Cold Climate Housing Research Center

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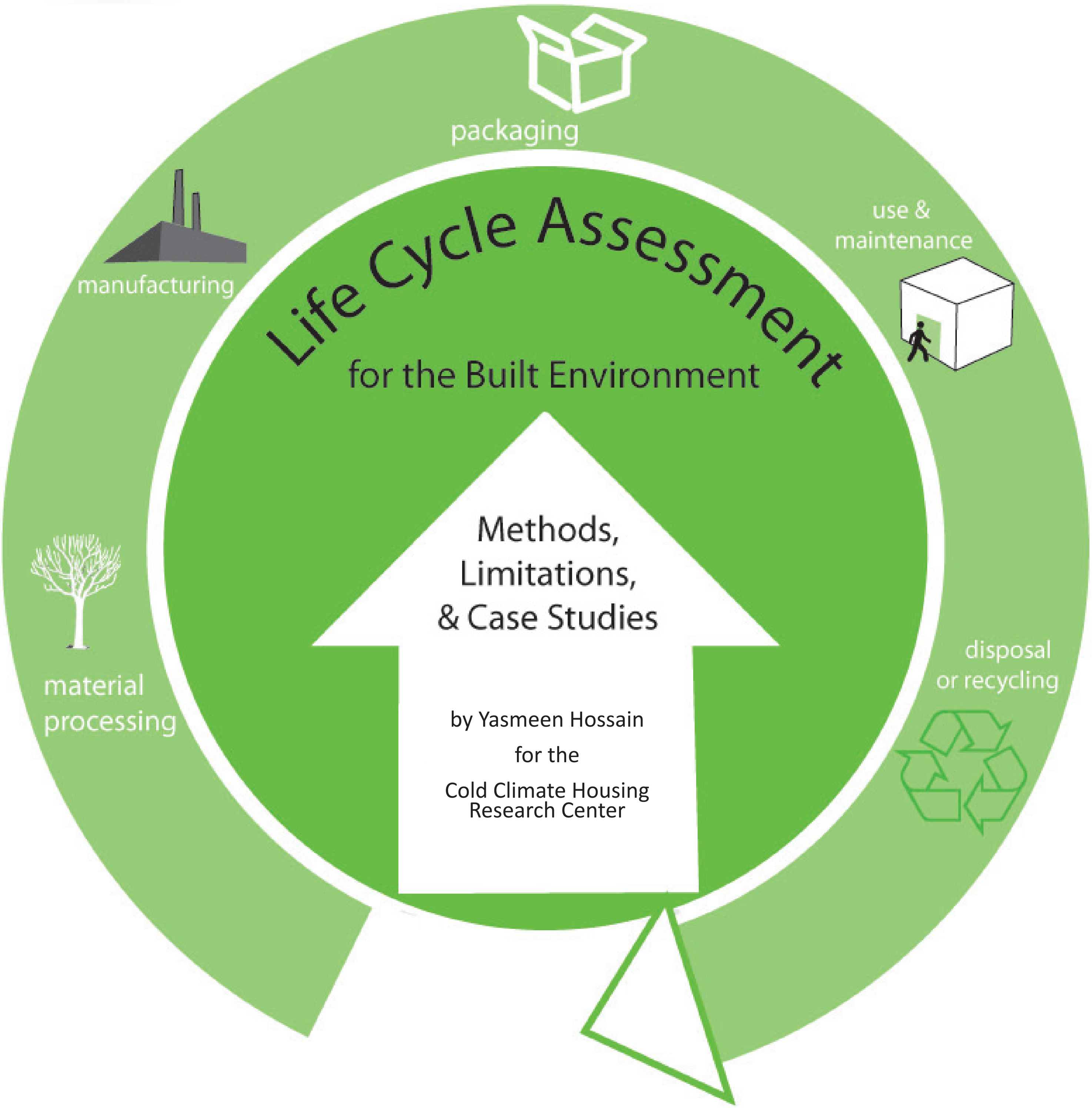

Life Cycle Assessment for the Built Environment

Methods, Limitations, & Case Studies

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Executive Summary

The U.S. Census Bureau estimates that by 2030, 14.5 million new homes will need to be built to accommodate the expanding population in the U.S. (U.S. Census Bureau, 2006). Construction needs for the world as a whole overwhelm these figures, as it is projected that 98% of the population growth in the first two decades of this century will occur in developing countries (UNEP, 2003). Such a level of new construction will have a significant impact on the environment. Correspondingly, professionals and homeowners alike are finding it useful to evaluate the environmental impact of buildings.

A Life-Cycle Assessment (LCA) is a quantitative cradle-to-grave calculation of environmental impacts from the input, operation, and output of products (Bayer et al., 2010; Huberman & Pearlmutter, 2008; ISO, 2006a). For buildings, each phase of construction can be evaluated separately or combined in a whole-building analysis. The building phases commonly begin with material sourcing and manufacturing, construction, operation and maintenance, and lastly decommissioning or recycling where appropriate (Bayer et al., 2010; Assefa et al., 2007; Bribian et al., 2009). This paper is an examination of LCA for the built environment, exploring the assessment tools, steps, and limitations for the general industry practitioner.

Purpose and Process

Conducting LCA on buildings can help inform decision-makers, justify design choices, evaluate the performance of material substitutions and budget decisions, and identify environmental improvements. Understanding the environmental impacts of different building techniques can also justify design decisions and long-term payback periods, thus allowing for a holistic view of design decisions.

LCAs can also be conducted for marketing purposes, such as the green labeling of buildings, to take advantage of tax incentives, or in the future to calculate a building's carbon emissions if they become subject to regulation. Lastly, a number of building assessment frameworks/rating systems are increasingly incorporating LCA in their point systems, such as Leadership in Energy and Environmental Design (LEED), Green Globes, International Code Council 700 National Green Building Standard, ASHRAE 189.1, CalGreen, and the International Green Construction Code (IGCC) (ATHENA Sustainable Buildings Institute, 2012; Bayer et al., 2010).

LCA studies are designed to answer specific questions, and those questions drive the design of the study.

Example questions could be:

How does the potential environmental impact of a new construction building compare to existing buildings?

How do two different manufacturing processes for the same product compare in terms of resource use and emissions?

The majority of LCA studies are based on a standard developed by the International Organization for Standardization (ISO): International Standard 14040/14044 for Life-Cycle Assessment. Following the ISO standard is a voluntary measure and does not provide compliance standards for tools (Martinopoulos, et al., 2007). The standard recommends four steps for conducting an assessment (ISO, 2006a; ISO, 2006b), the first is to define the goal and scope of the study, the second to create an inventory analysis, then conduct an impact assessment of the inventory and lastly interpret the results and report them appropriately. Conducting a LCA can be an iterative process, with results repeatedly refined or refocused based on initial findings.

Tools

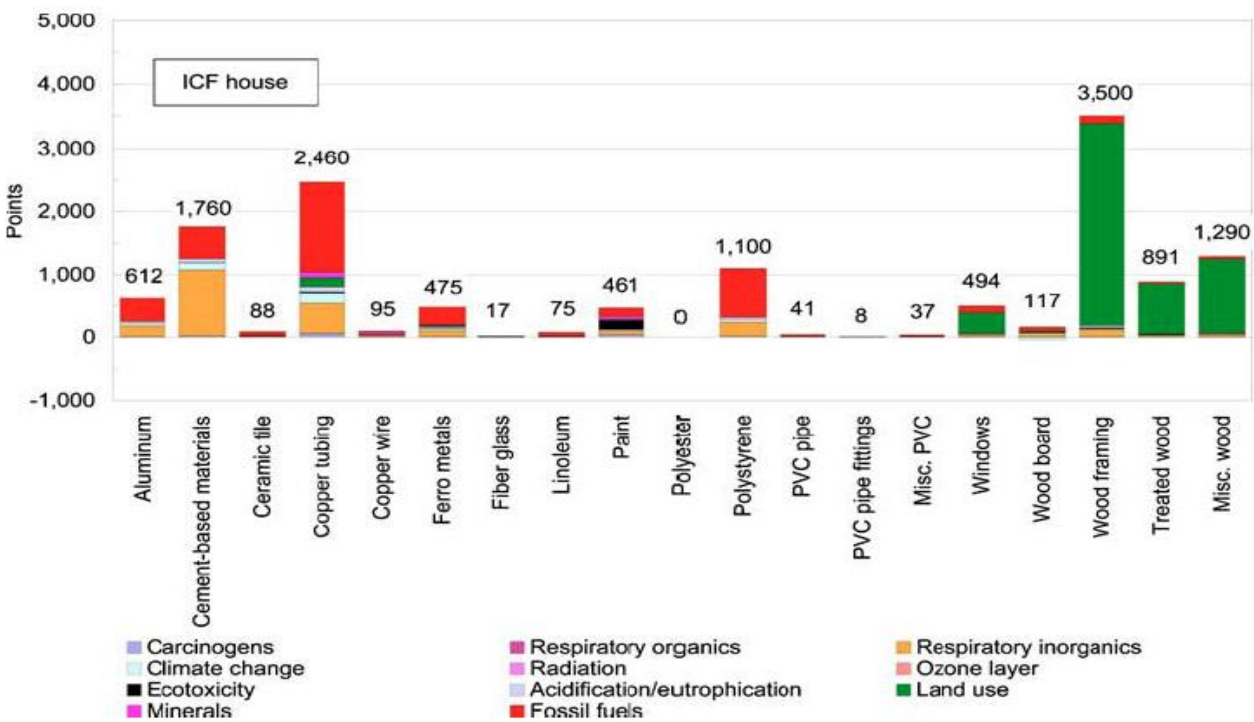
LCA tools are software applications used to guide the user through the four LCA steps. Some tools use their own database for the inventory analysis, while others can link to a large variety of existing databases, thus expanding the regional scope of the tool. The tools can be classified into assessing three separate categories for the built environment: building materials, assembled products, and whole-building analysis. The U.S. Environmental Protection Agency's BEES (Building for Environmental and Economic Sustainability) is an example of a tool that can be used to assess building materials, SimaPro assesses assembled products and ATHENA's Environmental Impact Estimator is designed for whole-building analysis. Tools can be used across these categories, for example several of the case studies discussed used SimaPro for whole-building analysis, but this may require substantially more input and detail compared to tools specifically designed for that category.

Tools are difficult to compare as each one is based on a different set of criteria, parameters, user-skill level, and geographic region and links to different databases. Users are advised to choose a tool that fits their specific LCA objectives. Due to the variances in tools, conducting a LCA for the same building but using different tools can produce varied results.

Case Studies

Six case studies included in this paper center around building life-cycle energy input and output, heating and cooling systems, and energy efficiency features of homes. The examples range from existing buildings to modeled buildings in different climate zones for comparison. Three common LCA tools were used for building analysis: ATHENA Environmental Impact Estimator, U.S. EPA's BEES, and SimaPro.

One case study models residential homes in five climate zones in the U.S. to determine the environmental impact of insulating concrete form (ICF) versus wood frame construction (Marceau & VanGeem, 2006). Wood used for framing, as well as copper tubing, was shown to have the largest environmental impact of all construction materials. See the graph below which assesses environmental impacts across multiple impact categories expressed as dimensionless units.



Another example compares central natural gas furnace coupled with conventional central air-conditioning, natural gas powered hydronic heating coupled with conventional central air-conditioning, and an electric air-to-air heat pump for both heating and cooling in homes in four regions of the U.S. The results of the LCA indicated that the boiler and the air-conditioning systems had the highest environmental impact over all categories and the air-to-air heat pump ranked lowest in environmental impacts when assessing the manufacturing phase, necessary infrastructure and maintenance needs of each system. However, the environmental impacts of the operational phase was strongly dependent on location, and the operational phase of the heating and cooling system life cycle was more significant in terms of environmental impacts than the construction and installation phase. The variation in LCA outcomes for each location illustrates the importance of including climatic conditions and regional energy sources in the study parameters.

Limitations

LCA can be valuable for many applications in the built environment, but is not without its limitations. The process of conducting a LCA can be very resource intensive and leaves room for user bias during parameter selection, weighting, normalization, choosing impacts and impact categories, and selecting from the variety of LCA tools available (ISO, 2006b; Haapio & Viitaniemi 2008). The fact that there are no LCA method certification programs, mandatory standards, or industry benchmarks leads to reliability and validity concerns and makes it difficult to compare LCA tools or LCA case study results. Data acquisition, accuracy, and omission are part of the limitations as well. Due to the individual parameters of each study, case study results cannot be generalized for the entire industry either.

LCA as a method aims to provide the user with a complete understanding of all quantified environmental externalities of a product or process. With the advent of some of the leading building assessment frameworks and rating systems, such as LEED, incorporating LCA into their evaluation criteria, the method will likely continue evolving and improving.

I. Introduction

Global population growth and increased urbanization rate projections lend themselves to the estimation that by 2032 70% of the world's land surface will be disturbed or impacted by the built environment (UNEP, 2003). Already in industrialized countries the increase in disposable income has led to an explosion of new home construction and sprawl developments (Horvath, 2004). In 2009, the Energy Information Administration (2009) reported 114 million housing units in the U.S., consuming a total of 10 quadrillion BTU of energy and spending $230 billion combined on energy. The construction industry utilizes roughly half of all mined or harvested natural resources and one-third of end-use energy is consumed by non-industrial buildings alone for heating, cooling, appliances, and lighting (UNEP, 2003).

Considering that roughly 40% of global greenhouse gas emissions can be attributed to the built environment (UNEP, 2003), the addition of a substantial amount of new homes will have a significant impact on the environment. For example, new construction requires raw material extraction, manufacturing plants for building materials, land clearing, transportation of construction materials, energy input and waste energy output during manufacturing and operation, noise pollution, indoor and outdoor emissions, water usage, waste water and other waste generation, and disposal of construction materials (UNEP, 2003; Reijnders & van Roekel, 1999). With the rising global concern of climate change as well as a trend for greening the building industry, professionals and homeowners alike are recognizing the importance of evaluating the environmental impacts of buildings.

The process whereby the environmental impact of the entire lifespan of a product or process is ascertained is called Life-Cycle Assessment (LCA) (ISO, 2006a). LCA refers to the summary of environmental impacts from the input, operation, and output of products (Bayer et al., 2010; Huberman & Pearlmutter, 2008; ISO, 2006a). It is a quantitative cradle-to-grave calculation of environmental impacts, which can be expanded to a cradle-to-cradle assessment when the recycling and reuse potential of materials is included. LCA can be used to quantify the environmental impact of a whole building, which can be made up of over 2,000 products and over 60 basic materials (Kohler & Moffatt, 2003). Since each component is unique in lifespan, material requirements, disposal options, and so on, assessing the environmental impact of a whole building can be a complex and involved process.

There are a large variety of types of LCA tools geared towards different goals and user groups. For example one type of LCA allows for a comparative assessment of two building designs to estimate which design would have an overall lower environmental impact over the lifespan of the building, geared primarily towards designers and architects. Another LCA may be appropriated by a general user to justify the decision to use one type of insulation over another type based on its environmental impacts and energy efficiency benefits it provides to the inhabitants of the home.

LCA can be used to inform decision-makers, justify design choices and budget decisions, identify environmental improvements, and for marketing purposes, such as eco-labeling or green labeling of buildings.

This paper focuses on the residential sector. It provides a brief overview of the LCA method for the built environment, including the steps for conducting an assessment as laid out by the International Standard ISO 14040/14044, incentives to the industry, and the life-cycle phases of a building. The practical applicability of LCA to the building industry is explored through highlighting six case studies relevant to energy efficiency and heating systems in North America using LCA tools appropriate for the region. This is followed by a review of LCA tool options for end-consumers. A critique and discussion on the limitations of the LCA method concludes the paper.

II. Life-Cycle Assessment for the Built Environment

Life-cycle assessments can be undertaken for a variety of products, processes, and industries. This section reviews the specificities of conducting a LCA for the built environment, including the incentives to the building industry, practical uses of LCA as it relates to buildings, the specific steps to conducting a LCA, the different phases of a building that can be assessed separately or combined, and lastly other life-cycle analyses that are complementary to the environmental impact assessment.

a. Purpose/Incentives

Conducting a LCA can be costly and time-consuming, but it provides distinct benefits and incentives to the building industry.

One of the applications of LCA is to compare the overall sum of environmental impacts of a specific building to other similar buildings. The assessment can also break down the distribution of the impacts over the various life-cycle phases and processes of a building (Scheuer et al., 2003). During the design phase, architects often use the results of an assessment to justify their design choices from a scientific aspect as well as provide informed choices between building design and construction options (Bayer et al., 2010). Furthermore, architects can use the tool to demonstrate to their clients the advantages of utilizing green building practices and the long-term payoff rate in terms of carbon savings. Green building designers are able to compare environmentally preferable building materials and their cost-effectiveness over the life of the building in terms of energy savings (Lloyd & Landfield, 2005). In a LCA that assesses the whole building, designers can furthermore determine how substituting materials will affect the performance of the entire building from a standpoint of impacts from energy use. An ex-post LCA helps researchers, planners, and officials assess whether the projected performance and benefits of a building design are achieved in reality, especially once real-time operating costs can be included (Blengini & Di Carlo, 2010). From a policy aspect, LCA of specific buildings can be used to provide data to justify building standards and regulations, including carbon emission reductions.

Homeowners in a number of states in the U.S. can draw on monetary tax incentives for utilizing green building techniques, which are justified through a LCA (Bayer et al., 2010). Manufacturers can receive tax benefits as well for complying with environmental regulations. Indirect monetary benefits can be accumulated through accreditation by building rating systems, which are valued by a certain customer base. Currently in the

U.S., the building assessment frameworks/rating systems that include LCA are (ATHENA Sustainable Buildings Institute, 2012; Bayer et al., 2010):

- Leadership in Energy and Environmental Design (LEED) – the recent LEED update includes points for conducting a LCA;
- Green Globes – directly awards points for the educational experience of conducting a LCA and the first in the U.S. to incorporate LCA in the rating system;
- International Code Council (ICC) 700 National Green Building Standard, National Association of Home Builders' residential green standard – awards points for conducting a LCA;
- ASHRAE 189.1 Standard for the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings - recommends conducting a LCA to assess the building's impact on natural resources, minerals, and the atmosphere;
- CalGreen – California's Green Building Standards Code offers LCA as an alternative to comply with material requirements on the whole-building level;
- International Green Construction Code (IGCC) – the ICC's standard offers LCA as an alternative to comply with material requirements on the whole building and assembly level.

Conducting LCAs will aid companies in attaining information for compliance with the American Clean Energy and Security Act that was passed by Congress in 2009 requiring U.S. emissions to be reduced by 17% by 2020 and by 80% over 2005 levels in 2050 (Broder, 2009). When the bill takes effect, emitting one ton of carbon dioxide will cost $13 with steadily increasing prices for emissions each year. The building industry will have a large incentive to utilize low carbon dioxide emission assembly and operation techniques and to compare building options to achieve low carbon emissions from building's life cycle.

Lastly, LCA-based construction materials labels, termed Environmental Product Declarations, are becoming increasingly popular in international business transactions. These International Organization for Standardization Type III labels, which are a voluntary measure in the U.S. and mandatory in Europe, label construction products or brands based on their environmental impacts (Trusty, 2011).

b. Steps for Conducting a Life-Cycle Assessment

The International Organization for Standardization (ISO) has developed an International Standard 14040/14044 for Life-Cycle Assessment. While following the ISO standards is a voluntary measure, the majority of LCA tools are based on the standards despite the fact that the ISO standards do not allow for tools to be certified as compliant (Martinopoulos, et al., 2007). It does however provide a framework, guidelines, and requirements for LCA tools to enable comparisons between LCA results that exist within the same assumptions and contexts (Figure 1) (ISO, 2006a). Conducting a LCA can be an iterative process that can be repeated based on the initial results. In Figure 1 the arrows highlight this iterative nature. The two ISO standards concerning LCA differ in that ISO 14040 defines the principles and framework and ISO 14044 encompasses detail on recommended steps to be taken to conduct a LCA (Martinopoulos, et al. 2007; ISO, 2006b; ISO, 2006a). The steps are further elaborated on below.

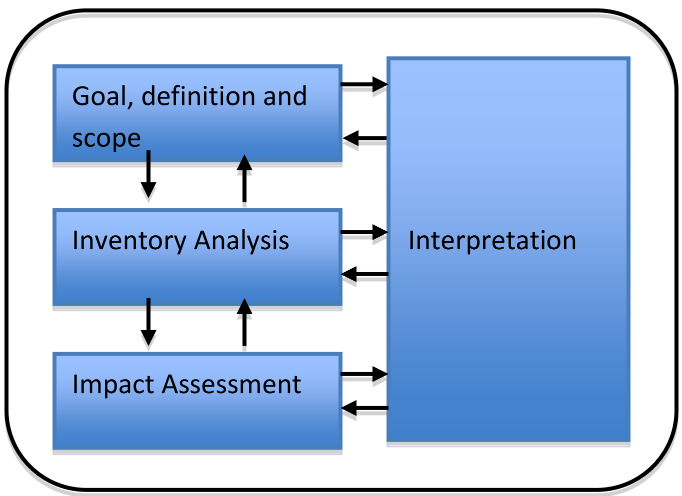


Figure 1: LCA Framework (ISO, 2006a).

1. Define goals & scope of LCA: Determining the goals of a study entails making a decision on the intended audience and the application of the results (ISO, 2006a). The scope defines the parameters, system boundary, functional unit of measurement (such as square meters for a house) and determines the data requirements and types of impacts (for more information see ISO, 2006a). Impacts from the built environment are plentiful and can range from measuring air pollutants to noise levels, to habitat destruction, etc.

2. Life-cycle inventory analysis (LCI): During the inventory analysis phase, data from the building system are collected and compiled (ISO, 2006a). The data are typically either process-based or economic sector input and output data, and can be based on existing libraries that contain data on indicators. The indicator datasets can include energy, raw material, physical inputs, products, waste, releases to air, water and soil, and any other environmental aspects (Figure 2). Choosing the indicators can be a subjective, value-laden activity if established industry benchmarks and standards are not followed (Dammann, 2008). The data in this step need to be related to the functional unit defined in Step 1 and undergo a validation check and sensitivity analysis.

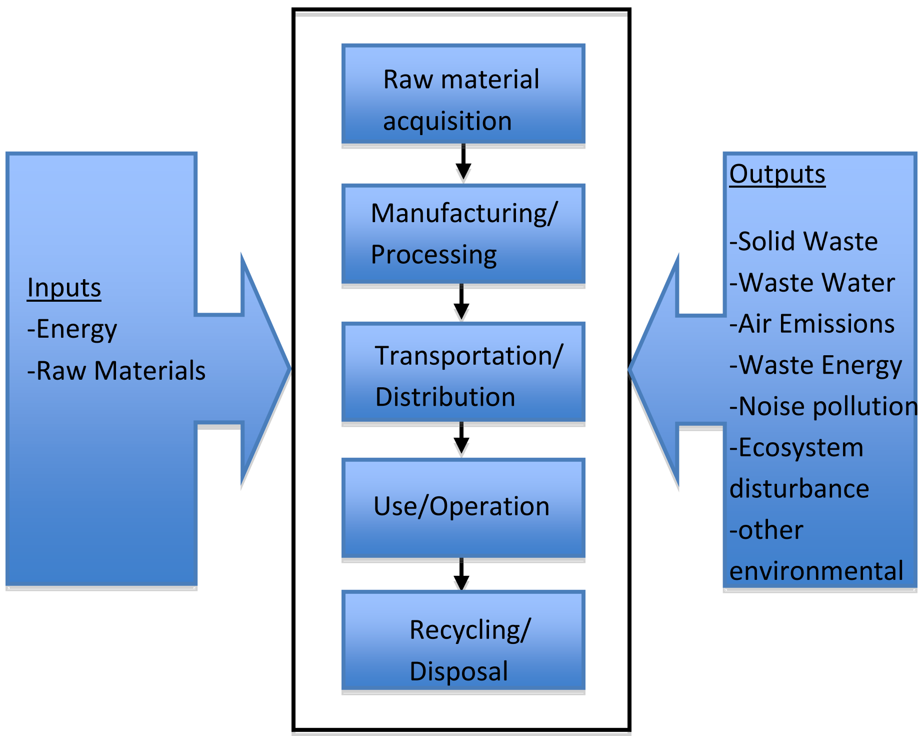


Figure 2: Input and Outputs in a Product's Life-Cycle (Tsilingiridis et al., 2004).

3. Life-Cycle Impact Assessment (LCIA): This step is typically completed by drawing on software tools or existing databases that quantify environmental impacts; TRACI, Eco-Indicator 99, and IMPACT 2002 are a few examples. The data acquired from the inventory analysis are grouped by impact categories and the impacts within each category are converted to a common denominator unit and aggregated, such as greenhouse gas emissions (ISO, 2006a; Bayer et al., 2010). Impact categories are selected by drawing on

existing categories. In the U.S. these are defined by government agencies such as the Environmental Protection Agency, Occupational Safety and Health Administration, or the National Institute of Health (Bayer et al., 2010). Optionally, after the data in the impact categories have been quantified and aggregated it can be normalized or set in context relative to reference information (Bare et al., 2006). One example of normalization is to use the emissions of a region to illustrate the significance of the emissions of a residential home for which an LCA was conducted.

The second optional part of the impact assessment phase is weighting. During this process, the data from all of the impact categories are aggregated by applying weights to each category. The numerical weights are based on value choices and as such are often a point of criticism. However, by utilizing this optional step and having one single score as the final outcome, the LCA tool provides a qualitative aspect to the quantitative calculations, allowing for a value-based outcome that is tailored to the specific needs of the decision-maker (Gloria et al., 2007). Each LCA tool applies a different scale of weights for their impact categories and as such cannot be compared across tools. Lastly, further LCIA data quality analysis can be conducted, including a gravity analysis, uncertainty analysis, and sensitivity analysis to eliminate biases and data errors.

4. Interpretation and Reporting: The final step in an LCA is the analysis and interpretation of the results, identifying significant issues, evaluating the results for completeness, sensitivity and consistency, and noting the limitations of the study (ISO, 2006a). Typically, the system parameters, boundaries, and functional unit are revisited to check for appropriateness and consistency. The International Standard recommends a critical review of the study by internal or external experts at this stage as a third-party verification to exclude biases and errors.

c. Building Life-Cycle Phases

The building phases commonly evaluated by a LCA begin with material sourcing and manufacturing, construction, operation and maintenance, and lastly decommissioning or recycling if appropriate (see Figure 3) (Bayer et al., 2010; Assefa et al., 2007; Bribian et al., 2009).

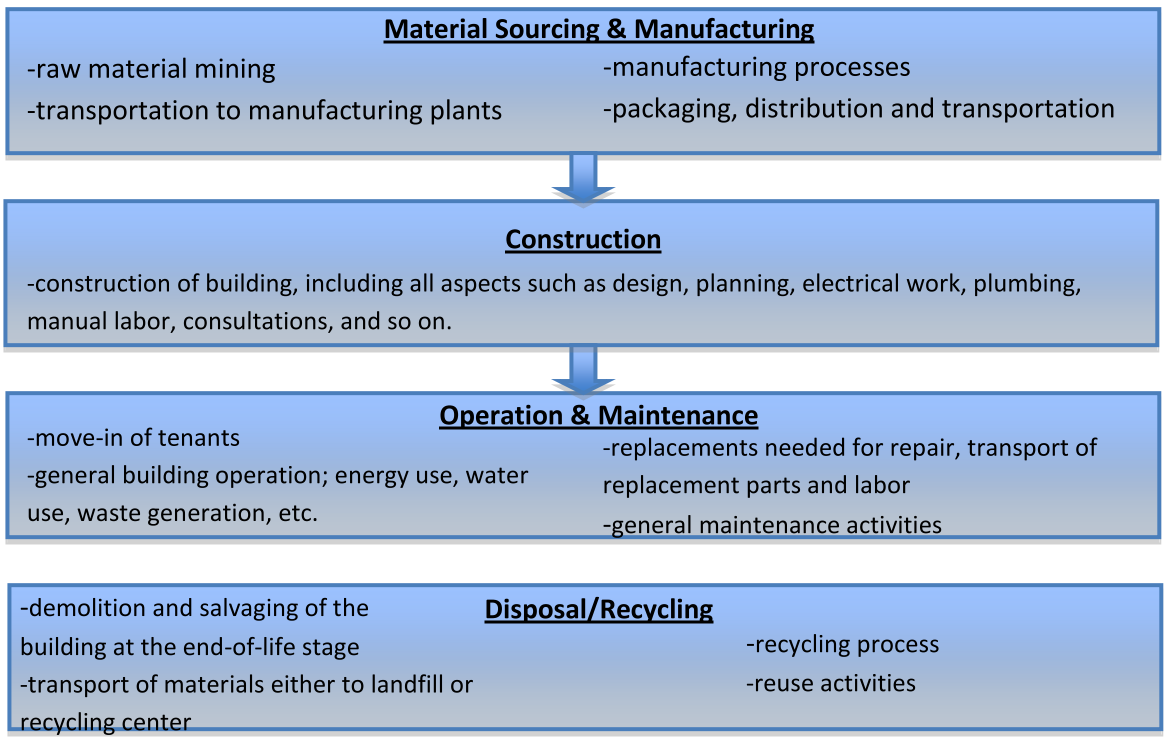


Figure 3: Building Life-Cycle Phases (Bayer et al., 2010; Assega et al., 2007, Bribian et al., 2009).

The phases can be evaluated separately to attain information on environmental impacts of manufacturing alone, which would be relevant to manufacturing companies, or they can be added to each other to be assessed as a symbiosis, where one phase may be dependent on another. For example, energy consumption varies in each of the stages and as such lowering the energy input in one of the stages may prompt the embodied energy in another to rise (Huberman & Pearlmutter, 2008). Building an energy efficient house with energy efficient walls, windows, and doors will lower the operational energy needs of the building; however, due to the energy necessary to produce the materials and the added volume of materials needed it will increase the energy demands during the manufacturing stage as well as the embodied energy of the whole building. Other environmental impacts, beyond energy, can have the same trend line as well. For example, Wilson's (2010) research on two types of foam insulation indicated that the greenhouse gases emitted during manufacturing and the blowing agents emitted post-manufacture of the foam produced a higher Global Warming Potential impact category of a LCA than the saved emissions from burning additional fossil fuel during the operation phase for heating and cooling. This study was not conducted as a complete LCA but rather an evaluation of products based on specific characteristics.

Including recycling of building materials in a LCA is not a standard practice in most LCA tools to date (Sartori & Hestnes, 2007). This can be attributed to the complexity involved in calculating the environmental impact of recycling, which can have high embodied energy but can also be counted as an offset if the materials are re-used in a new construction project. One accounting method of recycling is to attribute for it in each of the building stages, either through recycling waste material or utilizing recycled materials rather than attempt one sum total of all building phases (Bayer et al., 2010). However, if a whole building recycling assessment is sought, there are two common ways of attributing recycling credits to a project. The first one is a bonus method, attributing values for the impacts of the recycling process but also subtracting the values of the impacts of new material manufacturing that is avoided through using recycled materials (Lasvaux et al., 2009). The stock flow method does not count end-of life recycling of the building materials, however it does discount dismantling and transportation to the recycling facility of the materials. If a recycling facility is located at a large distance this can account for a higher environmental impact than not recycling the materials by dropping them off at a local waste disposal site. As the above examples show it is also up to each individual tool how to account for recycling, whether through end-of-life building characterization, using recycled materials as part of new construction, or recycling waste during construction.

d. Complementary Assessments

While LCA is the most common method of evaluating environmental impacts for buildings, there are a number of related methods that assess complementary facts of the built environment, such as the economic and social costs (Figure 4). Each method has specific goals, which means they do not have to be used exclusive of each other. In some instances, it may be useful to the professional to apply a number of methods to glean the most comprehensive assessment possible, or combine tools for a hybrid variation. Hybrid assessments are commonly undertaken by combining LCA and EIO-LCA to get a sense of how the environmental and economic impacts relate. This approach was used by Glick and Guggemos (2007) to assess the environmental performance of two types of heating systems in a residential house in Colorado. The authors used LCA in the building phases where product-specific data were required for an accurate assessment, construction, and decommissioning, and EIO-LCA was used in the other building phases where specific data were not available but aggregated economic industry-average data sufficed. Using this approach enabled the authors to utilize the strengths of each assessment method and reduce the complexity and time requirement of conducting the study.

Description		Primary use
Life-Cycle Energy Analysis	LCEA (Huberman & Pearlmutter, 2008)	• the only environmental impact measured and quantified is energy • evaluates energy-efficiency of a building
Life-Cycle Cost	LCC (ISO, 1997)	• calculates the monetary costs of a building project
Social Life-Cycle Analysis	SLCA (Jørgensen et al., 2008)	• evaluates social and socioeconomic effects of products and companies, i.e. worker health, human rights, labor practices, consumer safety, etc.
Economic Input-Output Life-Cycle Analysis	EIO-LCA (Matthews & Small, 2001)	• assesses the environmental impacts of economic sectors • typically large-scale systems, but can be applied to individual buildings • takes significantly less time to complete than an LCA
Regional Economic Input-Output Analysis-based Life-cycle Assessment	REIO-LCA (Cicas et al., 2007)	• calculates environmental and economic impacts in a specified U.S. regional area • complements local, process-based or national assessments
Region-type Life-Cycle Impact Assessment	R-LCIA (Li, 2006)	• calculates the regional environmental burden of a building as well as regional impacts of infrastructure needed to support & construct the building

Figure 4: Complementary Life-Cycle Tools.

An example of how LCEA was used by Huberman & Pearlmutter (2008) was to calculate the saved life-cycle energy consumption of using alternative materials to reinforced concrete for construction of a wall in a residential home in Israel. The alternatives were hollow concrete blocks, autoclaved aerated concrete, stabilized soil blocks and fly-ash blocks. The result of the analysis showed cumulative energy savings of 15-20% by substituting the alternative materials to concrete over a 50-year lifespan of the wall. The initial production energy would be reduced by 30-40% or the equivalent of 25-30 years of operational energy.

Through conducting a case study using R-LCIA, Li (2006) determined that the operational stage of a newly constructed store building produces a larger environmental burden on the region due to increased traffic, since the store includes a parking lot, versus the construction phase of the building.

Cicas et al. (2007) developed a model to calculate the regional environmental impacts of an industry entire supply chain or sector. Adding regional impacts to the EIO-LCA method produced the REIO-LCA model. The authors utilized regional economic and environmental data to assess the impact of petroleum refineries. The regional results showed pollution discharges 8% above the national models. The authors emphasize the importance of calculating impacts by region rather than across the nation, as there are marked differences between states in the U.S.

An example of Life-Cycle Costing (LCC) was used by Wong et al. (2003) to analyze the cost effectiveness of installing a roof garden on a building in Singapore. The case study showed that an extensive green roof would cost $40.51 more per square meter, however the energy savings to the building by having this green roof would be 14.6% net savings, thus reducing overall energy consumption and making the addition of a green roof economically viable.

Social LCA is not yet a common method used for the built environment. There was no case study exemplifying this tool for buildings in the literature. Common uses at present are for product comparison, such as Hunkeler's (2006) analysis of two detergents available for purchase in Switzerland. The functional unit used was labor hours. The results revealed that detergent 1 generated 20% less employment in Russia and 35% less in France when compared to detergent 2. However, the higher aluminum content in detergent 1 led to five times higher employment generation in Canada and South Africa. Employment opportunities in the country of sale remained steady as well as in Morocco, where the material waste was handled. The author also compares the trend in employment generation to societal benefits such as health care, education and income generation, thus making the conclusion that detergent 1 has higher societal benefits.

III. Practical LCA Applications – Case Studies

This section provides examples of practical applications of LCA. The overview of LCA tools provides a brief background on the importance of selecting the appropriate tool to achieve the desired goals and discusses the difficulty in comparing tools to each other. The five case studies exemplified in this section were chosen to reflect the application of the three common LCA tools used for building analysis in the U.S.: ATHENA Environmental Impact Estimator, U.S. EPA's BEES, and SimaPro. The cases furthermore focus on building energy and heating system assessments and demonstrate some of the applied functions a LCA can have for the built environment. Due to the complex nature of LCA studies and the subjectivity in selecting study parameters and tools, the results of case studies are typically valid only for the study specifications. However, some studies analyze a large number of individual case studies, such as case study #5 below, control for variables, and include general assumptions in their conclusions.

a. Overview of LCA Tools

LCA tools are software applications used for environmental impact modeling (Bayer et al., 2010; Ortiz et al., 2009). A LCA tool is a framework that guides the user through the steps of completing an LCA. Some tools incorporate their own database for the inventory analysis, while others have the capability to link to a large variety of existing databases, thus expanding the regional scope of the tool applicability. See Appendix I for a list of popular North American and International LCA tools available and their corresponding website links, as well as a comprehensive listing of inventory databases. See also Bayer et al (2010) for detailed assessment of LCA tools.

Tools can be divided into broad categories of users, such as industry professionals and general users (Bayer at al., 2010). Software for professionals in the building industry have a complex user-interface with multiple options for database modification and specification for individual needs, such as the option to conduct a LCA for individual components or assembled end products. The tools directed toward general users have a simplified interface with locked databases with fewer options for tailored results.

Usability

- ease of use & understanding
- practicality & accessibility
- time resource required for use
- cost
- data input method
- user skill level

Parameters

- databases included
- impact categories
- functional unit
- impact libraries
- geographic applicability

Outcomes

- targeted end-user limitations (single components, customizable, flexible, hybrid-construction accommodation, etc.)

Figure 5: Points of Divergence of LCA Tools.

LCA tools for the built environment can be further classified into three categories of types of impacts assessed (Bayer et al., 2010; Ortiz et al., 2009; Erlandsson & Borg, 2003). The first is assessments of building products, used mostly to compare construction materials to each other, which can also be considered taking a bottom up approach. The second is building assembly, which takes into account the joint environmental impact of assembled building components, i.e. roofs, by combining their effects. Lastly, the whole-building analysis considers the impact of the building and all the systems that are part of the construction, operation and disassembly phases, including maintenance and replacement of components. The latter two approaches are top-down, evaluating the entire finished building design (Erlandsson & Borg, 2003).

Tools are difficult to compare as each one is based on a different set of criteria (Sartori and Hestnes 2007; Ortiz et al. 2009; Haapio & Viitaniemi, 2008; Pal et al., 2001). See Figure 5 for a list of differentiating points between LCA tools. Furthermore, they each apply to differing geographic regions and are customized to user skill levels. As buildings are site-specific and region-dependent, comparing LCA building case studies to each other can be complicated as local conditions such as microclimate, ecosystem resilience, local infrastructure, and ecological carrying capacity will vary greatly and all play a role in estimating the environmental impacts (Kohler & Moffatt, 2003). For this reason comparison case studies often use prototype models of the same building in different climates or the same climate with different buildings rather than using existing buildings.

LCA tools feature solutions for divergent project goals. To select the most appropriate tool to achieve the project goals it is important to know the capabilities of each tool. A number of studies have been undertaken researching the differences between LCA approaches and tools; see Bayer et al., 2010; Haapio & Viitaniemi, 2008; Sartori & Hestnes, 2007; Ortiz et al., 2009; Zabalza Bribian et al., 2009.

As such conducting a LCA for the same building but using different tools can produce varied results. For example, Matrinopoulos et al. (2007) used three LCA tools, SimaPro, GEMIS, and Eco-It, to conduct a comparitive assessment of a domestic solar thermal hot water system in Greece. The results illustrate the inherent differences among LCA tools. For example, GEMIS weighs the impacts of aluminum higher than Eco-It and SimaPro but weights copper and steel lower than the other two tools. This produced marked differences in the end results.

To circumnavigate this problem, guidance manuals have been created to support consistency and quality assurance for LCA tools and practitioners. The European Commission's International Reference Life-Cycle Data System Handbook (Institute of Environment and Sustainability, 2010) is one example.

b. Case Study Examples

The following six case studies illustrate the functionality, usability, and types of analysis that a LCA has capability for in the context of the built environment. They are centered on building life-cycle energy input and output, heating and cooling systems, and energy efficiency features of homes. The examples range from existing buildings to model buildings comparing the impact of different climate zones.

The tools used in the following case studies can be differentiated by a selection of the following categories, used in Haapio & Viitaniemi's (2008) study of a selection of existing environmental assessment tools: the building to be assessed, tool target user, phase of life-cycle to be assessed, database the tool connects to, and the forms of results.

Case Study #	LCA Tool	Subject	Life-Cycle Phase(s)	Inventory Analysis Database/Impact Assessment Methodologies
1	SimaPro	5 model residential homes	manufacturing, construction, operation	Eco-Indicator 99
2	Various	60 houses	Manufacturing, construction, operation	Various
3	SimaPro	Mixed-use campus building	All	DEAM database, SAFL, Franklin and Associates
4	SimaPro	12 model homes	All	Impact 2002+, Franklin USA 98, ETH-ESU
5	ATHENA EIE	3 model residential homes	manufacturing	ATHENA EIE
6	BEES	12 commercial buildings	construction, operation	BEES 4.0 LCI, *eGRID*, emissions and electricity generation, state level emissions rates and FERC utility rates, US Environmental Input-Output tables

Figure 6: LCA Tool Comparison of Case Study Examples.

Case Study 1: Insulating concrete form vs. wood frame construction in five locations in the US

SimaPro, a process-based LCA tool, was used by Marceau and VanGeem (2006) to model theoretical homes in five climate zones in the U.S. to determine the environmental impact of insulating concrete form (ICF) versus wood frame construction. The results of the study showed that the wood frame house had 3-6% higher environmental impact load in all five case models. The range is due to climate variation throughout the models. This can be attributed to ICF walls having a higher R-value and therefore providing a higher energy efficiency than traditional 2x4 wood frame construction. For both materials the largest environmental impacts stemmed from electricity production and use during the operation phase of the house as opposed to the construction phase. For ICF homes this accounted for 84-91% of total environmental load and for the wood frame homes it was 87-92%. The decommissioning/recycling phase was not included in the assessment. Furthermore, some of the materials were not included because they were not represented in the database for the inventory analysis; this included gypsum wallboard, carpet, roofing materials, and sealants. When actual household usage information is not available, energy simulation software tools can be used as a substitute. This study used VisualDOE to simulate energy use. One noted difference between the two types of homes is that due to the larger R-value of ICF construction a smaller HVAC system could be used. When evaluating the impacts of the construction materials used, for both types of houses the wood and copper tubing were the largest load. See figure 7 for more detail. Other case studies revealed the large environmental impact of copper as well, see Prek (2004), Scheuer et al., (2003), Shah et al. (2008), Tsilingiridis et al. (2004).

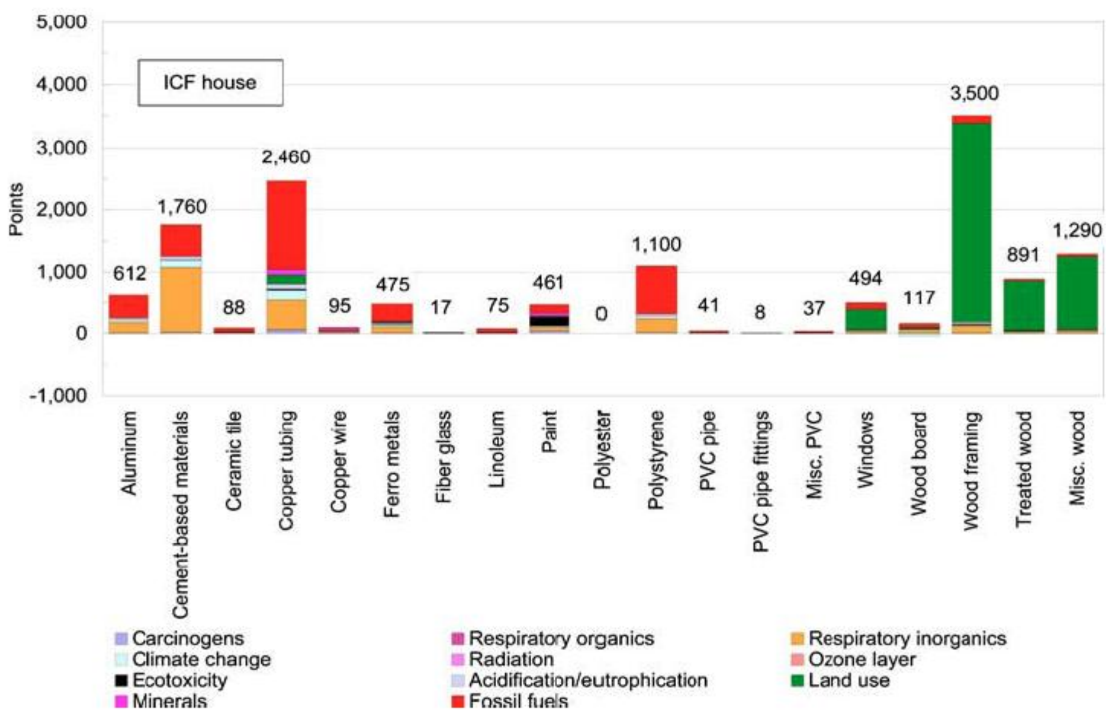


Figure 7: Eco-Indicator 99 model of environmental impacts of construction materials for ICF home in Chicago, IL (Marceau & VanGeem, 2006).

Case Study 2: Comprehensive LCA of a building on the University of Michigan campus

Scheuer et al. (2003) conducted a comprehensive LCA of a 6-story mixed-use building on the campus of the University of Michigan. The LCA was conducted with the SimaPro tool as well as drawing on the DEAM database, SAFL, and Franklin and Associates for data sources. The environmental impact categories chosen were primary energy consumption, global warming potential, nutrification, acidification, ozone depletion potential, and waste generation. The authors chose not to include human and ecosystem toxicity or resource depletion due to lack of methods to obtain accurate data. The energy and water consumption during the operations phase was deduced through modeling; eQuest was used for the electricity. The results indicated that building materials that comprise 72% of the embodied energy make up 98% of the building mass. This indicates that building materials that comprise a large volume do not automatically have high embodied energy values. On the other hand, materials used in lesser volume such as copper wiring, aluminum, latex and nylon for carpeting have higher embodied energy values and high replacement rates (see Figure 8). The authors point out that using materials with high replacement rates and a frequent renovation schedule of a building will invariably increase the overall embodied energy of the life-cycle of a building. Substituting materials that have a lower replacement rate in the design phase may reduce the environmental impact significantly. Overall, the operational phase of the building had the largest environmental impacts and energy use at 83%. During this phase 66% of solid waste was generated, 93% of the nutrification potential through NOx generation, 78% of ozone depletion potential through the generation of grid-tied electricity, and 97% of global warming potential due to CO_2 from fossil fuel use.

The authors point out the need for a standardized environmental product data sheet to provide detailed data on building design and component option to enhance LCAs in the design stages of buildings rather than an ex-ante LCA of existing buildings.

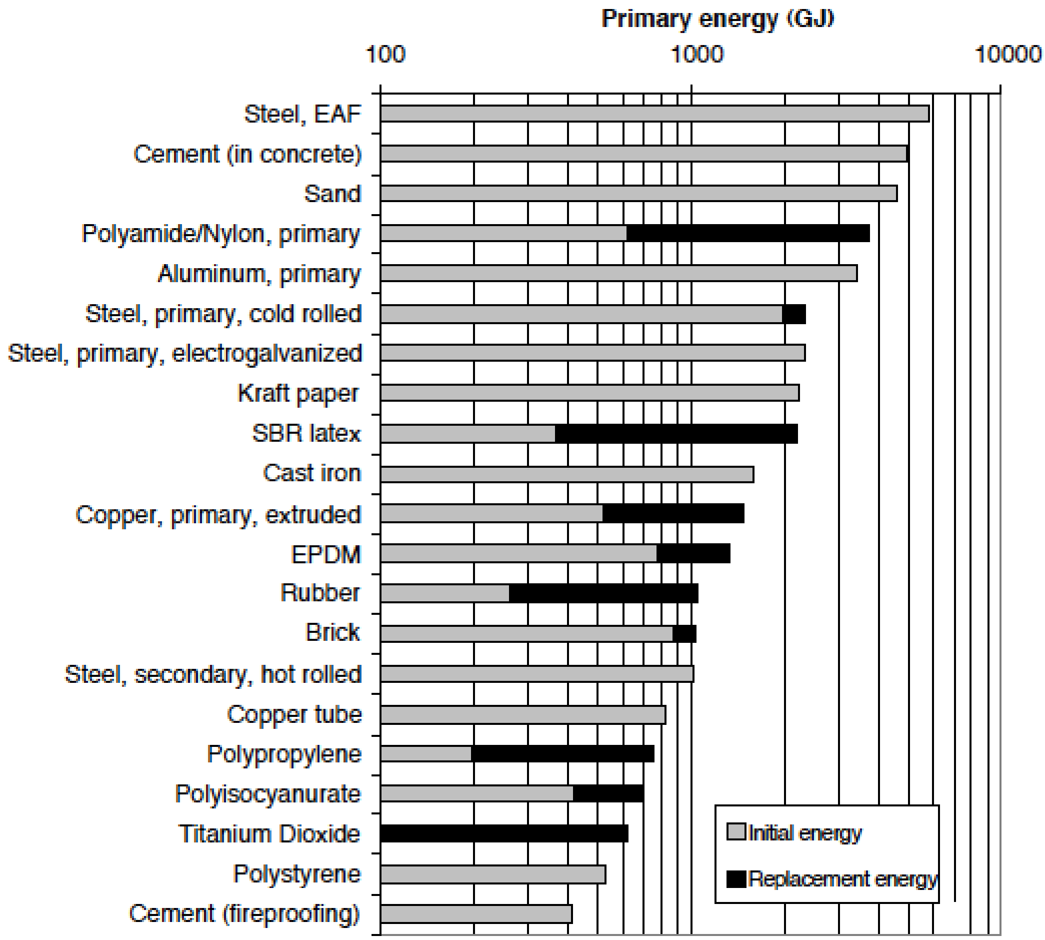


Figure 8: Construction materials making up 94% of initial embodied energy and 94% of life-cycle embodied energy requirements of the building analyzed in the case study (Scheuer et al., 2003).

Case Study 3: LCA of three heating and cooling systems modeled in four climatic locations in the US

An involved LCA was conducted by Shah et al. (2008) comparing heating and cooling systems of models of residential homes in Pennsylvania, Texas, Oregon, and Minnesota. The locations were chosen based on their climatic variances and differences in power generation mix (coal, natural gas, nuclear, petroleum, hydropower, and renewables). The systems studied were central natural gas furnace coupled with conventional central air-conditioning, natural gas powered hydronic heating coupled with conventional central air-conditioning, and an electric air-to-air heat pump for both heating and cooling. SimaPro was used as the LCA tool, drawing on Impact 2002+ for the impact assessment, and Franklin USA 98, ETH-ESU and manufacturer's literature for the data acquisition. The energy use was modeled by DoE2's Home Energy Saver software. The impact categories chosen for evaluation were human health, ecosystem quality, climate change, and resource depletion. The results of the LCA looking at the manufacturing phase, maintenance and associated infrastructure, indicated that the boiler and the air-conditioning system combination had the highest environmental impact over all categories, despite not needing to be replaced during the assumed 35-year lifespan. The authors note that this is due to the metals in the materials. Furthermore, copper pipe, steel radiators, and ductwork in these heating and cooling systems rank high in human health impacts associated with the extraction and manufacturing phases of these products. The air-to-air heat pump ranked lowest in environmental impacts.

When separated by location, the assessment of the manufacturing and operational phases indicated that the boiler and air-conditioning system had the largest environmental impact in Oregon. The heat pump rated highest in Minnesota, Texas, and Pennsylvania because of the high reliance on fossil fuels for electricity generation as well as nuclear energy in Pennsylvania. In Oregon the primary energy source is hydropower. Minnesota rated highest in environmental impacts for all three heating and cooling systems when compared to the other three locations due to the large heating load required annually and the state's electricity stemming largely from coal. The variation in LCA outcomes for each location illustrates the importance of including climatic conditions and regional energy sources in the study parameters, as the operational phase of the heating and cooling system life cycle was more significant in terms of environmental impacts than the construction and installation phase.

Case Study 4: Comparison of three building materials for a residential house in Toronto

The Canadian Wood Council utilized the services of the ATHENA Institute to conduct an LCA determining the environmental impacts of the building envelope and structure of a residential home in Toronto (Trusty & Mail, 1999). The three variations of the models were using softwood lumber with wood I-joist framing, light frame steel framing, and ICFs. The replacement and maintenance value of these components was not included in the study. The six impact categories identified were embodied energy, raw resource depletion, greenhouse gas emissions, air and water toxicity, and solid waste. The ATHENA Institute utilized its LCA tool, the Environmental Impact Estimator, as the software tool. Some modeling and customization was necessary, as the inventory analysis database did not include all of the components of the study. The study included only the manufacturing phase of the building life-cycle since the components were only to be analyzed, however, the authors indicate that a full life-cycle analysis presents a more comprehensive study as operation, maintenance, and replacement can significantly contribute to the energy input. For example, concrete, wood, and steel construction assemblies can all have different R-values that would result in different operating energy needs; the concrete house would be better insulated than typical insulation methods for the other two material options and require less energy for heating. The results of the study are shown in Figure 9.

	Wood Design	Steel Design	Concrete Design
Embodied Energy (GJ)	255	389	562
Global Warming Potential (kg CO_2 equivalent)	62,183	76,453	93,573
Air Toxicity (critical volume measure)	3,236	5,628	6,971
Water Toxicity (critical volume measure)	407,787	1,413,784	876,189
Weighted Resource Use (kg)	121,804	138,501	234,996
Solid Wastes (kg)	10,746	8,897	14,056

Figure 9: LCA results of wood frame, steel frame and ICF houses in Canada analyzing the building envelope and structure.

The authors caution against taking the comparison at face value since each house design includes a large variety of construction materials and design differences. Therefore, a complete comparison would span beyond wood, steel, and concrete variances as a building material.

Case Study 5: Life-cycle carbon and cost assessments of energy efficiency improvements in 12 commercial buildings

Utilizing 12 commercial building models in 16 locations throughout the U.S., Kneifel (2010) analyzed the life-cycle cost effectiveness of energy efficiency improvements as well as life-cycle carbon emissions associated with each design improvement. The author drew on a large variety of data sources for the entire study. Sources for the LCA portion were *eGRID* for energy costs, fuel mix, emissions and electricity generation, state level emissions rates and utility rates. He also obtained data from U.S. Environmental Input-Output tables for information on resource input and SimaPro7 provided information on pollutant flows which are adapted to be used in BEES and BEES 4.0 inventory analysis databases. BEES was used as the LCA tool to calculate the life-cycle costs, life-cycle energy assessment, and life-cycle carbon emissions for the construction and operation phases. The building prototypes included variations of dormitories, apartments, hotels, schools, offices, restaurants, and retail stores and were modeled in locations to represent seven climactic zones throughout the country, including Alaska. The analysis evaluated three energy efficiency design alternatives by using a combination of conventional energy efficiency measures: increased insulation, number of window panes, low-emissivity coating on windows, solar gain control films on windows, passive daylighting, and window overhangs. The combinations were applied to meet ASHRAE 90.1-2004, ASHRAE 90.1-2007 and the Low Energy Case (LEC) design standards. The first result of the study showed that a building's energy use can be reduced by 20-30% by using conventional energy efficiency measures that do not alter the building design. The second result indicated that it can be cost effective to increase a building's energy efficiency by 30% in terms of the payback period, which contradicts a finding from an earlier study. The LEC prototype allows for a smaller HVAC system that decreases the life-cycle cost enough to be life-cycle cost-effective. The energy efficiency measures can decrease a building's carbon footprint by as much as 32% over 10 years. The largest carbon reduction was modeled in states with a high percentage of coal-generated electricity and the lowest reduction in states with a large percentage of electricity generated from renewable resources. The results of the study led to broad recommendations for decision-makers, asserting that implementing energy efficiency components for buildings are cost-effective and have competitive annual investment returns in many climates in the US. Placing a cost on carbon emissions would increase the rate of return on these energy efficiency measures, especially in states with high carbon emissions from coal-generated electricity.

Case Study 6: Comparison of global LCA studies of passive houses, solar houses, green buildings and conventional homes

Sixty LCA case studies in nine countries were reviewed by Sartori and Hestnes (2007) to compare the embodied and operational energy requirements for a range of houses from low-energy green buildings to conventional buildings. The study did not include recycling or decommissioning of the buildings and focused on energy consumption and demand. Two of the case study homes were located in the U.S., the others across Europe, Australia, New Zealand, and Japan. The authors divided up the cases by low-energy houses, defined as requiring less than 70kWh/m^2 annually for heating, and conventional houses. The low-energy houses included self-sufficient solar homes, passive houses, energy efficient homes, and green buildings. Solar homes include both passive and active solar technologies. Passive house refers to a solar orientation that makes maximum use of passive solar gain and can include active solar technology, such as PV systems. Green buildings are classified as the minimization of synthetic building materials and substituting natural, environmentally sustainable materials, and energy efficient buildings utilize passive technology, such as increased insulation. The authors agree that case studies cannot be compared in absolute terms due to differences in the LCA tools used, geographic conditions, and housing designs, however, the study focused on the relative value of embodied versus operation energy for each case study, which enabled broad general assumptions in the conclusion.

The findings show a trend of low-energy houses having higher embodied energy than conventional ones in each case, and lower operational energy needs. Operational energy for all case studies was the highest energy-consuming phase. When comparing case studies that utilized different models of the same building, the authors noted that a solar house required less total energy than a similar house built with green materials. When the solar house was compared to a conventional building, it required double the amount of embodied energy but the total energy was reduced by half. When the solar house was compared to a passive house, the passive house proved more energy efficient. The passive house also required only one-third the total energy needs of a conventional house with only slightly more embodied energy. The authors recommend reducing the energy necessary for the operation phase of buildings to achieve the greatest changes in total energy demand.

IV. Consumer-friendly Life-Cycle Tools

Due to the complex and resource-intensive nature of conducting a LCA, the tools are mostly geared toward a building industry audience. For the end-consumers, i.e. homeowners, there are few options of LCA tools for private use. Depending on the users' industry knowledge and expertise level there are three general categories of free online tools that may appeal to homeowners (see Appendix I for more information on each tool).

Free-of-charge LCA tools are in the first category. These tools do not require a substantial financial investment for their usage and may appeal to end-users who have knowledge of industry terms and an advanced understanding of processes of the built environment. These tools include:

- Building for Environmental and Economic Sustainability (BEES), developed by the U.S. Environmental Protection Agency (EPA) and the National Institute of Standards and Technology, is marketed as a tool for selecting cost-effective and environmentally preferable building products;
- ATHENA EcoCalculator provides users with a quick snapshot of a building environmental footprint;
- CMLCA, developed and hosted by the University of Leiden, is a free software tool to calculate LCA, SLCA, EIO-LCA, LCC, hybrid versions and others;
- OpenLCA is a free open source software tool providing the basic LCA framework, currently being pilot tested in the US;
- Economic Input-Output Life-Cycle Assessment (EIO-LCA), developed and hosted by Carnegie Mellon University, calculates the energy, material resources and emissions output from activities in the US economy.

The second resource for homeowners consists of free online inventory analysis databases. The industry knowledge required would fall between low to medium to be able to maximize the utility of these databases. In the U.S. a number of emissions, energy generation and use, and transportation data are available to the public from the appropriate government agencies. The U.S. Department of Energy (DoE) Office of Energy Efficiency and Renewable Energy compiled a comprehensive list of databases and tools applicable to the U.S. market. The list indicates which tools are free (see Appendix I for a link to the database). A few of these database are highlighted below.

- The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET), developed by Argonne National Laboratory and the U.S. DoE, includes information on power cycles, fuel cycles, vehicles, fleet, and travel carbon calculators.
- U.S. Life-Cycle Inventory Database, hosted by the National Renewable Energy Laboratory (NREL), contains life-cycle information on over 1,300 flows and 600 processes on a large number of categories from air transportation to waste management.
- 3E Plus is a tool by the North American Insulation Manufacturers Association that evaluates insulation options from an energy, emissions, and efficiency standpoint.
- Rehab Advisor, developed by a private company, D & R International, is a tool geared towards homeowners and building professionals alike to determine cost-effective energy efficiency upgrades to existing buildings that have low environmental impacts.

Third, if homeowners are interested in the life-cycle cost (LCC) calculations there are a host of publicly available web-based LCC tools. Conducting an LCC versus a LCA can be significantly less complex, as the functional unit will always be monetary costs and there are fewer variables, assumptions, and impact categories to determine, thus introducing less variability. A sample of the free software tools to conduct a LCC are:

- eVALUator promoted by the U.S. Forestry Service to evaluate the cost-effectiveness of building design improvements to buildings from a life-cycle perspective;
- Building Life-Cycle Cost (BLCC) Programs, administered by the Federal Energy Management Program under the U.S. DoE, is a tool that conducts economic analysis on two or more alternative building designs to compare life-cycle costs;
- LCCLight, developed by ABB Corporate Research, is a very simple, easy-to-use spreadsheet to calculate the costs of each building life-cycle phase to evaluate replacement, maintenance, component alternatives, and overall building costs;
- LCCAid, developed by the Rocky Mountain Institute, is a spreadsheet-based tool specifically geared toward users without a financial background, guiding users through the LCC process step-by-step.

Lastly, for consumers interested in the carbon footprint of their building and their energy use habits as it relates to their home over the life-cycle of the house or an estimated human lifespan, there are a variety of footprint calculators available online. These calculators typically provide a simplified estimation. They do not require expertise or industry knowledge and are often used in classroom activities. A few samples of footprint calculators related to the building industry are:

- Green Footstep, a calculator developed by the Rocky Mountain Institute, assesses the carbon footprint of a building, contains benchmarks for net zero site energy and carbon neutrality;
- Household Carbon Footprint Calculator is U.S. EPA's tool to assess carbon emissions of a household and compare cost and energy saving alternatives;
- Target Finder, hosted by Energy STAR, is a tool that links up energy efficiency targets for buildings with carbon emissions and building designs;
- Building Carbon Footprint Calculator, hosted by Carbon Footprint, estimates the carbon emissions from energy use of a building;
- CoolClimate Carbon Footprint Calculator, designed by the University of California, Berkeley, is a calculator that estimates the carbon footprint of a household.

V. Critique and Limitations of LCA

The critique of LCA as a method has remained relatively constant over the years, despite improvements and updates to the ISO Standards and the LCA tools themselves. A common critique is the voluntary nature of conducting a LCA, which allows for a lot of variation in the methods used, since there is no mandated process or industry data to use as benchmarks (Bayer et al., 2010). This allows for a large range of variability in LCA results, which diminishes the reliability and validity to a certain point. This is exacerbated by the lack of financial incentives in the building industry to conduct a LCA. Conducting a LCA at present is not streamlined and as such can be very resource intensive for the industry.

User Bias

ISO 14040 lists the subjectivity of the assumptions made by users in a LCA as a limitation (ISO, 2006b). The subjectivity comes into play during the parameter selection, weighting, normalization, and choosing impacts and impact categories. This allows for user bias. Haapio and Viitaniemi (2008) point out that the large extent of variety between tools can feed into user bias as well. For example, tools can be selected to produce favorable study results as some items are omitted by certain LCA tools such as the service life of material components, recycling phase, transportation modes, etc. However, all of these items have an environmental impact and should be counted for an accurate assessment.

Data/Process Limitations

Limitations of LCA are often related to data acquisition, accuracy, and omission. Not having correct operational data can lessen the accuracy of a LCA. Oftentimes, if the assessment is conducted during the design phase, the operational energy is based on a model. The accuracy of the LCA could be boosted through conducting a user survey to gauge real-life user habits during the operation of the building, however, this type of survey is often not part of an LCA (Haapio & Viitaniemi, 2008). Geographic relevance of the data can play a large role in the preciseness of the results, for example inventory analysis databases that are relevant to large or global regions will not display data accurate for local conditions (ISO, 2006b). Due to the lack of the availability of complete industry-wide databases, practitioners draw on multiple data sources oftentimes piecemealing databases together for an assessment (Bayer et al., 2010). As each data source has different methods and boundaries it can be like adding apples to oranges. Furthermore, without industry-wide benchmarked data it is difficult to compare the performance of buildings across LCA studies. Data acquired directly from manufacturers can be inaccurate as there is also typically no third-party validation of this information. Having an established industry average would be a step toward benchmarking. Typically, LCA methods utilize a linear sequence when conducting an assessment, assessing the impacts from the materials to decommissioning phase. One critique is that this sequence does not always match up with building construction, where additions, improvements, and rebuilding often take place. Erlandsson & Borg (2003) suggest utilizing sequential life-cycle thinking that incorporates construction, rebuilding, maintenance, extension, operation, and decommissioning/recycling. They argue that the life-cycle phases should be assessed separately, allowing for multiple construction and renovation phases that are added up at the end.

Uncertainty and Variability

Common concerns with the interpretation of LCA results is the inherent uncertainty and variability (Huijbregts, 1998). The uncertainty stems from the difficulty in converting real life situations to LCA data and parameters. There are a few types of uncertainty and variability:

(1) model uncertainty referring to the aspects of the real world that cannot be modeled in LCA tools such as the spatial and temporal effects of environmental impacts;
(2) choice uncertainty allowing for individual users to make choices regarding the LCA that affect the outcome, which also refers to user bias (see above);
(3) spatial variability is typically neglected in regard to environmental impacts disregarding differences in ecosystems, population density, downstream effects of pollution, etc.;
(4) temporal variability occurs mostly in the inventory analysis where differences in time are not taken into account, such as the increased factory emissions during the workweek versus the weekend; and
(5) variability between sources and objects refers to the differences between factories that produce the same product, yet vary in technology used, number of workers required, waste handling, etc.

Since the majority of LCA tools for the built environment do not include a component to address uncertainty and variability, Huijbregts et al. (2003) recommend conducting an uncertainty analysis for every LCA conducted to increase the transparency, credibility and acceptability of the LCA results.

VII. Conclusion

Life-cycle assessment can be valuable for many applications in the built environment. As was exemplified in this paper, conducting a LCA can compare building materials to each other in terms of overall environmental impacts specific to the intended application, going beyond the conventional means of only considering monetary costs, thus allowing for a more holistic view of design decisions. The assessment can evaluate the net effects of energy efficiency of home components during the operation phase of a building and compare this to the environmental burden of manufacturing those components. Using LCA models can compare the performance of the same home design in different climates for research purposes. Conducting this type of environmental impact assessment of similar buildings for comparison can justify design decisions, policy recommendations, and long-term payoff rates.

The assessment method is not without its limitations, however, and the process of conducting a LCA can be very resource intensive and leaves room for user bias. The fact that there are no LCA method certification programs, mandatory standards, or industry benchmarks to date leads to reliability and validity concerns and complicates comparing LCA tools to each other or LCA case study results. Due to the individual parameters of each study, case study results cannot be generalized for the entire industry either. LCA is differentiated from other similar evaluation frameworks such as LCC or carbon footprint analysis in that its output aggregates all environmental impacts versus only looking at isolated midpoint factors, such as monetary cost or embodied energy. With the higher complexity of assessing multiple impacts of the built environment comes a larger uncertainty in the method and results of LCAs. However, with the advent of some of the leading building assessment frameworks and rating systems incorporating LCA into their evaluation criteria, the method will likely continue evolving and improving.

Appendix I

LCA TOOLS	
European Commission, Joint Research Center - LCA Tools, Services, Data "List of Tools"	http://lca.jrc.ec.europa.eu/lcainfohub/toolList.vm
Tools Applicable to North America	
ATHENA Institute EcoCalculator (Canada)	http://www.athenasmi.org/tools/ecoCalculator/index.html
ATHENA Institute Impact Estimator (Canada)	http://www.athenasmi.org/tools/impactEstimator/
BEES Tool (US)	http://www.bfrl.nist.gov/oae/software/bees/
Green Globes (US & Canada)	http://www.greenglobes.com/default.asp
EIO-LCA, Carnegie Mellon University (US)	http://www.eiolca.net/
SimaPro (Netherlands & Global)	http://www.pre.nl/default.htm
LCA Tools Specific to the Built Environment	
ECO-QUANTUM (Netherlands)	www.ecoquantum.nl
LEGEP (Germany)	www.legep.de
EQUER (France)	www.izuba.fr
ATHENA (North America)	www.athenaSMI.ca
OGIP (Switzerland)	www.ogip.ch/
ECO-SOFT (Germany)	www.ibo.at/de/ecosoft.htm
ENVEST 2.0 (UK)	www.envestv2.bre.co.uk
BECOST (Finland)	www.vtt.fi/rte/esitteet/ymparisto/lcahouse.html
BEES (US)	www.bfrl.nist.gov/oae/software/bees.html
GREENCALC (Netherlands)	www.greencalc.com
ECOEFFECT (Sweden)	www.ecoeffect.se
ECO-QUANTUM (Netherlands)	www.ecoquantum.nl
LEGEP (Germany)	www.legep.de
EQUER (France)	www.izuba.fr

Life-Cycle Inventory Analysis Databases	
List of Databases European Commission, Joint Research Center - LCA Tools, Services, Data “	http://lca.jrc.ec.europa.eu/lcainfohub/databaseList.vm
EPA TRACI (US)	http://www.epa.gov/nrmrl/std/traci/traci.html
Green Footsteps (US)	http://greenfootstep.org/
NREL LCI Database (US)	https://www.lcacommons.gov/nrel/search
Pharos Framework (US)	http://www.pharosproject.net/framework/index/
ecoScorecard	http://ecoscorecard.com/
CORRIM (LCI of wood products)	http://www.corrim.org
University of Bath, Inventory of Carbon & Energy (ICE)	http://perigordvacance.typepad.com/files/inventoryofcarbonandenergy.pdf

Energy Simulation/Assessment Tools	
Energy Profile Tool	www.EnergyProfileTool.com
VisualDOE	http://www.archenergy.com/products/visualdoe/visualdoe-version-history
US EPA Emissions & Generation Resource Integrated Database (eGRID)	http://www.epa.gov/cleanenergy/energy-resources/egrid/index.html
US DoE – Building Energy Software Tools Directory, by country (US)	http://apps1.eere.energy.gov/buildings/tools_directory/countries.cfm/pagename=countries/pagename_menu=united_states

Free Databases and LCA/LCC Tools	
University of Leiden - CMLCA: SCIENTIFIC SOFTWARE FOR LCA, IOA, EIOA	http://www.cmlca.eu/
OpenLCA	http://www.openlca.org/index.html
Carnegie Mellon EIO-LCA	http://www.eiolca.net/
Argonne National Laboratory/US EREE -	http://greet.es.anl.gov/main

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET)	
eVALUator, US Forestry Service	http://www.energydesignresources.com/Resources/SoftwareTools/eVALUator.aspx
LCCLight, ABB Corporate Research	http://www.dantes.info/Tools&Methods/Software/webbasedtools_LCCLight.html
LCCAid, Rocky Mountain Institute	http://www.rmi.org/ModelingTools
Green Footstep, Rocky Mountain Institute	http://www.greenfootstep.org/
Household Carbon Footprint Calculator, US EPA	http://www.epa.gov/climatechange/ghgemissions/ind-calculator.html
Target Finder, Energy STAR	https://www.energystar.gov/index.cfm?fuseaction=target_finder.
Building Carbon Footprint Calculator, Carbon Footprint	http://calculator.carbonfootprint.com/calculator.aspx?c=Powwownow&tab=2
CoolClimate Carbon Footprint Calculator, University of California Berkeley	http://coolclimate.berkeley.edu/uscalc

Further Information	
American Center for Life-Cycle Assessment	http://www.lcacenter.org/
EPA LCA Research	http://www.epa.gov/nrmrl/lcaccess/index.html
SETAC	http://www.setac.org/node/32
The International Journal of Life-Cycle Assessment	http://www.springerlink.com/content/0948-3349
Earthster 2 Turbo (open-source free LCA software tool)	http://www.openlca.org/index.html
Carnegie Mellon University, Research on LCA	http://www.ce.cmu.edu/greendesign/research/lca.html

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