PHRC - 2ND RESIDENTIAL BUILDING DESIGN AND CONSTRUCTION CONFERENCE 2014

LIFE CYCLE ASSESSMENT OF RESIDENTIAL STRUCTURES

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ABSTRACT

Building owners, contractors, architects, engineers, and consumers are demanding more efficient and environmentally friendly residential projects and products. However, credible and transparent information on building materials is currently very limited, hampering the ability of designers to conduct an accurate analysis. Life Cycle Assessments (LCAs) are increasingly being used to evaluate structures and building products for environmental impact and performance.

While LCA is an excellent tool for practitioners to identify environmental impacts, it is not a practical communication device for the design and consumer community. Environmental Product Declarations (EPDs) are starting to appear in the US as the common methodology to report product performance, eliminating the need to wrestle with dozens or more individual sources of a data in the LCA. An EPD is a comprehensive, internationally recognized report that compiles and standardizes technical sustainability information. The US Green Building Council's LEED v4 Rating System and Architecture 2030 Challenge for Products are starting the demand for EPD's.

This paper considers life cycle assessment methodologies for accounting residential structure's environmental impacts, the environmental product declarations that lists the relevant product impacts in a clear, consistent, and concise manner, and the international standards that are increasingly integral to production, marketing, and communication strategies across every industry. Material specifiers and design professionals can use these tools to meet today's carbon-constrained challenges and other environmental goals of residential structures.

Market Transformation

The green-building industry is in the mist of rapid change. Residential design professionals are increasingly interested in characterizing and reducing the environmental impacts of the projects they design. Recycled or bio-based content and travel distances have long been used as proxies for material sustainability. Now, we are starting to understand that these substitutes may not achieve the environmental outcomes we seek and a move towards more performance-based outcomes are starting to appear. A key aspect of moving towards this goal in sustainable design is the use of Life Cycle Assessments (LCAs) and Environmental Product Declarations (EPDs).

Over the past two decades the US Green Building Council has been transforming the marketplace with their Leadership in Energy and Environmental Design (LEED) green-building rating system. Virtually every federal agency as well as over 300 city and local governments instituting green building policies have adopted the voluntary rating system. The newest version LEEDv4, launched at their annual GreenBuild convention in 2013, will dramatically change the way designers and consumers consider building products.

LEED has always encouraged the use of environmentally-friendly products in the Material and Resources (MR) credit category, driving market innovation and rewarding design teams with points towards certification. With LEED v4, design teams that take a life-cycle approach to understanding materials and building products are rewarded. While this overhaul of the MR credits did not specifically get adopted in the LEED-Homes rating system, it sets the stage for residential projects to benefit from material reporting and disclosures that require life cycle-based information in order to get closer to the goal of building with lower total environmental impacts.

Life Cycle Assessments

Life cycle assessment (LCA) is the investigation and evaluation of the environmental impacts of a product, process or service. LCA evaluates all stages of a product’s life and considers each stage interdependently, meaning that one operation leads to the next. Inputs to the process may include raw materials and energy. *Life cycle stages* (Figure 1) may include raw material acquisition, manufacturing, building use or operations and, finally, recycling or waste management. The outputs, many of which impact the environment negatively, include atmospheric emissions, waterborne wastes, solid wastes, co-products and other releases.

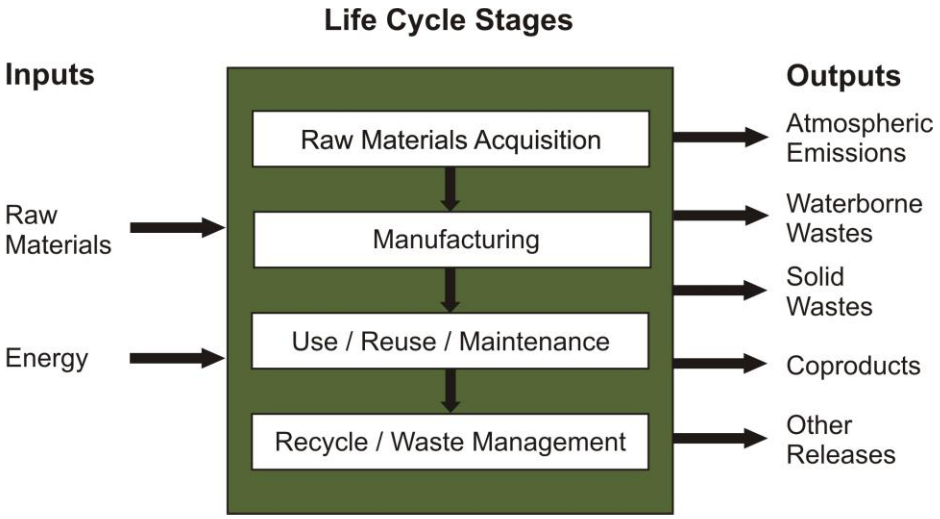

Figure 1. Life Cycle Stages per the ISO 14040 standard

Per the ISO 14040 (ISO 2006a) and 14044 (ISO 2006b) standards, LCA is conducted in four distinct *phases*:

1. *Goal Definition and Scoping* - Define and describe the product, process or activity being analyzed. Identifies the system boundaries.
2. *Inventory Analysis* - Identify and quantify energy, water and materials use and environmental releases. Environmental releases may be solid waste, air emissions and waste water discharges.
3. *Impact Assessment* - Assess the potential human and ecological effects of energy, water and material usage, and the environmental releases identified in the inventory analysis. Environmental impact categories include: ozone depletion, global warming, acidification, eutrophication, photochemical smog, human health issues, ecotoxicity, fossil fuel use, land use, and water use.
4. *Interpretation* - Evaluate the results and select the preferred product or process.

LCA is a more comprehensive way for evaluating the environmental impacts (Figure 2) associated with the entire life cycle of a product, process or building. An LCA of a building, for instance, will tell you how much impact was caused by the building from the point where minerals were mined to the point where the building waste is landfilled. This means the LCA uncovers the whole environmental story and allows the designer to understand the trade-offs that influence design decisions. That way, if a building product has more impacts during manufacture but saves impacts during use, they can see if it is a better environmental choice.

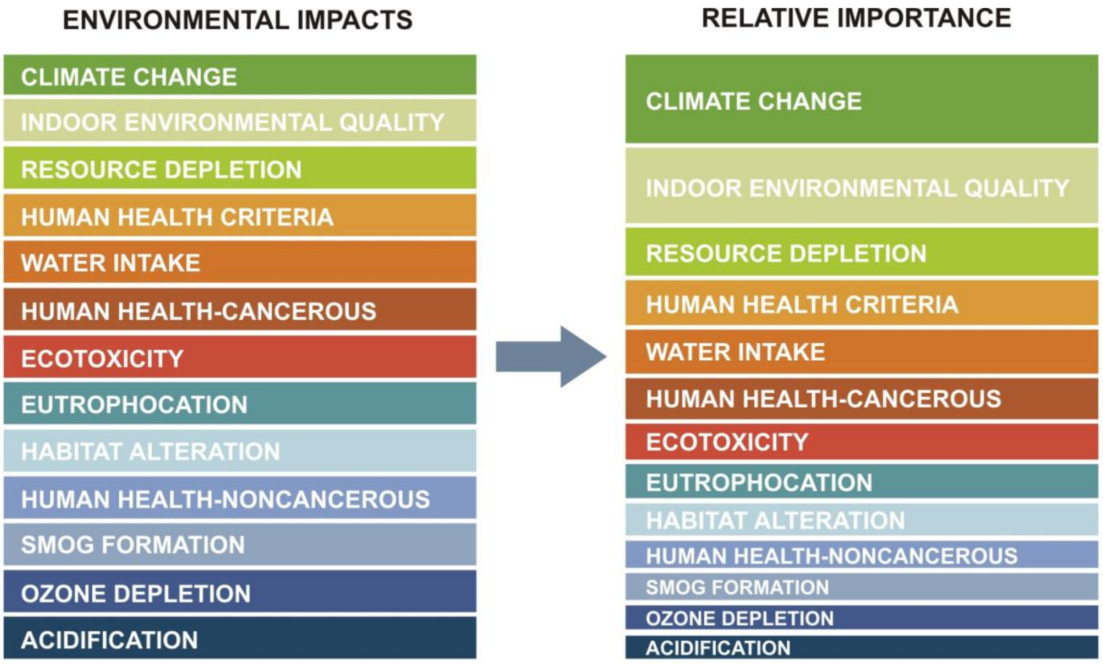

Figure 2. Example of Environmental Impacts and Weighting

For example, the more insulation is added to the house, the less energy you need to heat or cool the building. By adding insulation the designer is adding manufacturing impacts, but the environmental benefits of insulation are so large that the more insulation you add the fewer environmental impacts (specifically carbon as a result of energy use) you get overall, for a net positive environmental outcome. The point is to beware of the past tendency to focus only on single attributes. The essence of LCA is to cast the net wide and capture all of the relevant effects associated with a product or building over its full life cycle.

For residential buildings, the use or operational life cycle stage impacts are significantly greater than those in the other life cycle stages. A home usually operates for decades consuming energy and raw materials with associated environmental releases. This operational stage impacts typically dwarf the environmental impacts from material extraction, manufacturing and end-of-life stages for the building. Although it depends on the type of the residence and the impacts being measured, the operational stage impacts are typically 5 to 20 times larger than stages associated with building product manufacturing and demolition. In fact, operating buildings in the U.S. consumes 19% of the nation’s energy and 37% of the nation’s electricity. In total, residential buildings account for 21% of the CO_2 emissions in the U.S. (Energy Information Administration 2011) Therefore, when conducting an LCA for buildings, it is extremely important to include the operational stage.

While LCA is simple in concept, designers considering LCA for general use face challenges. Most design professionals will need to rely on LCA practitioners to conduct an assessment on their building project. This can be costly and time consuming. There are also problems with consistency, and availability of data on building products especially in North America where LCA is new to the construction market. Here, environmental product declarations (EPDs) based on the LCA will also be introduced in this latest version of LEED as a communication tool to describe the results of the assessment of products.

Environmental Product Declarations

While a whole building LCA is a preferable methodology to assist designers in understanding the impact of the project, the reality is that it may be too costly and resource-intensive an undertaking for most residential projects. Until a streamlined tool is introduced into the market, it may be best to start with individual manufacturers' information based on the product LCAs. This can be found in an *Environmental Product Declaration* (EPD) which disclose life cycle-based impact information based on data collected during an LCA of material production and use, eliminating the need to wrestle with the unwieldy, background LCA documentation. This information allows customers to compare different products and decide which product has better environmental attributes, giving customers the ability to confidently choose products with low environmental impacts.

Often compared to the nutritional label found on virtually every food product, an EPD lists the relevant environmental impacts of a product or service in a clear, consistent, and concise manner. There is no evaluation or "grading" information since no predetermined environmental performance levels are set. Instead, an EPD builds on well-structured and quantitative data certified by an independent third party. It states factual information and leaves the decision of evaluation to the decision maker. For marketing purposes, EPDs can also be used to show how the impact of production is reduced over time.

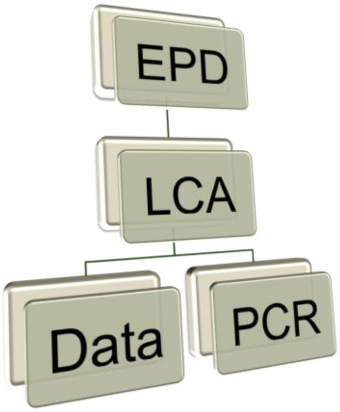

Figure 3. Environmental Product Declarations from LCA

EPDs are developed in accordance with strict international standards that include a transparent verification process for adopting Product Category Rules (PCR) by which

EPDs are developed and verified (Figure 3). EPDs are based on the ISO 14025 (ISO 2010), an international standard with principles and procedures for the development of EPDs and Product Category Rules (PCRs). While EPDs are widely available in Europe, they have only appeared in North America the past few years. For this reason many manufacturers are scrambling to get on board by developing their PCRs and conducting the LCAs to develop their first EPDs. This alphabet soup of new standards and processes will likely cause confusion initially, but as more data become available, the design community only stands to benefit from the increased awareness and disclosure.

LCA Case Studies

LCA is still a relatively new science and can be extremely time consuming and expensive to conduct. Most researchers have only conducted partial LCAs and choose to limit the scope of an LCA by ignoring certain life cycle stages because of the lack of data or scope of research. Others focus on specific impacts to simplify the LCA process. Two examples compared life cycle impacts of insulated concrete form (ICF) and wood-framed residence developed at the CTL Group and the Massachusetts Institute of Technology (MIT) Concrete Sustainability Hub (CSHub) are summarized here.

Case Study 1: Comparison of the Life Cycle Assessments of an Insulating Concrete Form House and a Wood Frame House, *M. Marceau and M. VanGeem, CTL Group, 2008* (Marceau and VanGeem 2008)

In a study conducted in 2008 by Marceau and VanGeem, the researchers compared the results of the environmental attributes of Insulated Concrete Form (ICF) construction (Figure 4) to wood-framed construction. Each house is a two-story single-family building with four bedrooms, 2.7-m (9-ft) ceilings, a two-story foyer and family room, and an attached two-car garage. Each house has 228 square meters (2,450 square feet) of living space. The house was modeled in five cities, representing a range of U.S. climates: Miami, Phoenix, Seattle, Washington (DC), and Chicago. The life of the houses is 100 years. In this study, however, additional environmental impacts were considered instead of solely examining the global warming potential.

The LCA was conducted by first assembling the relevant LCI data from published reports and commercially available databases. The LCA software tool, SimaPro, was used to perform a life cycle impact assessment. Impact assessment is not completely scientific, so three different models were used. The methods chosen are Eco-Indicator 99 (Dutch/Swiss), EDIP/UMIP 97 (Danish), and EPS 2000 (Swedish). The prior version of the report was reviewed by the Technical Research Centre of Finland (VTT, Valtion Teknillinen Tutkimuskeskus) (Häkkinen and Holt 2002).

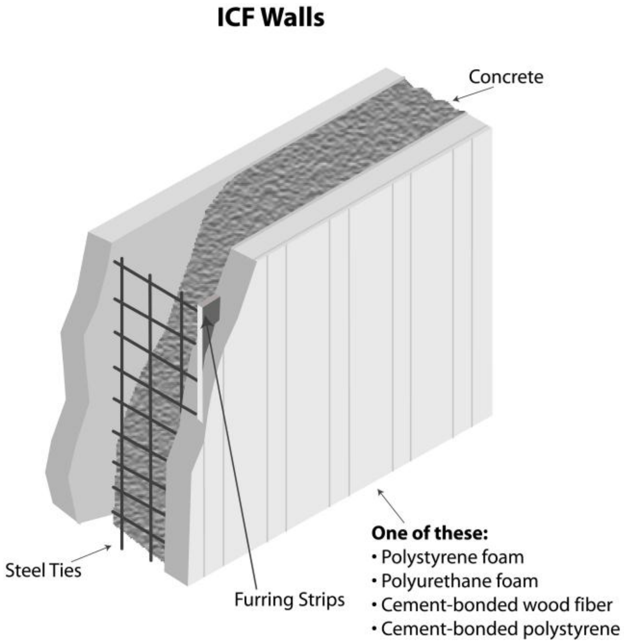

Figure 4. Cross Section of ICF Wall

The data show that in all five methods, for a given climate, the impact indicators in each category are greater for the wood house than for the ICF house. Furthermore, in each of the five methods, the ICF house has a lower single score than the wood frame house in almost all impact categories. The most significant environmental impacts are not from construction materials but from the production of electricity and natural gas and the use of electricity and natural gas in the houses by the occupants. Furthermore, the largest impacts from these uses are in the form of depletion of fossil fuel reserves and release to the air of respiratory inorganics (categorized as damage to human health).

The household use of electricity and natural gas represents 96% of the negative impacts in the ICF house, and 97% of the negative impacts in the wood frame house. The study demonstrated that the energy use is a predictor of LCA results. The ICF house performs better than the wood frame house because of the additional added R-value of the insulation and the thermal mass of the concrete.

Case Study 2: Methods, Impacts, and Opportunities in the Concrete Building Life Cycle, *J. Ochsendorf, et al., Massachusetts Institute of Technology, Concrete Sustainability Hub, Sep 2011* (Ochsendorf et al. 2011)

The general LCA methodology was applied to residential building applications again in 2011 by researchers at the Massachusetts Institute of Technology CSHub. Both Insulated Concrete Form (ICF) construction consisting of concrete walls encased in expanded polystyrene (EPS) insulation and typical light frame wood construction were studied. For all buildings, the roof, partitions and floors are designed in the same manner. Design of the exterior walls and foundations vary between the different buildings. Two types of residential buildings were considered:

1. Two-story, 2400 ft^2 (223 m^2) single-family building.
2. Four-story multi-family apartment building with a total square footage of 33,763 ft^2 (3,137 m^2).

All LCAs were carried out for two different cities in the U.S. to model regional and climatic differences: Chicago, representing a cold climate, and Phoenix, representing a hot, dry climate. The annual operating energy, determined using the EnergyPlus building energy analysis software, was conducted for a 60-year life cycle. Benchmark single-family houses are designed and modeled based on the Building America House Simulation Protocol (BAHSP).

The resulting Global Warming Potential (GWP) was then quantified using CO2 -equivalents (CO2 e) for a number of purposes, including benchmarking emissions for current practices, comparing concrete with wood and understanding the relative importance of different phases of the life cycle. In particular, their work demonstrates that there are measureable differences between various construction materials. The MIT study specifically quantified the carbon emission impact of building systems over its complete life cycle. Information on system boundaries (Figure 5) and processes allocation was clearly outlined and peer reviewed.

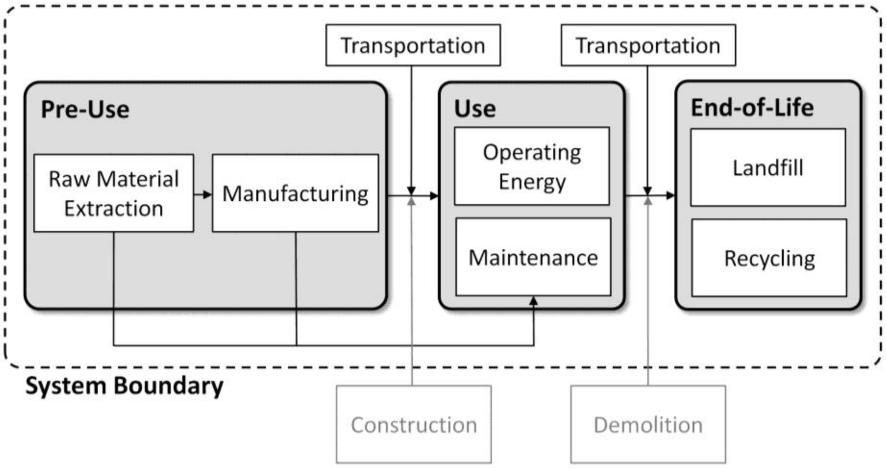

Figure 5. System Boundary Considered

Similar to the earlier study, considering the buildings' entire operational life, the MIT research uncovered concrete's ability to offer a highly resilient structure while providing thermal mass benefits resulting in energy savings. According to the report:

- Concrete homes have a higher embodied GWP in the pre-use phase— but this phase accounts for only about 2-12% of the overall GWP for the life of the home;
- For a cold climate, such as Chicago, the energy savings of an ICF house built

from average to tight levels of air infiltration saves 23% of total operating energy; and

- Over a 60-year life cycle, the lower (5%-8% for single family, 4.4%-6.2% for multifamily) operating GWP outweighs pre-use emissions.

Opportunities to Reduce Life Cycle Impacts of a Concrete Home

The research results demonstrate the benefits of concrete construction over the complete life cycle of a residential structure. There are additional opportunities to reduce the environmental impacts of design teams can take advantage of.

Figure 6. Concrete Components

1. Low Processing Energy- Water, sand, stone, gravel and other ingredients make up about 90% of a concrete mixture by weight (Figure 6). The process of mining sand and gravel, crushing stone, combining the materials in a concrete plant and transporting concrete to the construction site requires very little energy and therefore only emits a relatively small amount of CO_2 into the atmosphere. The amount of CO2 embodied in concrete is primarily a function of the cement content in the mix. Concrete uses between about 7% and 15% cement by mass depending on the performance requirements of the concrete. The average quantity of Portland cement is around 250 kg/m^3 (420 lb/yd^3). This average quantity has consistently decreased with better optimization of concrete mixtures and increased use of supplementary cementitious materials (SCMs) that can improve the strength and durability characteristics of concrete. As a result, approximately 100 to 300 kg of CO2 is embodied in every cubic meter of concrete (170 to 500 lb per yd^3) produced or approximately 5% to 13% of the weight of concrete produced, depending on the mixture proportions, which is relatively low when compared to other building materials (Marceau et al. 2007).

2. Recycled Materials- The U.S. concrete industry uses a significant amount of industrial byproducts such as fly ash, blast furnace slag and silica fume to supplement a portion of the cement used in concrete. These industrial byproducts, which would otherwise end up in landfills, are called supplementary cementitious materials or SCMs for short. The use of SCMs in concrete work in combination with Portland cement to improve strength and durability, in addition to reducing the CO2 embodied in concrete by as much as 70%, with typical values ranging between 15 and 40%. In addition to the use of SCMs in the concrete mix, concrete from demolition can be crushed and recycled as aggregate. Recycled aggregate is often used as backfill and pavement base and is sometimes used for making new concrete. Reinforcing steel in concrete (which often is made from recycled materials) can be recycled and reused (NRMCA 2013).

3. Thermal Mass- Thermal mass is the term used to describe a material that absorbs and stores heat energy. In a building system, it is the mass of the building elements that stores heat during the hottest periods of the day and releases the heat during the cooler evening hours. Concrete is one of several building materials that possess thermal mass properties. In the winter season, high thermal mass concrete walls and floors absorbs radiant heat from the sun and gradually releases it back into the occupied space during the night when the outdoor temperature drops. Concrete is an ideal building material for commercial and residential structures due to its high specific heat, high density and low thermal conductivity.

4. Urban Heat Island Reduction- On warm summer days, the air in urban areas can be 3-4 ºC (6-8 °F) hotter than its surrounding areas. This is called the urban heat island effect (Lawrence Berkeley National Laboratory 2013). The use of light colored pavements, cladding and roofing in urban areas can contribute to overall energy savings and reduced carbon emissions. Because concrete is light in color, it absorbs less heat and reflects more light than dark colored materials, therefore maintaining a relatively low surface temperature. Concrete has been demonstrated to have a positive impact on the localized ambient temperatures and therefore reduce energy required to air condition buildings.

5. Reduced Lighting Requirements- Using concrete for pavements can also help reduce energy demand for lighting. A research study analyzed the lighting required to meet specified luminance for an asphalt and a concrete parking lot. Results indicate that a 250 watt lamp used in a concrete parking lot would produce background luminance equal (or greater) to a 400 watt lamp used in an asphalt parking lot with the same geometric configurations. Therefore, by using a concrete parking surface, energy savings of up to 41% could be realized. With the assumption that an average parking lot lighting system operates up to five hours per day, in one year the asphalt parking lot would consume 60% more energy than the concrete parking lot. In addition, with the increased luminance of a concrete parking lot, the number of light poles can be reduced (Jobanputra 2005).

Conclusion

Life cycle assessment (LCA) is a valuable tool for assessing the environmental impact of buildings. LCA provides a scientific approach to evaluating the merits of design alternatives. The adoption of LCA tools into green building rating systems represents a major step forward in what will likely be an ongoing integration of LCA into the sustainable design process. It is extremely important to include the operational stage of a residential building life cycle since the operational stage impacts dwarf the impacts of material extraction, manufacturing, construction and end-of-life life cycle stages.

Environmental product declarations (EPD) are used to communicate the life cycle based data regarding the environmental profile of products and services, and can be used as a tool in environmental management. The main purpose of EPDs is to provide quantified measure of the environmental impacts of a product or service to professional purchasers, management, government and consumers. Important characteristics of EPDs are objectivity, comparability and validity.

For the few LCAs conducted that compare the environmental impacts of ICF- and wood-framed buildings, it has been demonstrated that concrete buildings can offer energy savings and significant reductions in carbon emissions. Concrete building systems combine insulation with high thermal mass and low air infiltration to make buildings more energy efficient, therefore reducing the environmental impacts of buildings over their entire life cycles. Most importantly, because of concrete’s thermal mass, concrete homes can be extremely energy efficient.

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