases of the life cycle of a building material and environmental impacts.

3.2 BACKGROUND

3.2.1 Insulating Concrete Form

ICF is a building material that is increasingly being used in construction. An ICF wall section consists of expanded polystyrene (EPS) forms and poured concrete with polymer ties connecting the EPS forms, depicted in Figure 2. One difference between ICF and traditional construction is that after the concrete has cured, the polystyrene forms remain in place. Additional reinforcement, such as rebar, can be added according to the structural design using internal strapping made of polypropylene.

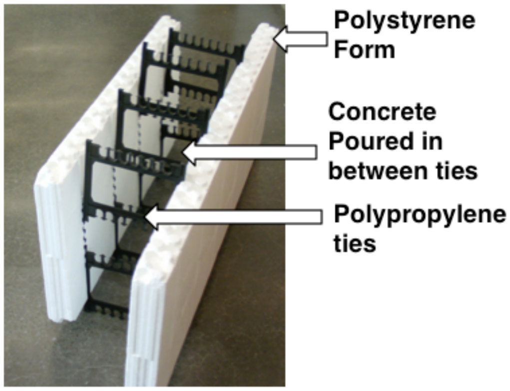


Figure 2: Insulating concrete forms

ICFs have several advantages; they are durable and resistant to hazards and natural disasters and reduce energy consumption during a building's use phase compared to traditional building materials. Several organizations, including the National Association of Home Builders

(NAHB), have evaluated ICFs' performance through demonstration homes in several locations across the United States (NAHB 1997).The NAHB study showed that ICFs are increasingly becoming popular and the higher initial price can be overcome by focusing on the desirable qualities of the product such as durability, serviceability and energy conservation properties. An ICF structure has energy savings of more than 25 percent during the use phase, since the forms provide additional insulation and improve energy efficiency in building structures (VanderWerf 2006). The heating, ventilation and air conditioning (HVAC) energy consumption can be reduced by 25 to 50 percent (VanderWerf 1997). The factors contributing to energy efficiency of ICFs are the R-value (typically at least 20), air infiltration reduction and thermal mass. Generally, if wall sections of the house are made of ICFs and the doors, windows and roof are made of traditional construction materials, air flow rates will be 10 to 30 percent lower than typical frame construction (VanderWerf 2006).

Experiments are being conducted at Oak Ridge National Laboratory (ORNL) to determine the relative energy performance and the air tightness of residential homes constructed from ICFs (USDOE 2009). To demonstrate that ICFs can withstand severe forces, the United States Department of Defense (DoD) conducted its Force Protection Equipment Demonstration (FPED) using ICF boxes blasted with trinitrotoluene (TNT) and found that minimal cracking with no structural damage occurred (Panushev and VanderWerf 2004).

There are other advantages to ICFs; from a homeowner's point of view, less air leakage equates to greater thermal comfort and fewer temperature variations. ICF homes provide structural strength as well as less acoustical transmission, reducing undesirable noise in the house and the homes made of ICF are fire-resistant, durable and require less maintenance (NAHB 1997). Finally, an ICF structure can potentially obtain points in the United States Green Building Council's Leadership in Energy and Environmental Design (LEED) green building rating system for categories of Sustainable Sites, Energy and Atmosphere, and Materials and Resources (USGBC 2009).

3.2.2 Cost

The initial construction cost of ICFs is higher than conventional construction; the cost of ICF exterior wall homes is \$1 to \$4 per square foot more than the cost of building a house with a conventional wood frame (VanderWerf 1997). Savings are achieved during the use of the building with more efficient HVAC systems along with decreased operating costs of ICF homes. Due to the ICF thermal wall efficiency, contractors can downsize the HVAC capacity by as much as 50 percent as compared to wood frame homes. ICF construction prices are beginning to fall due to improved designs with more efficient assembly procedures that reduce installation labor. Most insurance providers offer a premium reduction for high fire or wind resistance homes, which ICFs provide, and the savings for an average home are in the range of \$40 to \$100 per year (VanderWerf 1997).

Exterior finishes (e.g., brick and vinyl siding) can be applied to ICFs at a similar cost (VanderWerf 2006). ICFs allow the designer to deviate from the traditional shapes of structures. Rather than being constrained to rectangular footprints and openings, curvilinear shapes are easily achieved using ICFs.

3.2.3 Construction Practices

Architects, engineers, and contractors are becoming aware of ICF as a building material. Training programs are available for construction crews by all major ICF suppliers. ICF construction involves assembling the wall sections together onsite and concrete pouring (Polysteel 2008). The concrete mix for ICF construction typically has a compressive strength of 2,500-3,000 psi and a slump of 4”- 6” to facilitate easy pouring through a pump. The free flowing mix allows the concrete to reach all the corners in the form; voids can decrease the strength of an ICF wall. ICF wall construction performs well during temperature extremes (NAHB 1997). For temperatures below 10°F, the top form is protected using insulation blankets and when the weather is hot, to prevent evaporation, a plastic moisture barrier is used to cover the form, similar to typical concrete pours. In all weather extremes, the insulation helps the curing process.

In comparison to traditional structures, ICFs require additional planning before construction of the structures (NAHB 1997). The location of the openings of doors and windows, attachments of floors, roofs and walls, and utility equipment placements needs to be decided before construction, as changes after concrete has cured will increase the cost of construction. For ICF construction, the bracing is erected on the inside of the wall thus reducing site disturbance to the outside perimeter and helps in preserving natural areas around the site (ICFA 2008).

3.3 METHOD

This study obtained in-depth data from an ICF manufacturer based in New Brighton, PA. The manufacturer is a producer of various packaging solutions and ICF forms is one of the products manufactured in their manufacturing facility. The study team had one-on-one data collection meetings with the manufacturer. The manufacturer provided data for modeling the manufacturing phase of an ICF home in addition to sample ICF forms produced by the manufacturer. The study team was given a detailed tour explaining the manufacturing process of the ICF forms. This information was utilized in modeling the manufacturing phase of an ICF home with industry-specific data instead of using defaults.

A comparative LCA was performed to study the environmental impacts of ICFs and traditional wood frame homes. The LCA of both the ICF and the wood structures are divided into five phases: raw materials extraction and manufacturing, transportation, construction, use, and end of life of materials.

Extensive research was conducted to select data for each stage. An example of the decision making process is illustrated in Table 3 for ICFs, and a similar procedure was used for the other building materials. Detailed information from an ICF manufacturer was used, therefore it was important to select databases and unit processes from software that could be altered to incorporate the specific ICF data. Several potential databases and software tools were reviewed such as ATHENA, BEES, the US LCI database, ecoinvent and other European databases before selecting primarily a collection of European databases for compiling the LCI. The data from the European databases was more suitable for modeling the ICF and wood manufacturing as the US databases such as Franklin did not provide adequate information. But where available, data from US databases such as Franklin was utilized. The ATHENA database is a North American LCA tool that can be used for modeling an entire structure (ATHENA 2003). While the ATHENA database does have ICF data, more flexible data sources were required for modeling purposes; thus a custom LCA was created. The impact assessment for the life cycle was performed using the Tool for Reduction and Assessment of Chemical and other Impacts (TRACI), a tool used to assist in impact assessment for sustainability metrics, LCA, industrial ecology, process design and pollution prevention (EPA 2009). TRACI is a midpoint level impact assessment tool that was developed by the United States Environmental Protection Agency (EPA) to assess environmental impacts through a decision-making framework. Several scenarios were modeled for the use phase with the energy-modeling program eQuest (DOE 2009).

3.3.1 Raw Materials Extraction and Manufacturing Phase

When modeling ICFs, it was necessary to account for additional industry input and combine multiple relevant datasets. For concrete, several unit processes were available, and a triangular distribution was developed from the datasets, as there was only limited data in the form of minimum and maximum values. Triangular distribution is used as illustrated in various studies (Bilec, Ries et al. 2006; Thabrew, Lloyd et al. 2008). The "concrete not reinforced" unit processes from ETH-ESU 96, IDEMAT 2001, and ecoinvent were used to create the triangular distribution for the concrete process used in this model. The ecoinvent unit process for polystyrene was modified with the manufacturer's data to create a new unit process for polystyrene. The ecoinvent polypropylene unit process was selected for the ties used in ICFs. For the other building materials, such as wood, the unit processes were selected from the databases mentioned below.

3.3.2 Transportation Phase

The materials used on the construction site were assumed to be transported by trucks at an assumed distance of 31 miles (50 km). A fixed distance was assumed to demonstrate the differences in number of truck trips required for transporting different quantity of materials for the same distance. The number of trips required to transport materials 31 miles (50 km) from the manufacturing site was calculated. A standard heavy duty truck with dimensions of 15 feet x 48 feet x 8 feet with a carrying capacity of 16.5 tons was assumed to transport the materials from the manufacturing site (FHWA 2009). Based on the material quantities and the dimensions of the materials, ICFs require two trips by truck while ten truck trips were required to transport materials for a traditional wood home. Emissions from truck manufacturing, constructing the associated infrastructure and driving the truck were obtained from the Franklin database. ICFs are lightweight materials when compared to wood frames and stacking of ICFs increases the space available for transportation.

Table 3: Data sources for life cycle stages of insulating concrete forms. Similar databases are used for wood structures

LCA Phase	Process Involved	Unit Processes and Databases	Remarks
Raw Materials Extraction and Manufacturing	Concrete	Concrete not reinforced (ETH-ESU) Concrete I (IDEMAT 2001) Concrete normal at plant (ecoinvent)	Several concrete unit processes were used and minimum, maximum and median values were obtained. The median value was selected when the data was available; the maximum value was selected when only one data point was available.
	Polystyrene	Polystyrene, general purpose, GPPS, at plant (ecoinvent) Modified with actual ICF plant data	Several databases were explored. Most of the databases except ecoinvent had no inventory items for polystyrene; therefore, the ecoinvent database was used. Manufacturer data was added to the ecoinvent data to create a new polystyrene unit process.
	Polypropylene	Polypropylene, granulate at plant (ecoinvent)	Several databases were explored. Most of the databases except ecoinvent had no inventory items for polypropylene; therefore, the ecoinvent database was used.

Table 3 (continued)

Transportation	Transportation of materials	Truck transport, diesel powered (Franklin)	Federal Highway Administration Standards for trucks (FHWA 2009) was used to determine truck dimensions. Number of truck trips was based on material quantity take-offs and truck dimensions. Assumed transportation distance was 31 miles (50 km).
Construction	Construction of house	ATHENA	ICF and wood-framed structures were created in ATHENA. Results for construction phase only were used.
Use	Use of the house based on 50 and 100 year lifetime	eQuest	Department of Energy freeware-eQuest was used to model houses made of wood, ICF.
End of Life	Concrete crushing and reuse	Disposal, building concrete, not reinforced, to sorting plant (ecoinvent)	Concrete was assumed to be reused as aggregate in future project. Concrete crushing was modeled with available equipment unit process.

3.3.3 Construction Phase

The modeling of the construction phase was carried out using ATHENA, LCA software for buildings. Two 2,450 square foot residential structures were modeled in ATHENA for both wood and ICF homes to obtain the construction inventory data. The manufacturing, transportation and end of life results are not included from the ATHENA model because the authors wanted to incorporate industry-specific data and evaluate the raw materials and manufacturing processes in detail.

3.3.4 Use Phase

The use phase of two 2,450 square foot single family homes was modeled in eQuest. Different materials were used for the different structural components of the ICF and wood house, see Table 4. The climate was assumed to be the Pittsburgh area for modeling purposes. This was to ensure that ICF was modeled for both hot and cold weather conditions and its environmental performance analyzed. Both houses had the same building footprint, door and window materials, occupancy schedules and HVAC systems were sized according to the heating and cooling requirements. Structural components such as roof, walls, ceiling and floors were different in the models to reflect common building practices unique for wood frame and ICF construction. The ICF home has higher insulation values in all structural components because of the high R-values associated with ICFs. Typically, a wood home doesn't have high insulation values. The thickness of wall sections and insulation used are in British units consistent with the style adopted by other authors in the field of LCA (Keoleian, Blanchard et al. 2000).

The ceiling was a drywall finish and the floors were vinyl tile finish. The cooling source in both scenarios was DX Coils and the heating source was a natural gas furnace. The thermostat set points were 65°F when occupied and 82°F when unoccupied for cooling and 75°F when occupied and 64°F when unoccupied for heating. The design temperatures were 75°F indoor and 55°F supply for cooling and 72°F indoor and 80°F supply for heating. Electricity was used for cooling, task lighting and other equipment around the house but heating and hot water source was assumed to be natural gas.

Table 4: Energy modeling scenarios for ICF and wood frame two storey residential structures

Component	Traditional Wood Home			ICF Home		
	Construction and/or interior finish	**Insulation**	**R-value**	**Construction and/or interior finish**	**Insulation**	**R-value**
Roof Surface	Wood frame	2" polyisocyanurate	14	4" concrete	6" polystyrene	30
Above Grade Wall	Wood frame	2" polyisocyanurate	14	8" concrete	3" polystyrene (exterior)	12
					Additional furred insulation (interior)	21
Basement Floor	4" concrete	No perimeter insulation		4" concrete	No perimeter insulation	
Basement Wall	6" concrete	exterior insulation	5	6" concrete	exterior insulation	20
Top floor Ceiling (2nd floor)	Wood frame	Batt	13	Wood frame	Batt	49
Ceiling (1st floor)	Wood frame	Batt	13	Wood frame	Batt	30
Floor	4" concrete+ vinyl tile	3" polyisocyanurate	10.5	4" concrete+ vinyl tile	3" polystyrene	12

3.3.5 End of Life Phase

The end of life analysis considered the environmental impacts of the building materials due to the dismantling and deconstruction of the house after its useful lifetime. Materials, quantities, and processes were the same as those used to assess the manufacturing stage. For the ICF waste scenario, it was assumed that the polystyrene and polypropylene are separated during deconstruction and demolition, but because recycling markets are lower for construction debris plastics, it was assumed the plastics were disposed of instead of reused or recycled. Therefore, only two waste streams were considered: concrete and all other waste. The processes involved in recycling the concrete were demolition, transportation to sorting facility, and crushing. All of the concrete materials within the ICF followed this waste stream. All remaining materials were sent to the landfill for disposal. For the wood frame waste scenario, research indicated that an average of 30 percent of demolition wood is recovered during deconstruction, chipped, and reused (McKeever 1999; Falk and McKeever 2004). The wood chipping waste scenario was modeled using the "Chopper, stationary, electric/RER/I U" process from ecoinvent. A new unit process was created with an hourly output of 3.3 cubic meters per hour and a lifetime output of 100,000 cubic meters. Wood chipping was applied to 30 percent of the wood and the remaining materials were sent to the landfill for disposal.

The five broad phases constitute the residential LCA model that is applicable for both ICF and traditional wood homes. Once the data was assembled, the five phases of the life cycle were compared on the basis of their energy consumption and environmental impacts. The life cycle impact assessment is performed using the US based tool, TRACI. The results of energy consumption and the life cycle environmental impacts are displayed in Figure 3Figure 4Figure 5.

3.4 RESULTS

3.4.1 Energy

The use phase of homes consumes the maximum energy in the life cycle of a residential structure (Blanchard and Reppe 1998; Keoleian, Blanchard et al. 2000; Ochoa, Hendrickson et al. 2002; Ochoa, Ries et al. 2005). This research also reiterated that the energy consumption in the use phase was significantly larger than other phases. A comparative LCA of a traditional home and an ICF home showed the energy consumption in each of the phases of the life cycle.

Initially, the two residential structures were compared assuming a 50 year lifetime, which is the value often assumed in LCA research of buildings (Blanchard and Reppe 1998; Keoleian, Blanchard et al. 2000). However, 50- and 100-year lifetimes were evaluated because ICFs are exceptionally durable. Traditional wood homes have a lifetime of 50 years so two wood homes of lifetime 50 years each were compared with a single ICF home with a lifetime for 100 years. Results showed that ICFs had lower energy consumption than traditional wood frame homes in all phases except the manufacturing phase (see Figure 3). However, manufacturing comprised only 18 percent of the total ICF life cycle energy use and 3 percent of wood home.

The use phase is a continuous activity for 50 or 100 years and was the most energy intensive phase and accounted for more than 50 percent of energy consumption in both ICF and wood homes. The eQuest simulation provided the annual end use demand of the various components that required electricity and natural gas (see Figure 4). Since factors that influenced electricity consumption, such as the orientation of the house, the location, and the heating and cooling equipment were the same for both houses, the difference in electricity consumption were attributed to the differences between structural elements. For space cooling, the traditional wood house had higher electricity consumption. Energy use for heating and cooling were calculated based on various envelope components such as floors, walls, windows, lighting systems, occupancy profiles and miscellaneous equipment. Miscellaneous equipment was defined as other equipment that contributes to heating and cooling loads. Both structures had equal electricity consumption in vent fans, pumps and auxiliary and miscellaneous equipment category as the occupancy profiles and use of equipment was considered the same

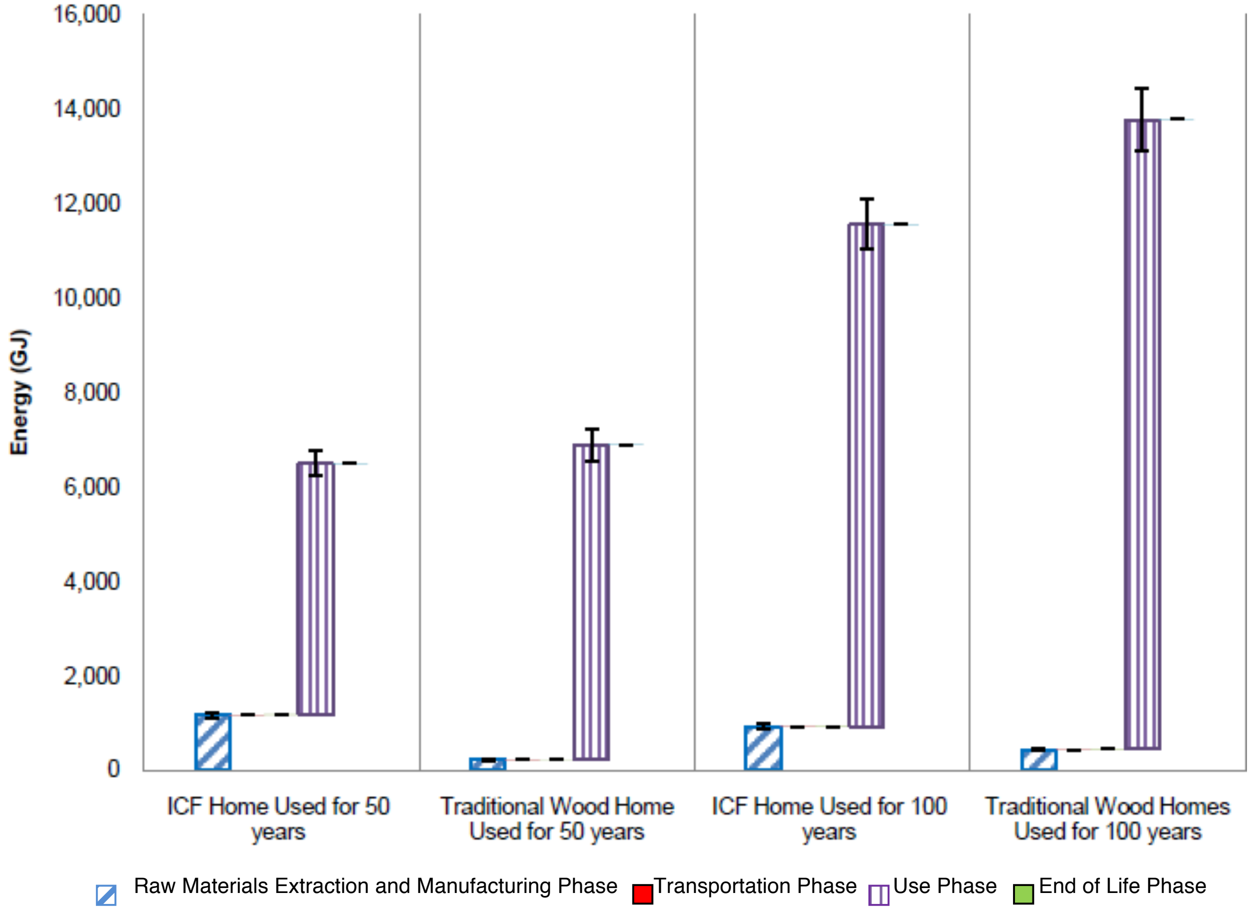


Figure 3: Energy consumption of ICF and wood homes for 50 and 100 year lifetimes. The use and raw materials extraction and manufacturing phase have significant energy consumption while the transportation, construction and end of life phases consume minimal energy when compared to the other two phases. The positive and negative error bars are shown with an error of 5 percent. Since traditional wood homes have a lifetime of 50 years, two wood homes built for 50 years each are compared with an ICF home standing for 100 years

To validate the use phase model qualitatively, statistics provided by the Energy Information Administration (EIA) – Residential Energy Consumption Survey (RECS) was used

(USDOE 2005). The energy consumption of a house of 2,000 to 2,499 square foot consumed 110 GJ of energy annually in 2005. The energy consumption of households has been increasing since 2005 but since new data has not been published, the 2005 data was used to validate the eQuest model's energy consumption. Figure 4 shows that the ICF house has overall lower energy consumption (106 GJ) when compared to a traditional wood house (133 GJ). In a region such as Pittsburgh, where cold weather lasts for almost seven months a year, annual energy consumption can be greatly reduced by using a building product such as ICFs.

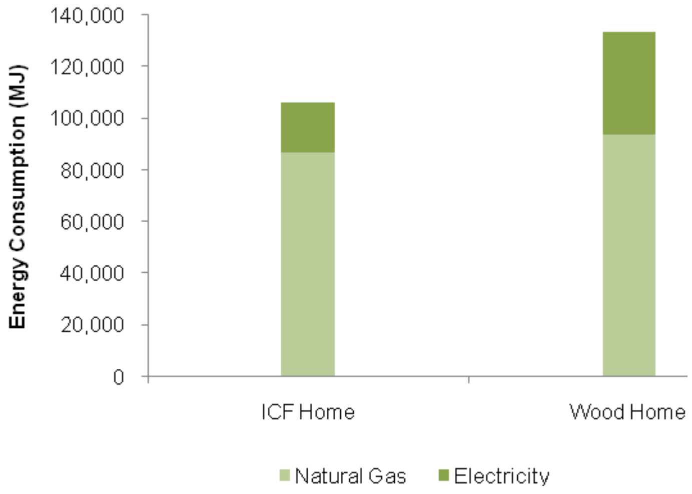
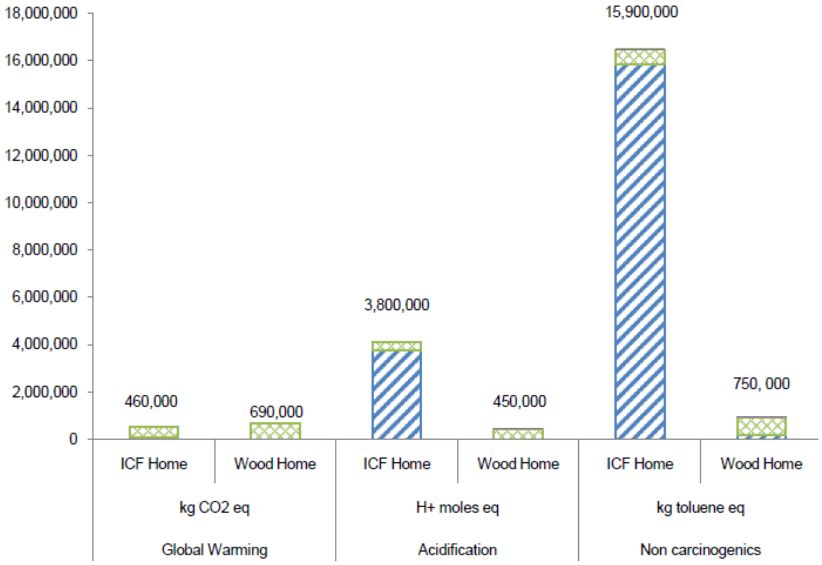


Figure 4: Energy consumption for ICF and wood homes for one year

3.4.2 Life Cycle Impact Assessment

The life cycle environmental impacts were analyzed for both ICF and wood homes. The energy was separated from the environmental impacts to show the benefits of ICF homes in terms of lower energy consumption over the life cycle. With energy savings, it is important to conduct LCIA studies to understand all the environmental impacts of ICFs. Previous studies on ICFs have conducted a partial inventory (Marceau, Gajda et al. 2002) or used LCA tools like ATHENA for the entire life cycle (Kahhat, Crittenden et al. 2009). This study systematically analyzed all phases of the life cycle of both ICF and wood homes and performed an LCIA on the inventory obtained from the LCI stage. TRACI was the impact assessment method selected and the results for the impact assessment stage show the comparative environmental impacts of all phases in the eight categories which are as follows: global warming, acidification, carcinogenics, non carcinogenics, respiratory effects, eutrophication, ecotoxicity and smog. Figure 5 a, b, c, and d show the environmental impact of both houses in all phases except construction as this phase was modeled in ATHENA. The environmental impacts were evaluated for a 50-year lifetime of the houses.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Global Warming
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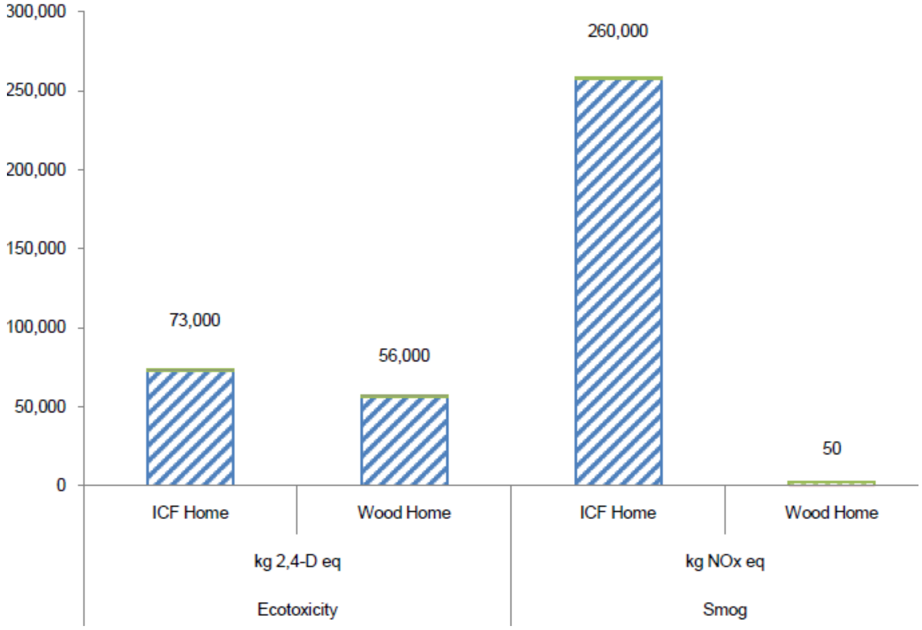
Non carcinogenics

(a)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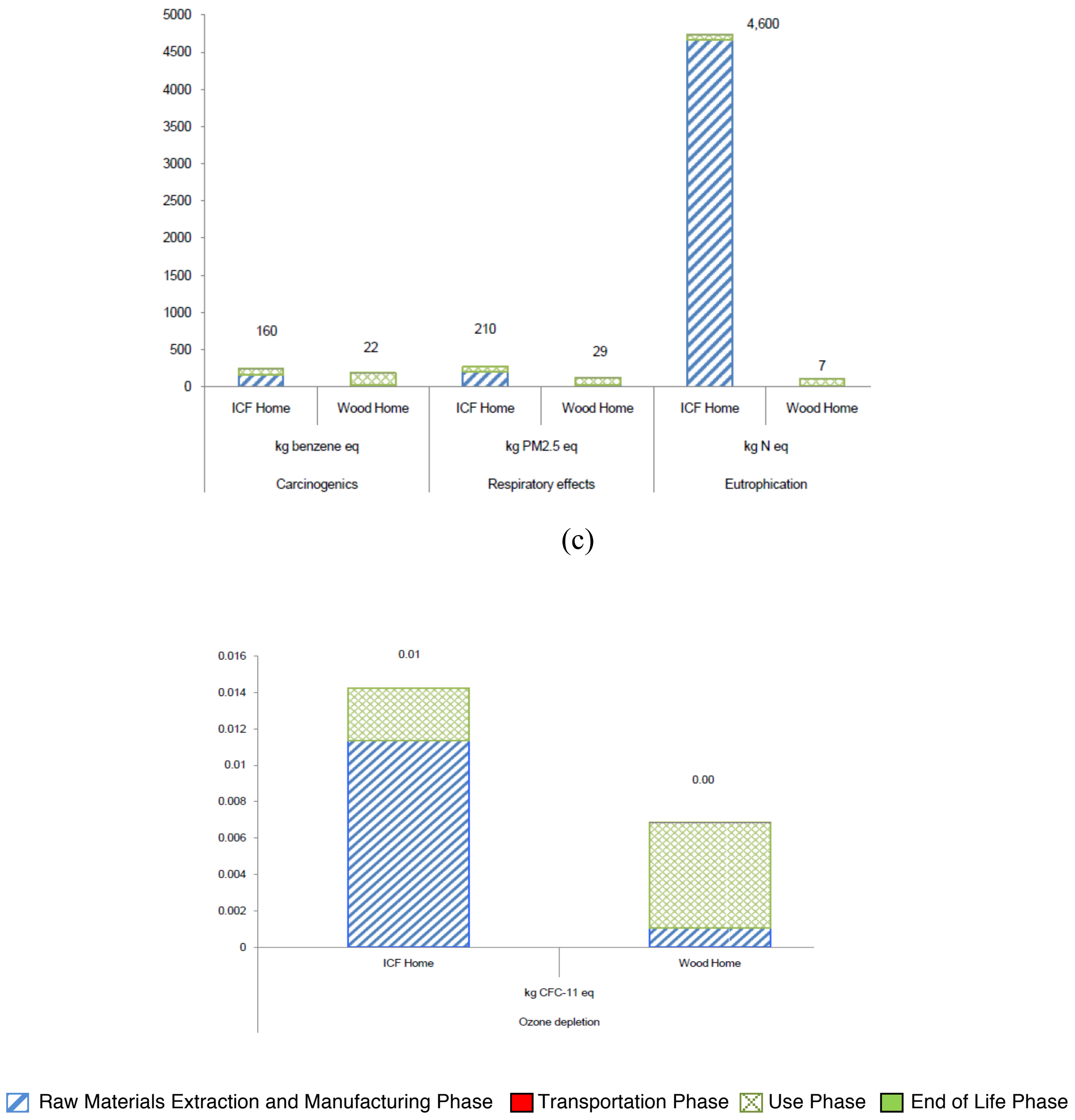

(c)

(d)

Figure 5: Life cycle environmental impacts using TRACI for 50 year lifetime of both wood and ICF homes in global warming, acidification, non carcinogenics, ecotoxicity, smog, carcinogenics, respiratory effects, eutrophication and ozone depletion categories. Construction phase is not included

The raw materials extraction and manufacturing phase of ICF homes had the highest contribution in all impact categories except global warming. However, for all impact categories, for wood homes, the use phase dominated. Raw materials extraction and manufacturing is a one-time activity while the use phase is a continuous activity for the lifetime of the home. The remaining life cycle phases (transportation and end of life) had minimal impact on the environment. Construction phase was not included in the impact assessment results due to limited inventory output. The categories cannot be compared amongst themselves numerically as the units are different for each category. Even though ICF homes have lower energy consumption and subsequently lower GWP, this study presented all the environmental impacts of both the homes. ICFs may be the products of choice if only energy and GWP are considered but tradeoffs associated need to be carefully considered.

3.5 DISCUSSION

A sensitivity analysis of the impact assessment results was performed using the other impact assessment methods of BEES, Eco-indicator 99 and IMPACT 2002+ (Lippiatt and Boyles 2001; Jolliet, Margni et al. 2003; Frischknecht 2005). The wood home had lower impacts in certain categories and ICF home had lower impacts in others when BEES impact assessment method was applied. When Eco-indicator 99 and IMPACT 2002+ methods were applied, the wood home had lower impacts in almost all impact categories. A direct comparison between

TRACI, BEES, Eco-indicator 99 and IMPACT 2002+ could not be conducted as TRACI and BEES are midpoint impact assessment methods while the others are endpoint impact assessment methods. Even though, ICF home had lower energy consumption over the life cycle, the environmental impacts from the life cycle were significant.

The main process and substance contributors for each impact category using TRACI impact assessment method were investigated. The raw materials extraction and manufacturing for the ICF assembly and the concrete manufacturing were the unit processes that had the maximum impact in the life cycle of ICFs. Even though intuitively the processes contributing the maximum for each of the impact categories can be inferred, the contributions from the actual unit processes are random. The processes and substances contributing the maximum to each impact category are shown in Table 5.

Most of the processes were either related to the polystyrene used in ICF or to the concrete used in the entire assembly. But some of the top process contributors such as the ones for carcinogenics, ozone depletion and ecotoxicity could not be instinctively inferred. The substance contributors to most of the categories such as acidification, eutrophication, carcinogenics, non carcinogenics and ozone depletion also appeared to be arbitrary selections instead of substances which are usually associated with these categories.

Table 5: TRACI impact categories and the main process and substance contributors for an ICF home

TRACI Impact Category	Unit process that contributed the maximum to the impact category	Substance that contributed the maximum to the impact category	Percent substance contribution
Global warming	Heat from natural gas	Carbon dioxide	94
Acidification	Polystyrene used in ICF	Ammonia	95
Carcinogenics	Disposal, municipal solid waste, 22.9 percent water, to municipal incinerator	Lead	91
Non Carcinogenics	Concrete	Antimony	69
Respiratory effects	Polystyrene used in ICF	Nitrogen oxides	93
Eutrophication	Polystyrene used in ICF	Ammonia	95
Ozone depletion	Transport, natural gas, pipeline, long distance	Halon 1211	67
Ecotoxicity	Disposal, municipal solid waste, 22.9 percent water, to municipal incinerator	Aluminum	56
Smog	Polystyrene used in ICF	VOC	98

The results of the impact assessment using TRACI and the subsequent sensitivity analysis using other tools show an uncertainty in the calculation methods and assumptions in the various methods. The unsystematic selection of processes and substances that contribute the maximum to any impact leads to an ambiguity in the results displayed. A method to reduce uncertainty would be to include more data on all the processes involved in a network. Since only very few input values like polystyrene and concrete were modified for the purpose of this research, a more detailed analysis which modifies the entire network chain for a product might yield more accurate results. Moreover, each impact assessment method has different characterization factors that are used for obtaining the impact categories and the results may vary depending on the impact assessment method used or the unit processes selected.

The findings of this research are consistent with other research. Kahhat et al (2009) performed an LCA study on a single story residential structure in Phoenix using different exterior wall materials including concrete block, poured concrete, insulated concrete, wood frame, and steel frame using ATHENA. The study divided the life cycle into pre-use, use and end of life phases and showed that in the case of ICFs, the structure had lower energy consumption over the use phase and hence lower global warming potential (GWP). The pre-use phase of ICFs had high environmental impacts and the end of life phase was found to be negligible. However, this study was different from Kahhat et. al (2009) because this study used ATHENA primarily to model the construction phase. This study had manufacturing data that could not be customized in ATHENA. Also, it is not possible to model the use phase in ATHENA. This study used eQuest to model the use phase separately.

Other LCAs of ICFs have shown that the energy consumption of a house is reduced when ICFs are used as wall sections (Gajda and VanGeem 2000; Marceau, Gajda et al. 2002). ICFs consistently exhibit higher raw materials manufacturing impacts and lower use impacts.

However, this study utilized manufacturing data for modeling the manufacturing phase and the manufacturing energy consumption were qualitatively compared with the above-mentioned studies and other traditional wood home studies. The results (Table 6) show that manufacturing energy consumption reported by this study is higher than other studies. This is because of inclusion of manufacturing data from an ICF manufacturer in this study while studies such as Kahhat et. al (2009) utilized defaults in LCA tools to model their ICF wall section. Marceau et. al (2002) modeled only the concrete embodied energy in their study thus leading to a lower raw materials and manufacturing energy. Traditional LCA of a standard home and an energy efficient home performed by Keoleian et al (2000) had higher pre-use phase energy consumption. This was because the pre-use phase included materials extraction and processing, construction materials fabrication and home construction phases. The use phase energy consumption in this study is comparable with the average energy consumption in residential homes in the US (USDOE 2009). All the other studies obtained values higher than the national average provided.

Table 6: Comparison of ICF case study results with other studies

	Rajagopalan et al (2010)	Kahhat et. al (2009)	Marceau et al. (2002)	Keoleian et al (Standard home)	Keoleian et al. (Energy efficient home)
Raw materials extraction and manufacturing energy (GJ)	1177	634	52	1509	1669
Use energy-1 year (GJ)	106	252	173	290	95
Lifecycle GWP (tons)	553	851	3.2	1010	370

The results from the case study were qualitatively compared and found to be among the bounds set by previous studies. The reason for higher values in phases such as raw materials extraction and manufacturing energy was due to use of manufacturer's data.

3.6 CONCLUSION

The comparative LCA results of a 2,450 square foot home made of both wood and ICF showed that the wood homes had the highest energy consumption and GWP over the entire life cycle. The use phase of wood home - a continuous activity for 50 or more years - consumed 97 percent more energy than all the other phases combined. When compared to the manufacturing phase that consumes 18 percent of the total energy of an ICF home, the use phase environmental impacts of a wood home are significantly larger. When looking beyond energy and GWP, the impact assessment results from other categories (acidification, carcinogenics, non carcinogenics, respiratory effects, eutrophication, ecotoxicity, ozone depletion and smog) are ambiguous as ICF homes underperformed when compared with wood homes. But the top process contributors for the impact categories are not instinctively inferred. Process flows are interconnected and an insignificant process in global warming category might contribute heavily in ozone depletion. Tradeoffs are associated with every building product and perceptions about levels of environmental impacts of a product (for example, wood) can alter when the complete life cycle is studied. Applying several impact assessment methods and selecting different unit processes could lead to greater uncertainty. ICFs have the potential to reduce the energy consumption if adopted on a large scale but the tradeoffs associated with reduced energy consumption such as increased environmental impacts in other categories should be carefully considered.

The case study approached described above was used to create a residential framework for all the life cycle phases of a home. The case study demonstrated a systematic approach for conducting a LCA of a home built with traditional building materials and compared it with other new building materials. The raw materials extraction and manufacturing phase in the case study was modeled by creating new unit processes from existing databases through distributions or by adding specific manufacturer data. The transportation phase in the case study was modeled using standard truck dimensions, carrying capacity on a truck and their emissions obtained by using databases available. The construction phase for the case study was modeled in ATHENA. A residential home was modeled and only the construction data extracted. Similarly, the use phase was modeled using another tool called eQuest. A residential home was modeled for 50 years use and the energy consumption of the home extracted. A waste scenario was created for the building products used in a residential home for the end of life phase. The databases used were relevant to the case study and are only a snapshot of the variety of data sources available. The framework is a guideline provided for future residential LCAs unable to obtain case specific data. A step-by-step approach of how the framework can be used as a guide is provided below:

1. This research study benefited from the ICF manufacturer data and created a new unit process to model the raw materials extraction and manufacturing phase. Modeling the raw materials extraction and manufacturing phase and obtaining company specific data will improve the quality of the inventory.
2. Creating a distribution of the data obtained from different databases is also another recommended strategy that should be employed by future studies. The method of creating distributions will eliminate the necessity of selecting a single data source.

3. Modeling the transportation phase using data from Federal Highway Administration should be employed by future studies. By employing this strategy, the quantity of material that can be held in a truck can be estimated and the associated emissions quantified. Another approach is to utilize GREET database for modeling the transportation phase.
4. Using actual construction data to model the construction phase is the best strategy. Unavailability of construction data can prove as a hindrance to modeling this phase. Future studies can use ATHENA to model the construction phase in their LCAs as demonstrated in this research or preferably develop construction phase models.
5. This study modeled the use phase using the DOE freeware, eQuest. This tool allowed for changing the R-values for ICF homes, typically higher than traditional wood homes. Future residential LCAs should use eQuest or EnergyPlus to model the use phase when modifying insulation values are required.
6. While modeling the end of life phase, future disposal scenarios should be considered. Assumptions about how the reuse of certain materials will take place should be made. An example of how materials are disposed or reused is provided in this study and should be used as guide by future residential LCAs.

3.7 LIMITATIONS OF THE FRAMEWORK

The framework was created as a guideline for future residential LCA studies. The case study approach analyzed all the phases of a 2,450 square foot traditional wood home and compared it with an ICF home. But the following limitations need to be considered.

1. The functional unit of the study was a 2,450 square foot two story home in Pittsburgh. The results are based on the functional unit of the study. The same conclusions might not hold true if the location is changed or the functional unit altered to increase the number of floors in a home. The residential LCA framework can be used to study a different residential home but the ICF case study results are not scalable to a different functional unit.
2. Only ICF was used as a new building product in the home. There are a number of building products which have energy saving benefits but those products were not included as part of this study.
3. The transportation and end of life phases have minimal impact in the case study results. But since process flows are interconnected, it cannot be determined to exclude these phases in future studies based on the results of this case study. When the functional unit changes, the associated results will be altered too.
4. Only a residential home was modeled in the case study. Modeling a commercial building was beyond the scope of this study. The results of this case study cannot be implemented on a commercial building.

4.0 LIFE CYCLE ASSESSMENT EVALUATION OF GREEN PRODUCT LABELING SYSTEMS FOR RESIDENTIAL CONSTRUCTION

4.1 INTRODUCTION, MOTIVATION AND BACKGROUND

This chapter addresses research question 3. The *general* background and motivation are provided in chapter 2 while the literature *specific* to this research question is provided in this chapter.

Homeowners are key players in the residential building sector as they engage in a greater role in the decision making process regarding the location of project, type of construction, selection of building products and in the ultimate use of their homes (Martin, Swett et al. 2007). Adoption of emerging and novel products is higher amongst single family custom home builders, multifamily builders and national and regional builders when compared with other industries such as commercial builders (Koebel, Papadakis et al. 2004). A number of consumers are concerned with the environmental and social impacts of the products they purchase and often prefer to buy green (Construction 2010). But when it comes to actually selecting green products, consumers are uninformed about the products available and often question the reliability and quality over their traditional counterparts. Additionally, consumers are increasingly suspicious about the environmental claims of the manufacturer (Bonini and Oppenheim 2008).

While the green building materials industry has flourished, the labeling of green materials is disparate, confusing, and complex. Many certification programs are available for various products used in buildings such as Green Seal, Energy Star, the Carpet and Rug Institute green label, Blue Angel and many others (GreenSeal 2008; EPA and DOE 2009; CRI 2010; RALgGmbH 2010). Many labels are often based on single criteria and may be required by law, such as flammable and toxic, for a product (James 1997). Marketing schemes often involve product information with generic claims of environmentally safe, recyclable and biodegradable (Howett 1991).

Green labels are available for a variety of products used in buildings. The products evaluated for this research were carpets, paints and linoleum flooring. Homeowners are often concerned with the indoor environmental quality of their residences; carpets, paints and linoleum flooring are target products for improving air quality in homes. Thus these products were selected for further research. Further, the three different products (carpets, paints, linoleum flooring) have varied labeling systems with separate requirements for achieving the respective label.

Most labels are voluntary, third party certifications, which mean they require an impartial organization to review the products that willingly choose their label. Some labels establish minimum content or emissions requirement for certain compounds like volatile organic compounds (VOCs), formaldehyde and other harmful items, used either in manufacturing of the product or in some cases emitted when the product is in use. Some green labeling organizations like the National Sanitation Foundation (NSF) have various levels of labeling such as platinum, gold, and silver with platinum being the highest level a building product manufacturer can obtain and provide labels based on several criteria (NSF 2010). Table 7 provides a summary of the various labels available for carpets, paints and linoleum flooring.

Table 7: List of green labels and standards available for carpets, paints and linoleum

Label	Product	Attributes	Comments
Floorscore (RFCI 2010)	Linoleum flooring	IEQ	Single attribute label testing VOC based on California Specification 01350 (CalRecycle 2010)
Greenguard (Greenguard 2010)	Paints	IEQ	Single attribute label testing VOC based on California Specification 01350 (CalRecycle 2010)
Indoor advantage gold (SCS)	Paints	IEQ	Single attribute label testing VOC based on California Specification 01350 (CalRecycle 2010)
Green seal (GreenSeal 2008)	Paints	Reduced use of hazardous substances, low VOCs	Standard for paints which focuses on improving performance of products, reducing hazardous substances emissions and VOC emissions
Green label (CRI 2010)	Carpets	IEQ	Single attribute label testing VOC based on California Specification 01350 (CalRecycle 2010)
Recycled material content (SCS 2010)	Carpets	Recycled content	Single attribute label
California gold (DGS 2011)	Carpets	Public health and environment, renewable energy and energy efficiency, biobased or recycled materials, factory or company based manufacturing, end of life management	Point based standard with Gold and Platinum levels. LCA principles adopted based on the NSF/ANSI-140 2005 standard. Currently all carpet products under the standard need to achieve NSF-140 Platinum level.

Table 7 (continued)

Sustainable choice (SCS 2011)	Carpets	Public health and environment, renewable energy and energy efficiency, biobased or recycled materials, factory or company based manufacturing, end of life management, innovation	Based on the NSF/ANSI-140 2007 standard
NSF (NSF 2010)	Carpets	Public health and environment, renewable energy and energy efficiency, biobased or recycled materials, factory or company based manufacturing, end of life management, innovation	Point based standard with Silver, Gold and Platinum levels. LCA principles adopted based on the NSF/ANSI-140 2005 standard. Currently all carpet products under the standard need to achieve NSF-140 Platinum level.
Cradle to cradle (MBDC 2010)	Carpets, paints and linoleum flooring	Material health, material reutilization, renewable energy use, water stewardship, social responsibility	Certification consisting of four levels- Basic, Silver, Gold and Platinum. Follows LCA principles
Eco options (Depot 2010)	Carpets, paints and linoleum flooring	Must have less impact than conventional products	Program that accepts several other certifications
Environmentally preferable products (SCS 2011)	Carpets, paints and linoleum flooring	Variety of environmental impacts	Consistent with SCS-002, an emerging standard for LCA metrics and conforms with the ISO-14044 LCA standard (ISO 1997)
SMART (MTS 2010)	Carpets, paints and linoleum flooring	Reduction of pollutants, use of green e-power, post consumer recycled or biobased materials, reuse or product reclamation, equity for manufacturer and suppliers	Rating system with sustainable, Sustainable Silver, Sustainable Gold and Sustainable Platinum levels. Life cycle environmental performance requirements

Given the confusing labeling systems, the potential use of LCA, was investigated to guide the development of green building product labels. A major criterion of this analysis was using current, off-the-shelf LCA data tools. Using current data and tools was important, since we are at a critical point in the relationship between green building products (and labeling) and LCA. Basically, the green building market is growing (McGraw-Hill 2010), and it is important to understand if LCA is leading or following the market.

Tools such as LCA may help in overcoming some of the problems that created due to the increased construction activities of buildings, especially green buildings. Buildings provide an opportunity for reducing greenhouse gases. Of the total building stock of 300 billion square feet, annually 1.75 billion square feet is demolished and 5 billion square feet is renovated, and another 5 billion is newly constructed (Architecture2030 2009).

As previously mentioned, one LCA tool for selecting and evaluating products is BEES, created by National Institute of Standards and Technology (NIST) (Lippiatt and Boyles 2001). BEES has a database of 280 building products to assist in selecting cost-effective and potentially green products. The tool is primarily useful for evaluating products during the manufacturing stage and has limited information in other phases such as installation, use and maintenance.

Adopting an LCA based approach for labeling of green products has the potential to boost the confidence of consumers, ultimately leading to increased use of green products in residential buildings. In general, LCA is often accepted as a method, but data availability is lacking. The presence of a variety of databases with different assumptions, boundaries and location specific data leads to confusion about selection of appropriate data. The results of different LCA studies with diverse boundaries and assumptions lead to inconsistent results, causing doubts in the minds of the consumer about the authenticity of the products' green claims. This research question examined: labels, LCA method, and current databases. Further, this research investigated if by using LCA, it could be elucidated whether a product labeled "green" was truly green when compared with its traditional counterpart.

For this research, the previously developed life cycle framework for residential structures was used (Rajagopalan, Bilec et al. 2010). The life cycle results for generic and green labeled building products of carpets, paint and linoleum flooring was analyzed to determine how effective LCA is in evaluating the products. Further, LCIs for the products were developed from different databases in order to evaluate the effect of different data sources on the resulting greenness of the products (e.g. ecoinvent (Frischknecht 2005) and environmental product declarations).

4.2 METHOD

This study used publicly available databases and tools to analyze various products and compare their LCA results. Generic and green labeled products were selected from BEES and comparative LCAs were performed to analyze if the products were deemed green or not.

The green product labeling grid developed by the Green Building Alliance (GBA) was used as a key to identify labels and corresponding products (GBA 2010). The green product labeling grid lists many labels and certifications available for building products. Selection of products under consideration were based on several factors: (1) robustness of labeling system (e.g., multi- or single attribute, number of registered products), (2) current LCA data for a given green and traditional product, and (3) relevance to residential market place. For example, carpets have two or more labels available: Green Label/Green Label Plus and NSF-140 for carpets. Green Label/Green Label Plus focuses only on a single attribute (indoor environmental quality) for awarding labels to the products while NSF-140 is a multi attribute standard. The main focus of single attribute labels for carpets is indoor environmental quality while the multi attribute standard follows LCA principles in its labeling process. The LCA data availability for carpets lead to choose BEES database. Based on these factors, the products were selected for analysis and shown in Table 8, column 1.

To evaluate the greenness of the product with LCA, data for the building product was obtained from the LCA database, BEES, a collection of product data obtained directly from manufacturers. Some manufacturers obtain green labels for their products and share their green labeled product data. Such green labeled products were compared with generic products available in BEES. When green labeled products manufactured by renowned manufacturers was not available, green products were selected on the basis of recycled content in the product based on the assumption that products with recycled content utilize less virgin materials and are generally considered green.

Once the carpets, paints and linoleum flooring were selected, one square foot gate-to-gate LCAs of the products was performed using BEES and the results between generic and green labeled products compared.

The next step was to include these building products in a home and to compare them on a whole home level instead of product level to determine the relative LCA impacts. From research question one, the results were used. Gate-to-gate LCAs on one square foot of carpets, paints and linoleum flooring was converted to 2,450 square foot home LCAs by calculating the product impacts on a 2,450 two storey home and adding the whole home impacts calculated by Rajagopalan et al (2010) to the product impacts.

Finally, results were compared with other data sources of Interface Environmental Product Declarations (EPD) (TheGreenStandard.com 2010) and ecoinvent (Frischknecht 2005) to evaluate how the green labeled products weighed against products from other data sources. The products selected for comparison are discussed below in detail, and Table 8 shows the products and databases utilized to construct LCIs.

4.2.1 *Building Product Description*

4.2.1.1 Carpets

BEES data was utilized to develop the LCA for generic and green carpet tiles. The carpet tile products selected were an anonymous carpet tile (environmental code: C3020S), Bentley Prince Street’s BPS UPC carpet tile (environmental code: C3020VV), C&A ER3 modular tile (environmental code C3020X) and C&A Ethos modular tile (environmental code C3020Z). These aforementioned products referred to as “generic” for anonymous carpet tile and “green” carpet tile respectively for the other three carpet products were compared for their environmental performance based on one square foot of material. The boundary for the “green” BPS UPC carpet tile inventory included the manufacturing phase, transportation of materials from manufacturing plant to construction site, use of carpet tile with a lifetime of 15 years and replaced 3 times over a 50 year use period of a home and the end of life with almost 12.5 percent of old carpet tiles reclaimed. The use of carpet tile was included in the inventory for the additional materials manufactured due to replacements. No actual emissions were included from the use phase. BEES did not provide information for the anonymous “generic” carpet tile with respect to system boundary, data and the life cycle phases included. All the products manufactured by BPS are certified to meet the Carpet and Rug Institute’s Green Label Plus and all products also achieve the NSF-140 Sustainable Carpet Assessment Standard at the Platinum level according to the BPS website (BPS 2010).

The boundary for the “green” C&A ER3 and Ethos modular tiles inventory included the manufacturing, transportation of materials from manufacturing plant, use of carpet with a lifetime of 15 years and end of life with 100 percent recyclable in the company’s in-house recycling process. The products manufactured by the manufacturer are certified with Green Label Plus and the products also achieve the NSF-140 Sustainable Carpet Standard (Tandus 2011).

For comparing BEES data with other sources, EPD for Interface carpets was used (TheGreenStandard.com 2010). All products manufactured by the company obtain the Green Label/Green Label Plus and NSF-140 labels (Interface 2010). The Interface EPD uses a life cycle approach to analyze one square meter of carpet. The EPD LCIA results were analyzed using TRACI and CML 2002 environmental impact methods (CML 2010).

4.2.1.2 Paints

The LCI for the paint products were obtained from BEES and evaluated on a functional unit of one square foot of paint for interior walls. The paint products compared were generic virgin latex paint (environmental code: C3012A), generic consolidated latex paint (C3012B), generic reprocessed latex paint (C3012C). The first product, generic virgin latex paint is made with virgin materials while the rest have recycled and post-consumer inputs in their manufacturing processes. The products are referred to as generic, green reprocessed (76 percent post consumer (PC)) and green consolidated (99 percent PC) latex paint. The LCI phases included were raw materials extraction, manufacturing, transportation and use. For the end of life, the paint was disposed in a landfill along with the surface it was painted on. During the use phase, the assumption of repainting every four years was made thus leading to 12 additional coats for a lifetime of 50 years of a home. The use phase data was included in the inventory for calculating the additional paints manufactured due to repainting. No use phase emission was included.

The generic virgin latex paint was compared with paint product from ecoinvent (Frischknecht 2005). The paint product selected for comparison was alkyl paint with 60 percent water. Due to unavailability of data for a direct water based paint comparison, the available data from ecoinvent was used. The LCIA results using TRACI for alkyl paint was compared with the generic virgin latex paint.

4.2.1.3 Linoleum flooring

Product level assessments (only the manufacturing, transportation, construction and end of life of the product is considered) of linoleum flooring were conducted using the linoleum flooring options available in BEES. The products compared were generic linoleum flooring (environmental code: C3020B) and Forbo linoleum flooring (environmental code: C3020R). Forbo linoleum flooring has the Floorscore label (RFCI).The phases included in the LCA of one square foot of flooring were raw materials extraction, manufacturing, and transportation and use phase. For the end of life, it was assumed that linoleum was transferred to a landfill. The use phase was utilized as a guide to calculate the extra material manufactured due to replacement of linoleum flooring over its lifetime. No use phase emissions were included.

Three products with a variety of labels and data sources are discussed in the methods section. Table 8 provides a list of all the products, green labels and data sources discussed for this research question. The columns 1-6 in the table give a list of products selected for this study, their associated labels, data sources and their greenness based on LCA results.

Table 8: Building products description and the databases selected

	Product (1)	Green Certified (2)	Green Labels (3)	Criteria and Method (4)	Data Source (5)	Is it green based on LCA results (6)
Carpets	Anonymous (generic) carpet tile	No	-	-	BEES (Lippiatt and Boyles 2001)	No except in eutrophication, fossil fuel depletion and water intake
	BPS UPC (green) carpet tile	Yes	Green Label/Green Label Plus, NSF-140 (CRI 2010; NSF 2010)	Green label is single attribute (IEQ) with no LCA component while NSF-140 is a multi attribute carpet standard		Yes except in water intake, fossil fuel depletion and water intake
	C&A ER3 (green) modular tile	Yes	Green Label/Green Label Plus, NSF-140 (CRI 2010; NSF 2010)	Green label is single attribute (IEQ) with no LCA component while NSF-140 is a multi attribute carpet standard		Yes except in human health cancer and noncancer
	C&A Ethos (green) modular tile	Yes	Green Label/Green Label Plus, NSF-140 (CRI 2010; NSF 2010)	Green label is single attribute (IEQ) with no LCA component while NSF-140 is a multi attribute carpet standard		Yes
	Interface carpets	Yes	Green Label/Green Label Plus, NSF-140 (CRI 2010; NSF 2010)	Green label is single attribute (IEQ) with no LCA component while NSF-140 is a multi attribute carpet standard	Interface EPD (TheGreenStandard.com 2010)	Yes

Table 8 (continued)

Paint	Generic latex paint	No	-	-	BEES (Lippiatt and Boyles 2001)	No
	Generic reprocessed (76 percent PC) latex paint	No	-	Recycled content		Yes except in global warming, indoor air quality and smog
	Generic consolidated (99 percent PC) latex paint	No	-	Recycled content		Yes except in indoor air quality and smog
	Alkyl paint with 60 percent water	No	-	-	ecoinvent (Frischknecht 2005)	Yes
Linoleum flooring	Generic linoleum flooring	No	-	-	BEES (Lippiatt and Boyles 2001)	No except in human health-cancer
	Forbo linoleum flooring	Yes	SMART (MTS 2010)	Multi attribute (IEQ) with LCA component		Yes except in human health-cancer

4.3 RESULTS

For all products evaluated, the LCA results were normalized to the maximum contributor in each impact category (Figure 6, Figure 7 and Figure 8). The comparative results of generic and green carpet tiles showed that the green carpet tile was more environmentally preferable than the generic carpet tile in all impact categories except eutrophication, fossil fuel depletion, water intake and human health (Figure 6). All carpet tiles had similar impact in the indoor air quality category; this result was surprising given that indoor air quality, here measured as VOC emissions, was a significant attribute of a green carpet. The BEES database does not provide information on the generic carpet tile but the Bentley Prince Street carpet manufacturers and the C&A carpet manufacturers supplied data for the green carpet tile.

Generally, the fossil fuel depletion profiles of products were expected to parallel global warming. But these results were contradictory to this premise. The inventory obtained showed that the BPS UPC green carpet tile had higher total fossil fuel depletion (11.2 MJ) when compared with the generic carpet tile (7.01 MJ). But the carbon dioxide (CO_2) emissions from fossil fuel depletion did not follow this trend. The BPS UPC green carpet tile had slightly lower fossil CO_2 emissions (4.3 kg) as opposed to the generic carpet tile (5.3 kg). The C&A green carpet tiles had lower fossil fuel depletion and low global warming potential as was expected. According to the BEES manual, fuel extraction process was not included in the fossil fuel depletion category but it was captured in the global warming category and the fossil fuel depletion category only represented the quantity of fuel extracted while the characterization factors remained constant for the fuel. Based on this information, the fossil fuel depletion for the generic carpet tiles was lower because it used larger quantities of coal whose characterization factors was lower (0.25 MJ/kg) and the BPS UPC green carpet tile used higher quantities of natural gas and oil whose characterization factors were higher (7.8 MJ/kg and 6.12 MJ/kg).

Other inconsistencies between green and non-green products in results occured in the water intake category where green carpet tiles have higher impacts than the generic carpet tiles. This impact category was not characterized through the TRACI impact assessment method but represented direct inventory water use. The inventory showed that the BPS UPC green carpet tile used approximately 40 times more water and the C&A green carpet tiles used 5 times more water than the generic carpet tile. No justification was provided in the BEES LCI about the data presented.

The BEES weighting system did not have a significant impact on the results. To understand the effects of weighting on the results, a comparison was conducted by changing the BEES weighting system to no weighting, EPA scientific advisory board weighting, and a user defined weighting to analyze the difference in the results. The results changed less than one percent in each category when the weighting system was changed from BEES stakeholder panel to EPA scientific advisory board weighting and no change was observed when the user defined weighting system was used.

For paints, the normalized environmental impacts (Figure 7) of generic latex paint were higher than the other two products when one square foot of wall paint was the functional unit in all impact categories except global warming where green latex paint with 76 percent PC materials had the highest impact. The green latex paint might be perceived to have lower impacts especially in global warming but the results showed otherwise. This disparity was caused by the manufacturing process for the green paint with PC products which was different from the paint made with virgin materials. The perception that paint with 99 percent PC materials will have lower impacts than paint with lower percent of PC materials was inconsistent with respect to global warming. The counterintuitive results for paints in the fossil fuel depletion and global warming categories were consistent with the carpet tiles results. Here again, changing the weighting did not change the results significantly.

In the case of linoleum flooring, green linoleum flooring performed better in all categories except human health cancer (Figure 8). Notably, there was an insignificant difference between green and generic linoleum flooring in smog and water intake categories. The counterintuitive trends seen for carpets and paints in the fossil fuel depletion and global warming categories were not observed in linoleum flooring.

Next, the relative importance of green products in the overall life cycle of a residential home was examined. For carpets, the one square foot results were scaled up to the total carpet area required for a 2,450 square foot home and the LCA results of carpet tiles were added to the LCA results of a whole home using the aforementioned residential life cycle study. Similarly, for paint and linoleum flooring, the functional units were scaled up to a whole home and added to the residential life cycle model. The comparisons of the carpet tiles assessed from the perspective of a whole house showed that the impacts of carpets are overshadowed by the use phase of the entire house; as shown in Table 9, the GWP of carpets contributed less than one percent to the total GWP of the house. Similar impacts were noticed in the smog impacts (Table 9) where the impact of all building products was less than one percent to the total home smog impacts. Only two categories (global warming and smog) were illustrated as representative of the entire home impacts.

The impacts of flooring were also insignificant when compared to the impacts of the entire home. The use phase of an entire home dominated over the life cycle of specific products such as carpet tiles, paints and linoleum flooring.

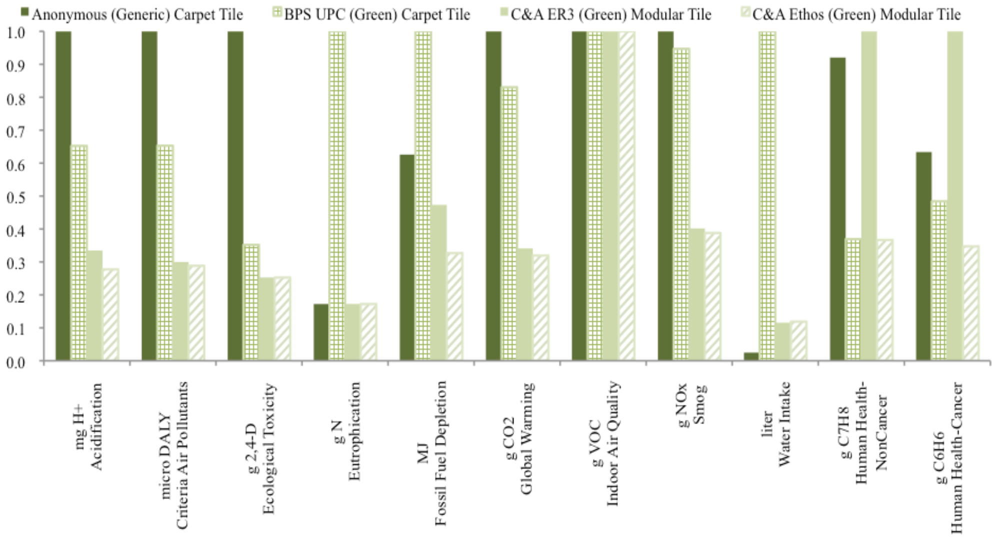

Figure 6: Comparative normalized environmental impacts of generic and green carpet tiles using BEES. Data obtained from BEES is for 1 square foot functional unit and no modifications have been made to the data presented here.

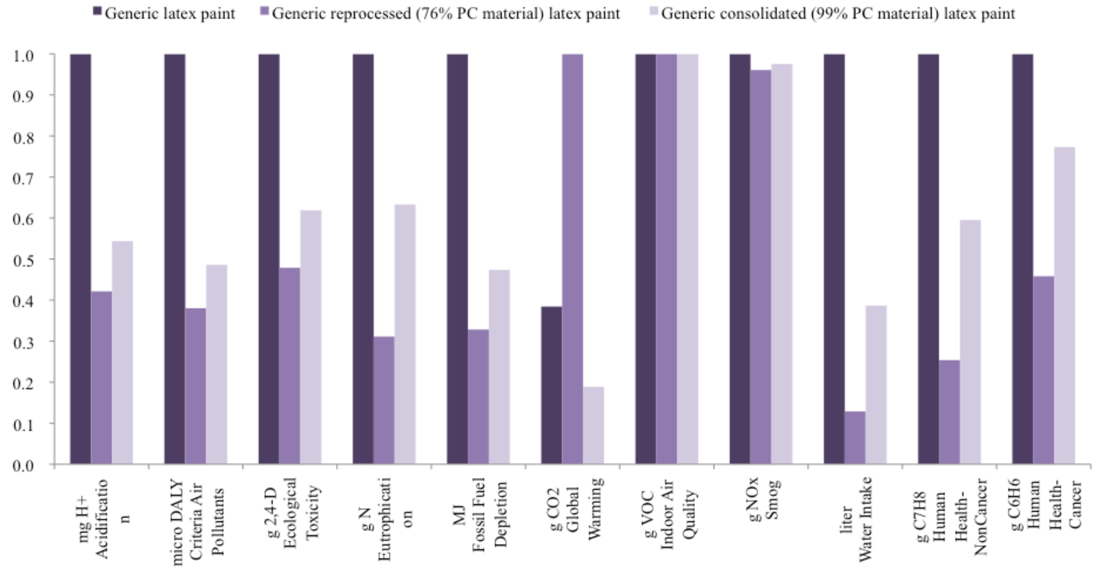

Figure 7: Comparative normalized environmental impacts of generic and green post consumer (PC) latex paint using BEES. Data obtained from BEES is for 1 square foot functional unit and no modifications have been made to the data presented here.

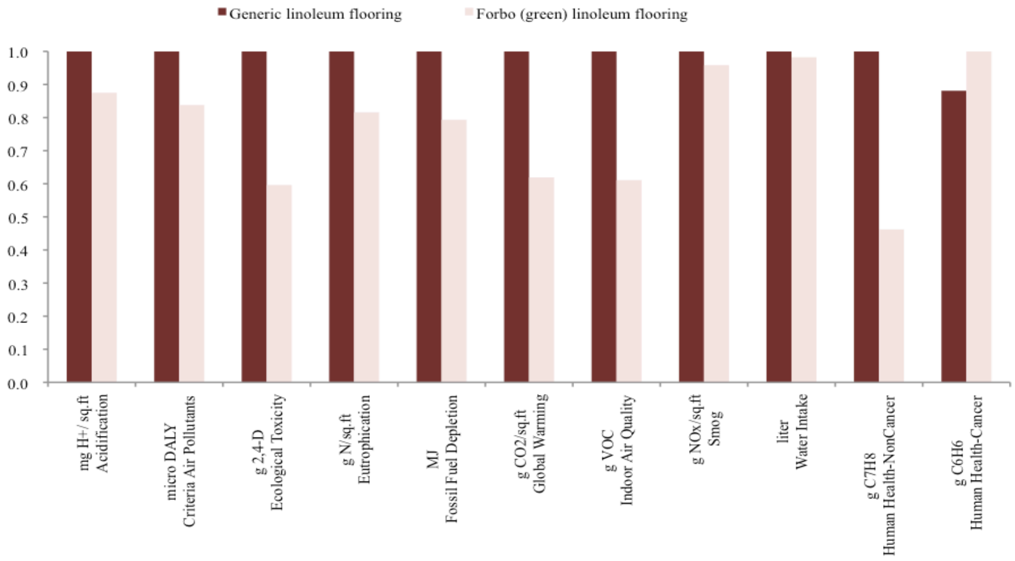

Figure 8: Comparative normalized environmental impacts of generic and green linoleum flooring using BEES. Data obtained from BEES is for 1 square foot functional unit and no modifications have been made to the data presented here.

When the products were compared on an individual basis, for example, when generic carpet tile was compared with a green carpet tile, the impacts of generic carpet tile were higher. But when the impacts were scaled up to the whole home, the home impacts were two to five orders of magnitude higher than the building product impacts. The use phase impacts of a whole home overshadowed the building product impacts. The results are shown in Table 9 where the impacts of the building products had negligible impacts in comparison to the impacts of the home. Global warming and smog impacts are shown in Table 9 while the other impacts are shown in Appendix A (Figure 13- Figure 17). Only two impacts are shown here as representative of the minimal impacts of building product additions to home. The appendix shows the rest of the minimal impacts from addition of building products. Table 10 is read from left to right for interpreting the global warming impacts of building product additions to a whole home. The traditional wood home impacts increase minimally diagonally when building products are added. Similarly for the smog impacts, reading should be done from top right to bottom left to decipher the building product additional smog impacts from a home.

The BEES database provides only one data point for comparing green and non-green products. A comparison of results was performed to illustrate the differences in the LCA data from other databases. Since a variety of databases were used, only acidification, eutrophication, global warming and smog categories could be compared across the products as these were the only common categories. The results in Figure 9 were normalized to the highest value from a database in the impact category for a product. For comparing carpet results, Environmental Product Declarations (EPD) by carpet manufacturing companies such as Interface was used (TheGreenStandard.com 2010). For paint, the comparison was performed using data from other databases such as ecoinvent (Frischknecht 2005). The BEES data for carpet tiles was provided by Bentley Prince, a sister company of Interface Carpets. The data may not be comparable for both products as they are not exactly the same, but other data was not available.

The BEES database and Interface EPD had similar results for acidification, eutrophication and global warming categories. But the smog result from Interface was insignificant when compared with the BEES data for carpet tiles. Differences in manufacturing process may lead to higher or lower impacts in the categories but both the data points had dissimilar results in smog whereas other impact categories correlate.

Table 9: Comparative life cycle global warming and smog impacts of a traditional wood home fitted with various building products. The boxes shaded dark correspond to the global warming impacts of a home with various additions and the light shaded boxes correspond to the smog impacts of a home due to building product additions

Building Product Additions to an entire home	**Life cycle global warming impacts (kg CO_2 eq.)**							
	Traditional wood home	Generic carpet tile	Green carpet tile	Generic linoleum flooring	Green linoleum flooring	Generic virgin latex paint	Generic consolidated latex paint	Generic reprocessed latex paint
No additions	810,000							2,700
Generic carpet tile		814,200					2,717	
Green carpet tile			813,500			2,716		
Generic linoleum flooring				810,700	2,709			
Green linoleum flooring				2,708	810,430			
Generic virgin latex paint			2,700			810,002		
Generic consolidated latex paint		2,700					810,001	
Generic reprocessed latex paint	2,700							810,000
	Generic reprocessed latex paint	Generic consolidated latex paint	Generic virgin latex paint	Green linoleum flooring	Generic linoleum flooring	Green carpet tile	Generic carpet tile	Traditional wood home
	Life cycle smog impacts (kg NO_xeq.)							

For paints, the data available yielded unequal comparison. As the analysis shows, the ecoinvent data had insignificant impacts in all categories compared. Insufficient data prohibited additional data points for comparisons for both paints and carpets. In the previous chapter, it was shown how unrelated and isolated processes contributed the maximum to a unit process and caused ambiguity in the LCA results. An approach where every process can be modeled and the whole process diagram of a product can be controlled needs to be built-in to every database.

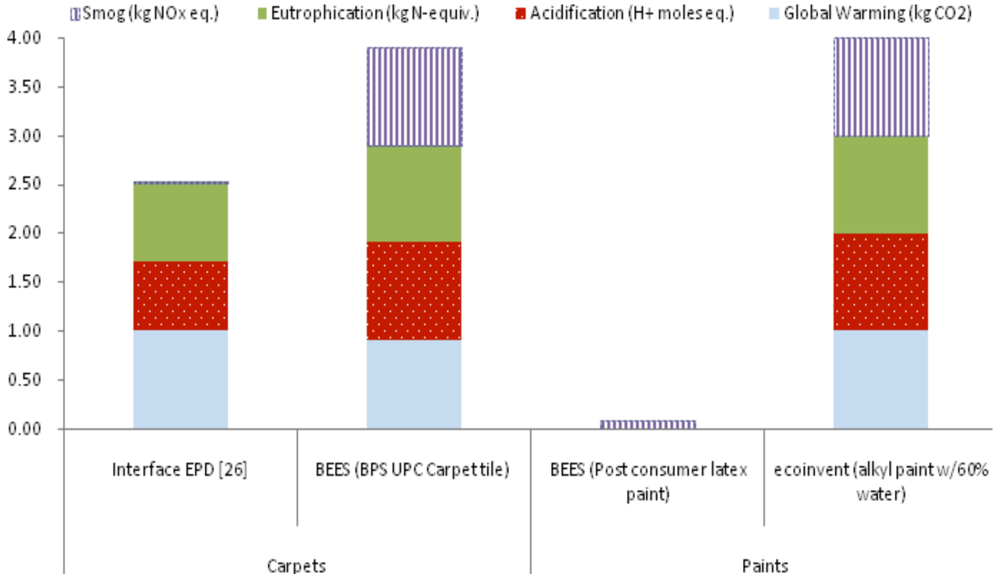

Figure 9: Normalized results for impact categories with data accessed from separate databases for carpets and paints. The results are normalized to the highest impact value from a database of the product

4.4 DISCUSSION

Life cycle thinking, in theory, has the potential to guide the development of green product labeling systems, but current state of LCA leads to results that are uncertain and strongly dependent upon the source or database. Inconsistencies in the data and missing impact categories add to the ambiguity in LCA results. While life cycle thinking in concept can improve green labeling systems, LCA data is lacking. For example, the products discussed herein were selected on the basis of labeling systems (e.g. Green Label Plus for carpets, a single attribute label), their relevance to the residential building sector, and availability of data in the current LCA databases. The LCA results had inconsistencies in several impact categories such as fossil fuel depletion, global warming, indoor air quality, and water intake. The green products, even though labeled green by single and multi-attribute labels and standards, did not always have lower impacts than its non-green counterparts. As already shown in Table 7 several standards use a life cycle approach but the fact remains that the current databases available for LCA do not provide a consistent labeling platform.

Green products will be used in a building, and when compared to the whole life cycle building impacts, many of the product impacts are minimal, but are still a part of the entire life cycle and should not be discounted. Some of the most toxic or human health impacts can occur during the manufacturing phase, while the energy use and associated greenhouse gases occur during the use phase. Therefore, all categories and all phases need to be considered to provide a complete picture of the product impacts. Product level/cradle-to-gate LCAs are an important part in understanding the product as a whole but a move towards systems level LCAs for labeling will help in incorporating all aspects of the product such as the manufacturing of the product itself and its use in a building and its disposal or reuse along with other building products.

4.5 CONCLUSION

LCA data and tools need to improve to parallel or exceed market trends. Further, LCAs results vary depending on the boundary, database and functional unit selected, and the filtering of the inventories and impact assessment methods takes a considerable amount of time, which the average homeowner (or designer) typically lacks. Statistical models that address the uncertainty associated with data should be incorporated into the labeling process. Decision makers are concerned with the possible ranges of outcomes for their actions (Sugiyama, Fukushima et al. 2005). Including uncertainty into the LCI process may help in the understanding the green claims of a product.

To incorporate LCA based labeling, more detailed information about the variety of building products and their manufacturing process needs to be documented. Improving the quality of data will help in reducing uncertainty in the labeling system. A move towards ISO 14001 standards for labeling was studied previously and it was found that having an ISO standard instead of an ecolabel does not oversimplify the product and provides room for changes and alterations in the future, thus using a holistic approach (Ball 2002).

Revamping the entire labeling process is an exercise which will lead to a lot of confusion owing to the use of labeled products in several buildings. But inclusion of LCA in the labeling process, as already discussed, is a good practice. The following changes are recommended to improve the labeling systems for building products:

1. A label should at the least be a multi-attribute label with an LCA component in the labeling process. There are already some standards which are multi-attribute and it is recommended that all green labels adopt the standard for their labeling process.
2. The LCA results are an important part of the labeling process and they should be accessible to all consumers. The system boundaries, databases used, the assumptions made to conduct the LCA and an explanation of the results should be transparent and accessible. Providing all information to the consumer is an important step in improving the labeling process.
3. LCA signage similar to the one proposed in Table 8, column 6 will provide information on the advantages and disadvantages of the product and the consumer can decide on the product of their choice based on their preferences. Improving the databases will eliminate conflicting results obtained from different sources.

A transparent labeling process will prevent doubts about green claims made by the manufacturer and help in providing more information to the consumer, the decision maker in the purchase of green products.

5.0 EVALUATION OF ENERGY SAVINGS POTENTIAL OF GREEN BUILDING PRODUCTS

5.1 INTRODUCTION

This chapter addresses the research question 4. The *general* background is provided in chapter 2 and literature *specific* to this research question is addressed in this chapter.

The greenhouse gas emissions from the building sector in 2004 were in the order of 8.6 gigatons (Gt) CO_2, 0.1 Gt CO_2eq-N_2O, 0.4 Gt CO_2eq-CH_4, and 1.5 Gt CO_2eq-halocarbons. The projections for CO_2 emissions from this sector in 2020 and 2030 are 11.1 Gt and 14.3 Gt respectively (IPCC 2007).

In this chapter, the focus is on the residential energy consumption as the residential energy sector alone used 40 percent of the total energy produced in 2007 in US (USCB 2009). Residential energy consumption is expected to grow by 27 percent from 2001 to 2025 (EIA 2003). Increased use of electricity is one of the major reasons for growth of energy demand. The end-use electricity consumption in 2001 for the residential sector was 16 percent for air conditioning and 10 percent for space heating (EIA 2001).

Reductions in energy use per square foot can be obtained from more efficient building designs, better insulation and more stringent building codes. Space heating is the most energy intensive phase in the residential building. Increasing the efficiency of the *building shell* is projected to reduce the energy demand by 9 percent per household by 2025 (EIA 2003). Several federal programs like Zero Energy Home which promote the increase in efficiency of building envelope components are projected to reduce heating requirements in an average new home by 60 percent (EIA 2008).

Heating and cooling energy consumption is dependent on various factors like building shell characteristics, HVAC efficiency, occupants' behavior, climate and the energy prices. Heating and cooling together account for 30 percent of the electricity, 70 percent of the gas consumption, and 90 percent of the oil consumption in the US (Koomey 1991a).

5.1.1 Goal

Reports published by McKinsey and Company and Architecture 2030 (Creyts, Derkach et al. 2007; Architecture2030 2009) have established guidelines for reducing energy consumption in buildings. Both reports address the need for action against rising greenhouse gases (GHG) emissions. While Architecture 2030 focuses specifically on buildings, the McKinsey report sets targets for buildings, electronics, and other energy-consuming infrastructure. The McKinsey report states that new shell improvements in residential buildings will reduce 0.7-0.9 Gt CO_2 per year. The report provides a number of options such as lighting retrofits, improving heating, ventilation and air conditioning (HVAC) systems, building envelopes and building control systems to achieve the carbon reductions stated.

The Architecture 2030 Challenge sets a target for new buildings, developments and major renovations to achieve energy consumption standard of 60 percent below the regional (or country) average for that building type. The fossil fuel energy reduction targets for all new buildings are 70 percent by 2015, 80 percent by 2020, 90 percent in 2025 and carbon neutral by 2030. The strategies suggested in the report to meet this challenge are appropriate planning and passive design, improved material selection, building envelope design, more efficient lighting, equipment and appliances and on-site and community scale renewable energy technologies.

While both reports suggest numerous strategies for reducing energy consumptions in buildings, *improving the building envelope in new residential construction* is the focus of this research. The research shown in earlier chapters illustrate the energy saving capabilities of a new building product called insulating concrete form (ICF). In this chapter, the benefits of using the new building product along with other energy saving products such as windows used in the projected new residential buildings stock will be evaluated at a national level. Replacing doors and windows has been de-emphasized in the Weatherization Assistance Program (WAP), a program to increase energy efficiency in low-income homes (USDOE 2011) but this strategy is a fairly simple exercise which may help reduce energy consumption in newly built homes by selection of appropriate energy saving products. Homeowners, the decision makers in the residential sector prefer to invest in green, energy saving building products and materials (Koebel, Papadakis et al. 2004; Martin, Swett et al. 2007) . Thus, even though there are a number of strategies, which can be used in reducing energy consumption in homes, this chapter focuses on new building products for wall sections and windows.

This chapter aims to quantify the national energy savings potential of green building products with a focus on the building's envelope. The energy savings achieved by using the product nationally are calculated and compared with targets set by the McKinsey report and Architecture 2030 (Creyts, Derkach et al. 2007; Architecture2030 2009).

5.2 BUILDING PRODUCTS DESCRIPTION

5.2.1 Insulating concrete forms

Air infiltration in an ICF home is low because of the two layers-one of the insulating polystyrene and second; the concrete layer prevents the entry of air. An increased 5 percent to 9 percent energy savings can be achieved in every single-family house with the use of ICFs in residential homes (Gajda and VanGeem 2000). New housing has a greater need for heating and cooling as they are larger than the current housing by about 18 percent (EIA 2003). The projected energy demand increases call for newer building shell efficiencies that can be addressed by ICF. Using ICFs can reduce the lifetime energy costs in the building thus reducing the national demand.

5.2.2 Windows

Other strategies studied were the use of double and triple glazing windows in homes instead of single glazing. A previous LCA study on window systems showed that even though the environmental impacts of advanced glazing systems is high, the energy reduction gains from the use of such products is too great to be disregarded (Citherlet, Di Guglielmo et al. 2000) . Another study found that windows filled with argon as the inert material had lower embodied energy that other materials and will allow for lower heat transfer (Weir 1998; Weir and Muneer 1998).

5.2.3 Doors

Replacing doors was another strategy studied. Solid core flush was selected as the replacement door. This strategy was applied in all the new residential construction in the US.

5.3 METHOD

A baseline case energy modeling was performed for the residential sector in eQuest (DOE2.com 2009). According to the National Association of Home Builders (NAHB), the average home size in 2010 was 2,438 square feet (NAHB 2011). Thus, a 2,450 square feet house made of wood with single glazing windows was chosen as a model case for residential sector.

The baseline case for the house was made of wood with single glazing windows. Various scenarios were modeled in eQuest by varying the wall sections to ICFs and changing the windows to double and triple glazing. Table 10 below shows the scenarios that were modeled in the single-family double storey 2,450 square foot home.

Table 10: Energy saving strategies implemented on a 2,450 square feet home

Strategies	Assembly R-value	Total energy consumed per year (MBtu)	CO_2 generated per year (tons)
Single glazing window	18	352	21
Double glazing window	21	315	19
Triple glazing window	27	273	16
Replacing exterior walls with ICF panels and single glazing windows	46	208	12
Replacing exterior walls with ICF panels and double glazing windows	49	202	12
Replacing exterior walls with ICF panels and triple glazing windows	55	194	11
Replacing basement walls with ICF and retaining double glazing windows	46	274	16
Replacing basement walls with ICF and retaining triple glazing windows	52	231	14
Replacing door with solid core flush (1 ¾”)	21	318	17

The historic data of new single family homes constructed in the US was obtained from United States Census Bureau data (USCB 2009). All new single family homes constructed were assumed to be 2,450 square foot two storey single family homes. The data obtained from the new construction was from 1969 to 2008. Historic data for natural gas and electricity consumption for homes was obtained from 1969 to 2007 from the United States Department of Energy (DOE)

(USDOE 2009). The CO_2 emissions from total energy consumed in homes was obtained from the emissions from natural gas and electricity consumption in new residential homes. The electricity consumption is assumed to be 45 percent coal and 23 percent natural gas. All the data was projected to 2050 using Crystal Ball (Oracle 2010), a spreadsheet based software package for forecasting and optimization. Crystal Ball is a tool widely used in engineering and research for various statistical analyses. The Predictor tool in Crystal Ball was used to forecast the historic data (1969 to 2008) for the new construction, natural gas and electricity consumption and their unit prices. The tool forecasts data based on the historic data and provides eight standard time-series forecasting methods: single moving average, single exponential smoothing, seasonal additive, seasonal multiplicative, double moving average, double exponential smoothing, Holt-Winters' additive and Holt-Winters' multiplicative. The historic data was used to create a double moving average time-series (a method which takes one time-series and transforms it into another time-series by taking averages of several sequential values of the first series) with a 95 percent confidence interval. This method was selected because of the best forecasting results obtained as compared to the other methods. The forecasting results were used to calculate the CO_2 abatement potential of each strategy shown in Figure 10.

The energy reductions obtained by using ICFs, double and triple glazing windows (41 percent, 10 percent and 22 percent respectively) as compared to a wood home with single glazing windows were then multiplied with the traditional wood home energy consumption and the corresponding CO_2 emissions obtained in each category.

Payback period was also calculated to assess the relative merits of utilizing one strategy over the other. An initial investment on each of the strategies was obtained based on average investment costs on a wood home, ICF home, and replacing windows and doors. The investment on a 2,450 square foot home in Pittsburgh was obtained from the national average for homes (Mewis 2011). ICF homes were assumed to cost 5 percent more than traditional wood homes. The simple payback period was calculated by dividing the annual energy consumption from the initial investment on the strategies.

5.4 RESULTS

Figure 10 shows the energy reductions observed when the strategies were applied and how they compare with the McKinsey goals. To amplify the projected energy reduction scenarios, only the years from 2008 onwards are illustrated in the figure.

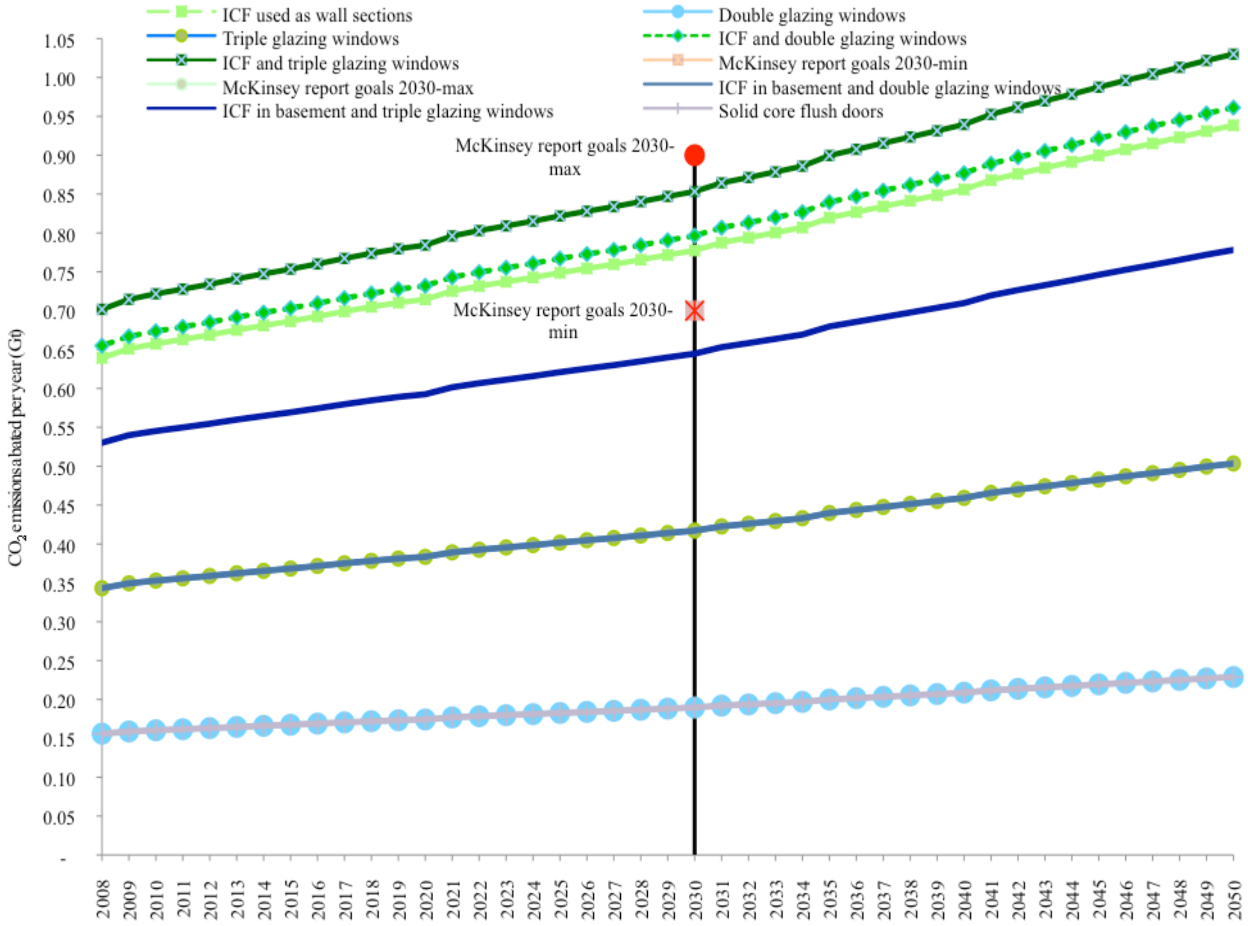

Figure 10: Energy reduction scenarios projected till 2050 and compared with the McKinsey goals

The results show that implementing only door and window replacements as energy saving strategies will not help in achieving the McKinsey abatement goals. But using ICFs in all homes combined with double and triple glazing windows will achieve the abatement goal. All strategies involving ICF in the entire home with window changes are in the range of the abatement CO_2 emissions goal.

Other strategies were modeled in a single home to simulate the real world. The use of ICF walls in the basement along with window replacements is a scenario applicable in most homes. The results show that implementing this change in new homes will be closer to the McKinsey report goals but still falls short of the minimum range.

The energy consumption of the scenarios discussed was compared to the national average energy consumption of 2,400-2,499 square foot homes. A single family home consumes 1.3 GJ of energy per square meter annually (Keoleian, Blanchard et al. 2000). Thus, a 2,450 square foot home consumes 296 GJ of energy annually. The Architecture 2030 goal of achieving 60 percent energy consumption of the national average was then compared with energy consumption per year of the scenarios (Figure 11).

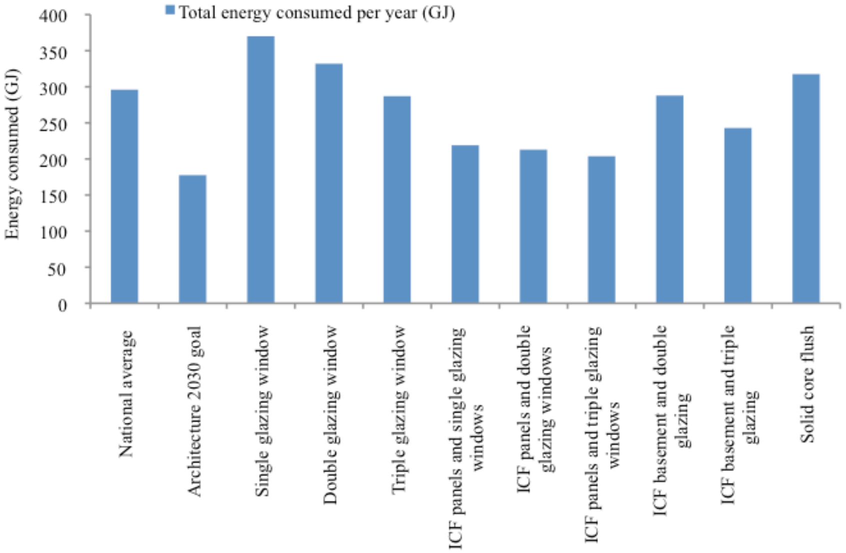

Figure 11: Performance of energy saving scenarios in homes when compared to the national average and Architecture 2030 goal

The payback period results compared with the energy consumption of the home is shown in Figure 12. The results showed that as the energy savings increased, the payback period increased. This is consistent with the findings of Keoleian et al (2000) that showed that even with an increase of 9.5 percent in life cycle cost of energy saving strategy, the payback period increases to 35 years in new building constructions. Soratana and Marriott (2010) studied the possibility of recovering energy savings in existing buildings, also concluding that as costs of energy saving strategies increased, the payback period became longer.

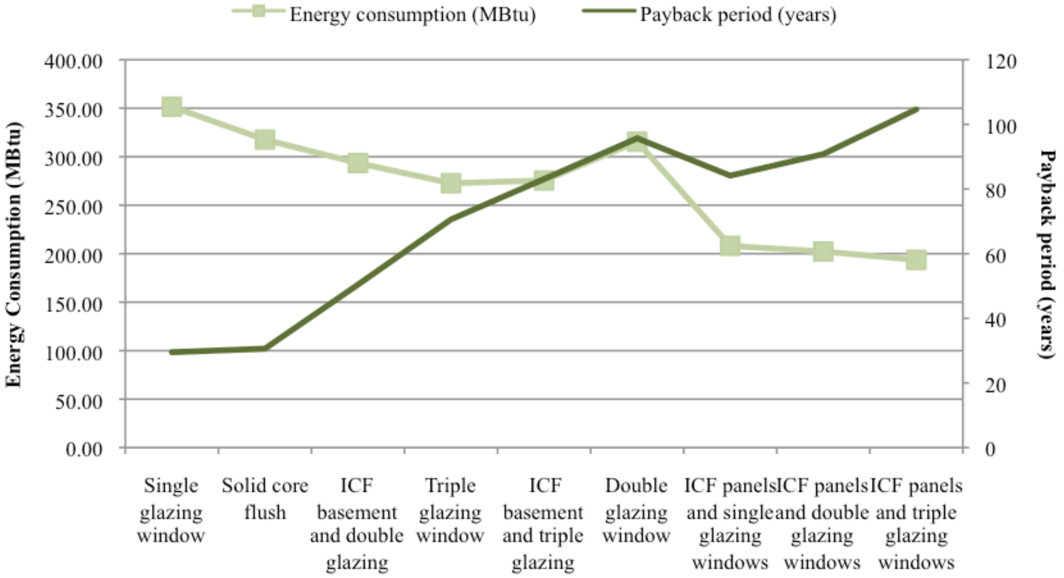

Figure 12: Energy consumption and payback periods of the energy saving strategies discussed

5.5 DISCUSSION

The results show the energy savings benefits of a green building product like ICF. The average values of ICF energy savings obtained from literature are obtained from energy modeling case studies. The scenarios modeled in this case study are a reflection of conditions in the Pittsburgh region. A detailed modeling scenario in which ICF can be modeled in various regions and a range of energy savings can be obtained is necessary.

All the results presented are based on the assumption of new residential buildings construction adopting building products such as ICFs in large numbers. The variety of strategies discussed singly does not help in achieving the goals set by McKinsey and company and Architecture 2030. A combination of strategies based on several factors including life cycle environmental impacts, costs and payback period can be implemented to achieve targets set by various reports and standards. There are several other energy saving tactics implemented in homes such as changing lighting, behavioral changes which have not been assessed by this research.

Existing homes generally have lower insulation than newly constructed homes (USDOE). Cost-benefit and energy audits analyses are required for determining if replacement of insulation, wall panels, windows and doors are feasible. The use of ICF in existing buildings is a study which encompasses energy auditing and building retrofitting research. To promote ICF as a green building product, research into its use in commercial buildings and multi-story residential structures is required. Experimental results which show the actual range of energy savings are required to validate the energy modeling scenarios.

5.6 CONCLUSION

This study evaluated the national energy saving impacts of ICF, windows and doors on future new residential construction. The energy saving impacts was compared with energy goals set forth by McKinsey and company and Architecture 2030. The results showed that a combination of using ICF, windows and doors will help in achieving the goals in new residential homes. Implementing each of the strategy was not a solution to reaching the goals. The payback period calculation showed that strategies with the highest energy saving qualities also had the highest payback period. For example, a combination of using ICF and triple glazing windows had the highest energy saving potential but the payback period was 100 years. Tradeoffs associated with high energy savings potential and payback periods exist. The consumer preference plays a major role in implementing energy saving strategies. Policy changes prioritizing energy savings will help in lowering initial investments of many energy saving products.

6.0 CONCLUSION

This research provides background information on the residential building LCA and the building products used. It discussed the creation of a residential framework used to analyze the green product labeling system for carpets, paints and linoleum flooring. It also showed the energy savings and CO_2 emissions abated from use of innovative strategies in homes.

The main contribution of this study was the creation of a residential LCA framework using a case study approach. Residential LCAs will continue to be conducted and the framework created in this research will serve as a guideline to future studies. The framework showed the life cycle phases to be considered while conducting a residential LCA along with a sample selection of unit processes and databases. Future residential LCAs can use this framework as a step-by-step methodical procedure for their studies.

When modeling building products, it is important to illustrate the functionality of the product in a building structure. Most product LCAs focus only on the manufacturing phase, but as this research showed, all phases contribute to environmental emissions and the modeling use of the building product in a building is essential to interpret the LCA results. The case study approach to creating a framework showed how the building product environmental impacts can be analyzed by using the functionality of the product in a residential building structure.

Another contribution of this research is to improve the understanding of green labeling of building products. Chapter 4 discussed the green product labeling system and the inconsistencies inherent in the LCA databases. Green labeled and generic carpets, paints and linoleum flooring impacts are compared and the framework is used to analyze building products impacts when used in buildings. The comparative LCA results of green and generic products are inconsistent and not intuitive. Changing the selection of databases adds to the inconsistency. This study showed that although LCA is theoretically useful in labeling of green products, the LCA databases need to be improved such that they can be useful to label products. The study also showed how adding building products to a home did not diminish the impacts of the use phase (also discussed in chapter 3). A new labeling system was proposed in which the labeling process was at the least a multi-criteria system and displayed the results of the LCA conducted. Displaying LCA results as shown in Table 8 column 6 for labeling of products was one of the major recommendations of this study.

This research also contributed to understanding the national energy saving impacts of emerging and existing building products used in residential homes. Chapter 5 discussed many strategies aimed at reducing the use phase impacts of a home. The products of interest reducing energy consumption are ICFs, windows and doors. Chapter 3 discussed a case study of a residential home constructed using ICFS and the results show that ICF homes consume 20 percent lower energy than traditional wood homes. The energy savings achieved in a single ICF home is extrapolated onto the projected new homes constructions in the US. Similar extrapolations are made with energy saving windows and doors. A combination of using these products in homes is also analyzed as part of this study. The results show that combining energy saving products in a new home construction will aid in reaching energy targets set by McKinsey & company and Architecture 2030. It is to be noted that the easiest strategies to implement might not be the cheapest in terms of energy savings and payback periods.

6.1 FUTURE WORK

The framework created in this research should be used in future residential LCAs to overcome data burdens regarding material use, transportation, construction method, use and end of life phases. The limitations of the framework have been outlined in Chapter 3. One of the limitations is that the framework was created using a case study on ICFs. While the framework created essentially includes a traditional wood home and a home made of ICF, future work should involve the inclusion of other emerging building products as well. The LCA case study was Pittsburgh specific. The framework can be used as a guideline to model residential homes in other locations. Some phases such as transportation, construction and end of life had negligible impacts in this case study. But an analysis of the process flows revealed that the unit process contributing to an impact are not intuitive. So future studies should model all the phases outlined in the framework as neglecting some phases based on case study results will not provide accurate results. Creation of a framework for commercial structures is beyond the scope of this research, but future work can be carried out in this area and develop on a commercial buildings tool currently available (Guggemos and Horvath 2005).

Evaluating the labeling process revealed the gaps in the LCA databases and a new LCA based labeling system was proposed in this research. Currently, LCA databases have several inconsistencies. Improving the databases, including LCA in labeling process, providing transparency in LCA (transparent functional units, system boundaries, inventories) will benefit the labeling of building products. Future work can include defining detailed metrics for the proposed labeling system, which can be promoted as a new labeling system for building products.

The national impact of energy saving products was assessed in Chapter 5. The study showed that a combination of ICF, energy saving windows and doors was required to achieve the national energy saving goals. This study only looked improving the building envelope and only studied at three kinds of products: ICF, windows and doors. A number of strategies aimed at reducing energy consumption in homes are available. Future work can include studying the effects of energy efficient lighting, changing the energy mix, modeling occupant behavior on energy consumption in homes.

APPENDIX A

BUILDING PRODUCT IMPACTS IN A HOME

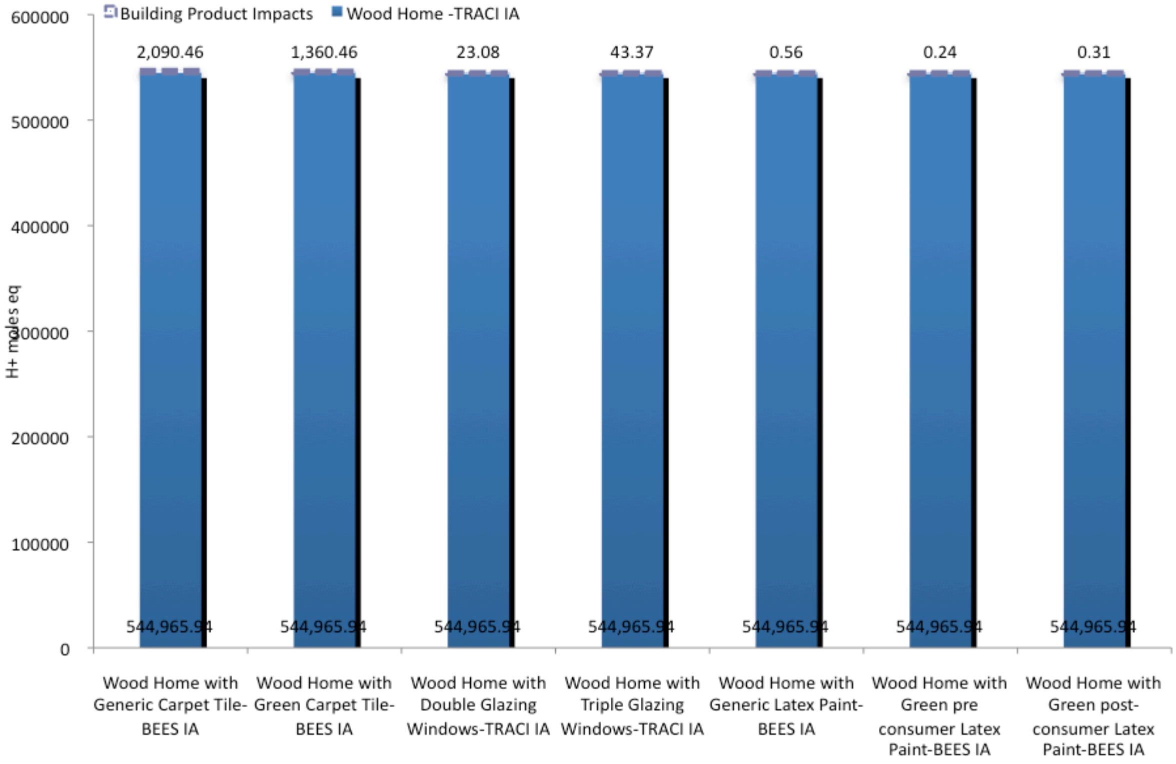

Figure 13: Life cycle acidification impacts of building products when used in buildings

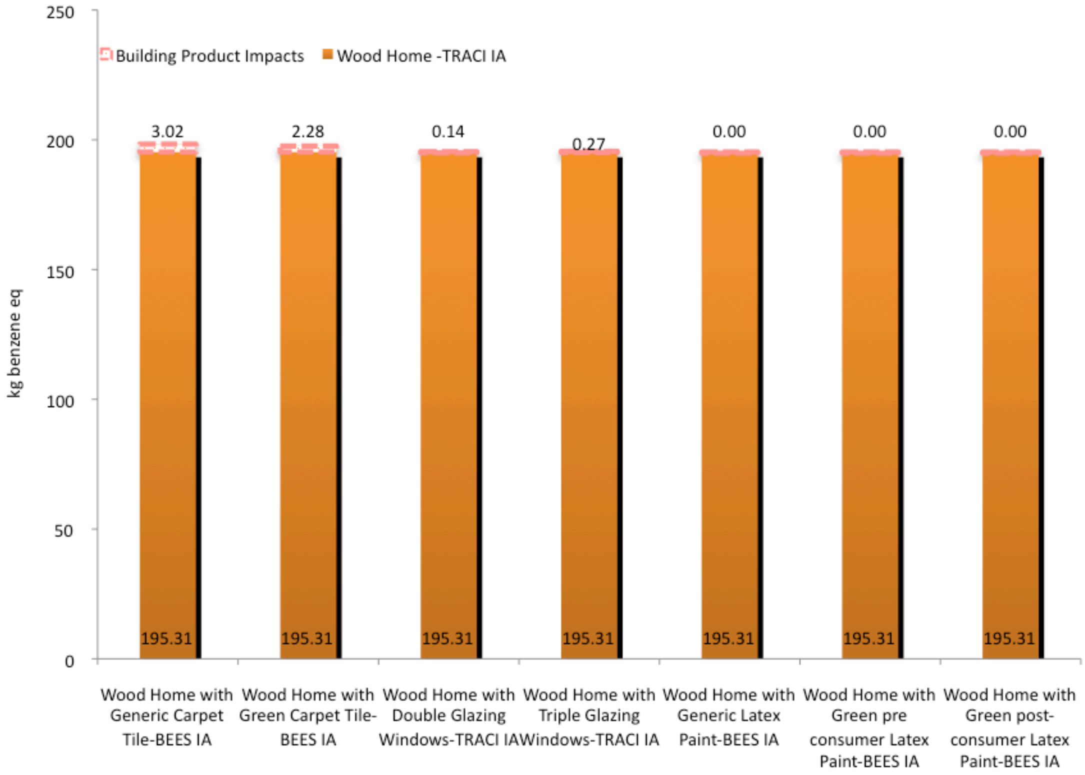

Figure 14: Life cycle carcinogenic impacts of building product when used in a building

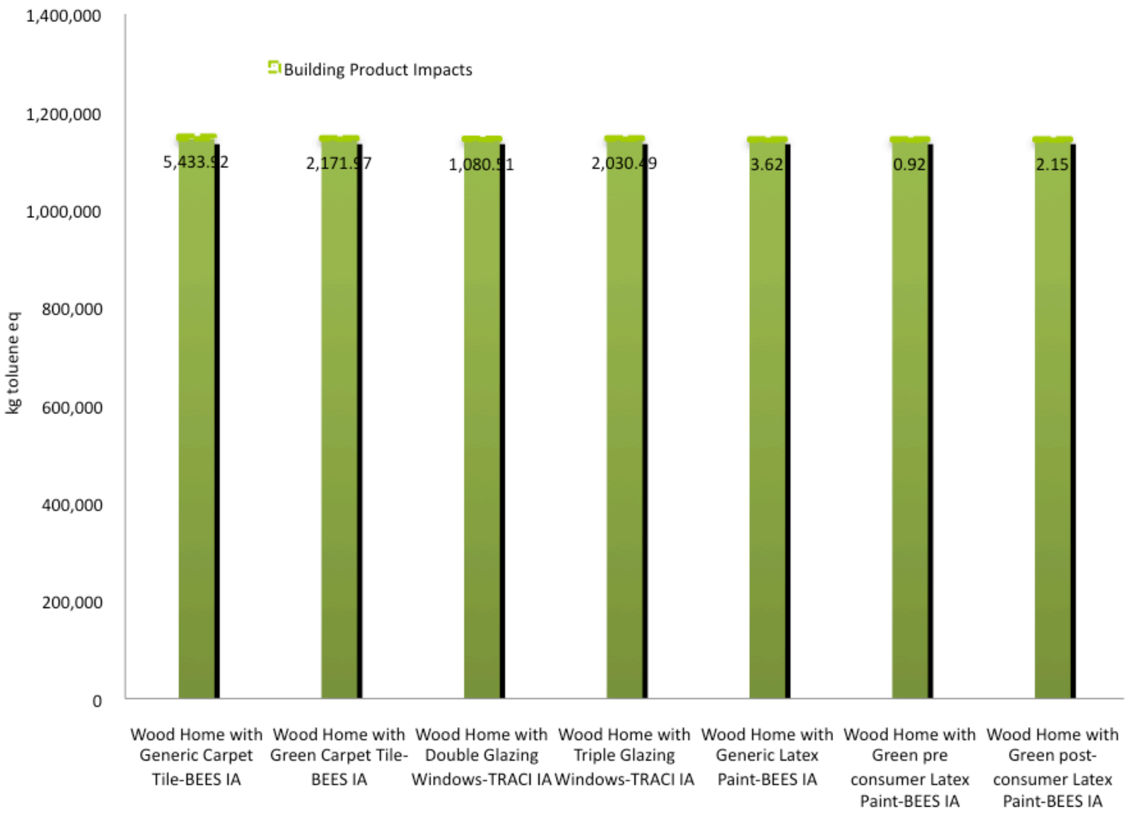

Figure 15: Life cycle non carcinogenic impacts of building products when used in building

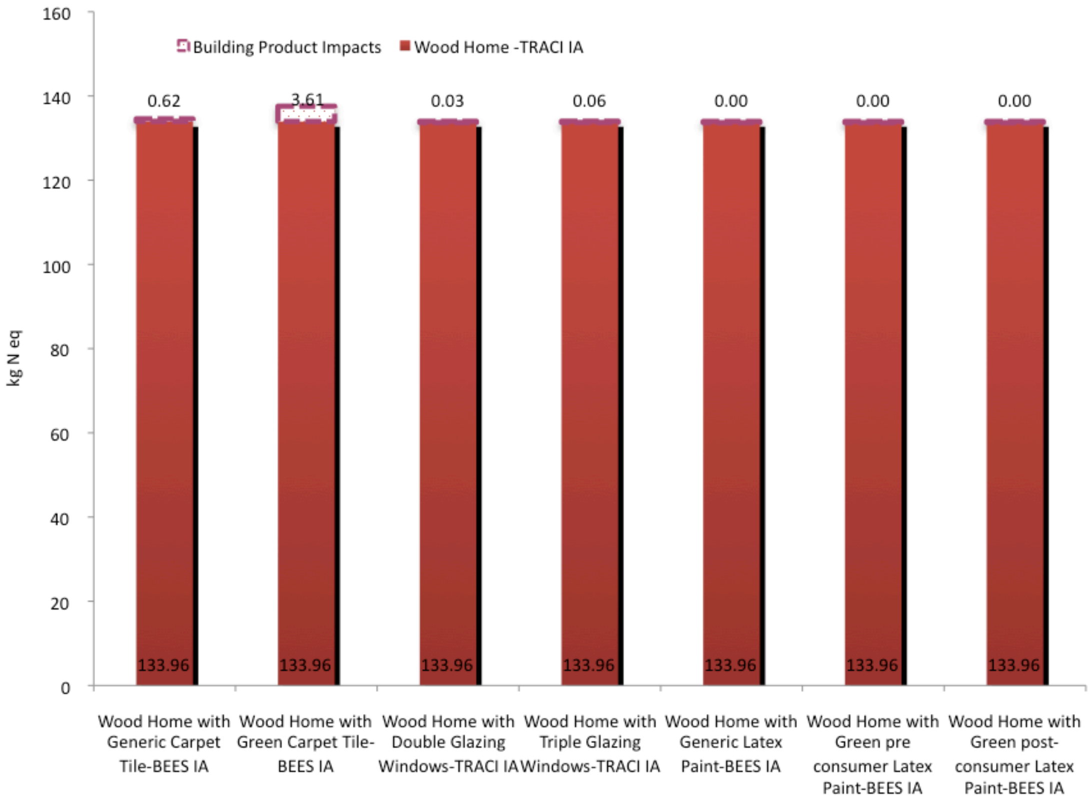

Figure 16: Life cycle eutrophication impacts of building product when used in building

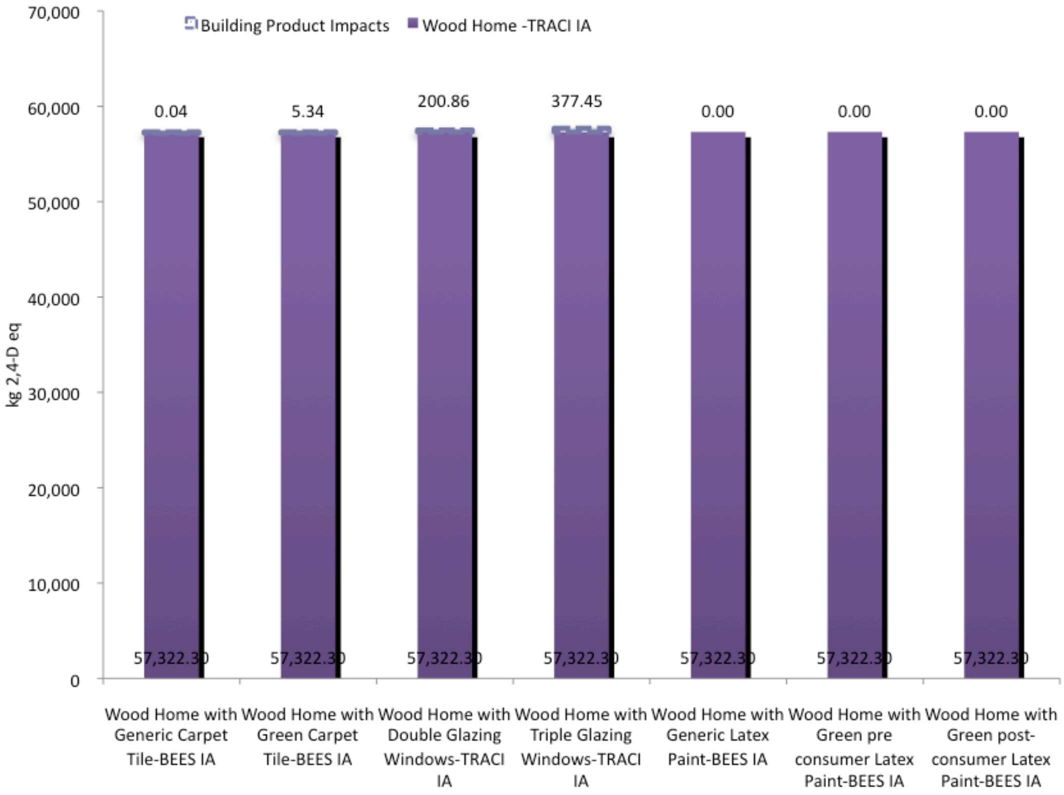

Figure 17: Life cycle ecotoxicity impacts of building products when used in building

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