(*by*)Metrics (*by*)Design: Building for Endurance

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01 A New Approach

Abstract

Sustainability is not just about efficiency but also longevity. Enduring building design is flexible enough to change with future needs and uses material and energy efficiently. If configured properly with good detailing and infrastructural design they will endure through multiple cycles of use and be adaptable to changing needs. Studying the Bullitt Center in Seattle's Capitol Hill neighborhood, this thesis demonstrates how a long lifespan in a high performance building could be an effective strategy for sustainable design. It looks into the Bullitt Center to evaluate how it would be flexible enough to be commercially viable for 250 years. It also investigates how lifecycle assessment (LCA) can be used to provide credibility through metrics to the call for longer, more enduring buildings.

Architects, engineers, indeed all of society should care about what happens with the built environment. With the amount of energy used by buildings, approximately 48 QBTUs in 2009 alone[1], there is significant alarm as to how that energy is being used. Most of that energy, about 88% of it, went into the operation of building, the systems, lighting, etc. That other 12%, or about 6 QBTUs, is embodied in the materials and the construction process. That seemingly small amount is the focus of this research because over time the impact of that 12% will grow considerably and become a significant part of a building's impact due to the dramatic shift toward higher energy efficiency standards.

This research thesis examined the Bullitt Center with two points of evaluation:

- Create an environment profile of its initial embodied energy and carbon and then project how this will look throughout its long life
- Evaluate the detailing, configuration and infrastructural design to see how it is set up for adaptability and how can other buildings learn from it

Building this profile will illuminate how much environmental impact can be allocated to a building's materials and construction, as the Bullitt Center is design to be a net-zero operational energy building and to last viably for 250 years. This profile was built and evaluated using standard and modified lifecycle assessment (LCA) methods. Three methods were employed, standard tools, hybrid modeling and economic input/output (EIO). Six versions were modeled and the results compared to better understand how LCA can be useful in determining where a designer should focus their attention to on building assemblies that will wield a greater environmental footprint in a long-life building.

It is the position of this thesis that careful consideration during design phases focusing on three areas will enhance the enduring qualities of any building: Configuration, Infrastructural design and Detailing. The Bullitt Center was again evaluated in these respects to exemplify how it is intentionally design to last for 250 years. What lessens can be learned here and applied to other buildings? The techniques employed are shown to be simple and straightforward, require little additional material and without adding costs. The detailing is not extraordinarily different, only arranged in a more intentional way. The architects were able to optimize the materials used allowing them to pull "double duty" with regard to being compositional elements while aiding in the building's performance. This is resource efficiency.

[1] Architecture 2030, The 2030 Challenge, http://architecture2030.org/2030_challenge/the_2030_ challenge

This research yielded these recommendations for lifecycle management and building for endurance:

- LCA is not about precision but overall orders of magnitude leading to lifecycle management.
- Integration of LCA into practice will probably come in combination of regulation and incentives.
- The use of EPDs in specifications can be used as a pre-qualification of product performance
- Architects need to frame lifecycle thinking as a value-adding proposition, not as a barrier.
- Design with practical mechanisms for repairability making it easier to maintain and update.
- Bring longevity into the conversation: construction costs, energy costs, and maintenance & repair.
- Consider longevity and durability on a multitude of scales: small, mid sized and planning.

Introduction: A deeper meaning of *Green Design*

The practice of building almost always begins with demolition. What has become clear is that a LOT of that demolition debris ends up in the landfill. How can designers engage to better this process? The US EPA keeps extensive records on Municipal Solid Waste, of which Construction Waste and Debris (C&D) is NOT included. C&D is also not kept as a separate category.[2] However, they estimate that about 35% of their landfills are filled C&D.[3] In 2010 alone 136M tons of Municipal Solid Waste was landfilled. There are staggering amounts of statistics that point to the same conclusion; we have a pervasive cyclical habit of build and replace, build and replace.

There has got to be a better way to design to avoid this excess waste and to break this habit. Architects have been trained to design buildings in situ with a specific purpose. It is a philosophy that has been around for years. With the societal and technical influences today, this philosophy, though no less poignant, needs to be modified. Inflexible forms and material composition that are too rigid has lead to short-lived buildings (Images 01-03). Some are lucky to have been historically classified such as Dorton Arena in Raleigh, NC. Others have not had the same luck such as the former Wyndham Grand Bay hotel in Coconut Grove, FL, which will be demolished in late 2012. Prentice Women's Hospital in Chicago is at the forefront of this debate currently. These buildings have all had the struggle of adapting and none of them are more than 60 years old. The opposite can also be true of buildings that feel temporary in nature (Images 04 and 05). They are often designed as a kit of parts and seem to lacking a sense of place though they are meant to have a universal appeal, location and flexibility. How can we have buildings that are fully rooted to site, of their place, while still maintaining an air of flexibility?

Images 01. Dorton Arena, Raleigh NC, 02. Grand Bay Hotel, Miami, FL, 03. Prentice Women's Hospital, Chicago, IL

[2] EPA, Municipal Solid Waste, http://www.epa.gov/wastes/nonhaz/municipal/msw99.htm
[3] EPA, Municipal Solid Waste, http://www.epa.gov/wastes/nonhaz/municipal/msw99.htm

Images 04. Cellophane House, NY, NY 05. Temporary Exhibition Structure, anywhere, USA

Perhaps there are strategies that lie somewhere in between such as site built structural frames with added prefabricated component or buildings that open and universally acceptable to variations used types. There should never be a single solution but architects and engineers must take the opportunity to begin talking about how buildings can go together in a way that breaks from tradition. Buildings are torn down for a variety of reasons least of which is because of structural failure. Most often it is land use change, non-structural material failure and outdated aesthetics.[4] Measures taken within this thesis will help with these aspects.

Better, smarter buildings can be many things but ones that are durable, longer lasting and can adapted to future changes are much more sustainable. With high performance buildings we usually think of energy efficiency first. Although energy efficiency has been the trend for several years now, making better buildings is not JUST about efficiency. As mentioned roughly 88% of energy consumed by buildings goes into its operation and therefore becoming more energy efficient is essential though not the only criteria. Better buildings are also about higher grade indoor air quality, better ventilation and more fresh air, increase daylighting and better thermal comfort. Embodied energy in materials and construction is a neglected component that should be addressed on an equal basis with these other measures and durability is an overlooked attribute that is taken for granted. We must add durability as perhaps the most sustainable attribute that a building can have.

Buildings are a collection of a lot of materials and parts representing as much as 425 kBTUs/sqft to construct cradle to gate.[5] This amount of energy could operate a building from between 5 and 13 years based on typical energy use efficiency of 90 to 32 kBTU/sqft/yr. Over the life of the building some of its components, e.g. mechanical systems or thermal envelope, will have to be replaced more often. This recurring energy embodied in the materials and reconstruction grows exponentially over the next 100 years. With each replacement that footprint of energy is added. Right now operational energy makes up most of the impact a building has in its life with embodied energy playing a minor role. As the operational

[4] Athena Institute. (2004) "Minnesota Demolition Survey: Phase Two Report
[5] Cole, R.J., & Kernan, P.C. (1996). Life-Cycle Energy Use in Office Buildings. *Building and Environment, 31* (4), 307-317.

energy efficiency increases, the overall energy pie profile will shrink and unless embodied energy in materials also follows this trend of efficiency, it will become a dominant factor in any building's environmental profile (see Image 06, page 15). Most clients are concerned with maintenance and repair costs. They understand that a single part will not last forever and will need to be replaced. Architects must also start thinking about building design in terms of lifecycle management. A building is not an event; it is a marathon needing strength, flexibility and replenishment along the way. It needs to last in good condition for a long time.

Endurance, Durability and Adaptability in Building Design

Durability of a product is not just about the solidity of its material but also its longevity and how well it lasts over time. Enduring building design is durable to the elements and to the users within them. This type of building is designed to manage the changes that must occur, changes in use, occupant type, refurbishment of systems through maintenance and reconstruction, aesthetics and many others. Designers play a role in how flexible and adaptable a building can be. Adaptability can be construed as many things within the nomenclature of architecture. Common ones would be to accommodate changes of use, renovation, and/or possibly additions. For the purposes of this thesis, adaptability and adaptable design refers to the holistic design of a building that allows for it to be easily maintained and changed so that it encourages a longer lasting building. Rather than a descriptive word labeling a building as *Adaptable*, it should be recognized that buildings exist and endure; they are always changing as people occupy them and as weather takes its toll. Buildings endure over time slowly breaking down, needing to be maintained and repaired. Although stationary they are not static objects but dynamic ones. Architects must understand and work with this in a tangible way. Applying strategies for designing for adaptability and endurance will help architects and engineers get closer to the ideal harmony of sustainability by design buildings and using materials in such a way that they can be reused in the future as a renewable resource.[6]

Current building practices, as well as being fueled by real estate systems, puts a lot of pressure on building owners to rebuild or replace rather than reuse. This leads to wasted materials hauled to landfills and to buildings that will once again become obsolete too quickly perpetuating the cycle.

> *The National Association of Homebuilders projects that 20 million tons of debris could be diverted from landfills if only one quarter of the buildings demolished every year were deconstructed. National Association of Home Builders, "Deconstruction: Building Disassembly and Material Salvage," 1998*

Understanding facts and gathering information regarding embodied energy, operational energy use, transportation, life cycle assessment, and others is important. Without turning them into actionable items nothing will be done to redirect from the current condition of our built environment. These actionable items could take many forms but this paper asserts that adopting strategies of endurance and adaptability into the initial design phases will benefit future owners and building occupants with little added cost. It remains to be fully proven that higher performing, "green" buildings have an initial higher value, retain that value longer and will have a greater appreciation than more conventionally built and operated

[6] Webster, Mark D. (2010) "Design for Adaptability and Deconstruction," *Sustainability Guidelines for the Structural Engineer*. American Society of Civil Engineers, Reston, Va., pg 85

buildings.[7] However, speculation about this is high and case-based experiments are underway that could prove valuable keys to this view of the next generation of buildings.

Environmental, Social, and Economic aspects

Designing better buildings could not be complete without recognition that they are a part of the built environment, used by people, have costs associated with them and have environmental burdens linked to them. Their designs should adhere to the *Triple Bottom Line*. John Elkington, a British environmental consultant, first used the term; the Triple Bottom Line in 1997, to refer to ways a business should understand the full cost of doing business and their role in it. This included the three Ps: Profit, People and Planet as a strategy of recognition that their practices contact people on multiple levels and must therefore take responsibility for it.[8]

Building design crosses all three realms as well and should not to be lost on the architecture profession. Reasonable profiles of environmental impacts associated with a building product can be produced today through the use of lifecycle assessment (LCA). The International Organization for Standardization (ISO) has written guidelines concerning lifecycle assessment. It is an accounting method of collecting the data of all the inputs and output associated with the making of a product over the duration of its life.[9]

Accounting for the environmental impact is necessary but those other aspects must also be included to garner a holistic picture. Economic and societal benefits and burdens play just as much of a role in the health and balance of the built environment. These aspects must be considered a part of an integrated system and should therefore be accounted for. Although ISO guidelines do not provide for a structure to gather these, they do recognize their importance.[10] Other standards, specifically the EN 15643 series developed by the European Center for Standardization (CEN), specifically address ways to effectively capture and communicate this data. The EN 15643 series is formulated to be complimentary to the ISO 14040 standard and even expand upon it.[11]

Considering the amount of effort that is needed to do a thorough accounting of all inputs and outputs, then adding expanded parameters, economic and social information is not easily collected. The economic evaluations could be measured by surveys of the local demographic (e.g. rentable rates, rental contract length, lease turnover, etc.) but even that does not necessarily paint a deterministic picture. The social or cultural aspects are even more subjective and qualitative. There are currently new standards attempting to guide this inclusion of social and economic factors into LCA, such as EN 15643-3 out of Europe, defining social performance with multiple keywords to be folded into LCA. Although intriguing and very important, this report will not dig deeply enough into these theoretical aspects of LCA to put forth any solid opinions.

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[7] Wright-Chappell, Theddi and Chris Corps (2009). "High Performance Green Building: What's it worth? Investigating the Market Value of High Performance Green Buildings."

[8] Hindle, Tim. (2008). "Guide to Management Ideas and Gurus," The Economist, The Economist Newspaper Ltd.

[9] ISO (2006c) 14044:2006 Environmental management-Life cycle assessment-Requirements and guidelines. Geneva: ISO.

[10] ISO 14040: 2006

[11] Simonen, K and Liv Haselbach (2012). "LCA for WA: Life Cycle Assessment (LCA) and Buildings Research for WA State."

When economics and cost relationships to a product's lifecycle are considered, usually the term Lifecycle Costing Analysis is used. Strictly speaking, LCA and LCCA are two separate methods and systems of study. However, cost associations are intricately connected. Although there are new attempts to fold the two together (e.g., EN 15643-4, considering two types of values within a building: collective product costs (the building cost) and its financial value) LCCA will not be further discussed.

Because there are so many decisions to be made in any one building design, no single attribute can fully define its direction. Within any owner's brief will be certain preference criteria for what will lead, i.e., the new headquarters of a mineral water packaging company may have a strong inclination to know how much water is used to create the building's materials—its water footprint. The same could be said for any attribute like global warming potential, carbon dioxide emission, toxic chemicals in materials, etc. A study of the environmental impacts of a building with LCA tells one part of the story but economic and societal concerns must also be considered accordingly. Although this Triple Bottom Line approach is essential a larger discussion but given the limitations of current methods of integrating social aspects and the time limitations related to cost, this thesis is focused on the environmental aspect of sustainability.

Literature Review

In 2003, Ed Mazria wrote three articles that set in motion the movement of the *Architecture 2030 Challenge*. "It's the Architecture, Stupid" was published in *Solar Today Magazine*[12] as a call to action for the architectural community. It article had a great balance of facts and figures with a philosophical metaphor of how to change the world as architects. The inspiration caused by this article has resonated throughout this research as a beacon of striving for change, a call to action, a technical guide to translation of information and many others. It was a starting point for both the *Architecture 2030 Challenge* and for this thesis: *(by)Metric (by)Design: Designing for Endurance*.

The research for this thesis found itself moving in two currents. The first was through several vantage points of those professionals it would impact such as architecture, engineering (specifically structural), scientists and industry representatives. Many of these fields are forging ahead looking for ways to dramatically change the way buildings operate, they way they are put together and in general ways to create better buildings. The other current was typically more technical in nature, mostly papers of scholarship, journal writings and historical reports. These provided a technical link to using metrics in a practical way as well as forcing this thesis to translate difficult information into concise, targeted and palatable communication collateral.

Many practical books have been written on the subject of adaptability in design, designing for disassembly, energy efficiency, etc. What is possibly more meaningful are those that take a philosophical look at these and work through how it is done and why it would be beneficial to various groups. James Douglas takes on many different aspects of remaking buildings in *Building Adaptation*.[13] His longing for the actions of "adapt and refurbish first, rebuild second" are felt throughout and his very detailed expression of best practices are a great help to understand how. It is aimed at educating the young designers and inspiring a different path. Stephen Kieran and James Timberlake take a similar approach to call architects to recognition that other industries are blazing ahead without them in *Refabricating*

[12] Mazria, Ed. "It's the Architecture Stupid." *Solar Today Magazine*, May/June 2003.
[13] Douglas, James (2006). *Building Adaptation*. Elsevier Ltd. Oxford, UK.

Architecture.[14] Their thesis is about how architecture can look to other industries that have embraced automation as a blueprint to making better buildings. It does not hold a single focus to highlight prefabrication as the only solution; it explores many avenues of smarter buildings and smarter design. These books call architects to rethink the way that they have always done their work and to look for more than typical solutions.

The Bullitt Center's architects realized that with their client's brief asking for a building that would last well for 250 years that they had to think strategically about it in layers. Stewart Brand has made this concept of the six S's popular with his 1994 book, *How Buildings Learn*. How buildings react to their environment is the key to their continued longevity and the Bullitt Center has learned that lesson in its proposed shearing of its skin over time to protect its structure from needing to be replaced. The only part of the project that will not change, Brand argues, is its site. However, the structure will change much slower than the skin or the services. This piqued this author's interest as a way of understanding lifecycle management of buildings and led to the question of how could a building learn in a proactive way, not simply be reactive to its environment.

Engineers take a different view of material efficiency and lifecycle assessment design, which was incredibly valuable perspective for this research. *Sustainability Guidelines for the Structural Engineer* is a collection of guidelines assembled by the Sustainability Committee of the Structural Engineering Institute of the American Society of Civil Engineers. Several essays outline benefits of resource optimizing and how to better allocate those resources within a building's design. The guidelines three major sections were all poignant for this research especially when looking at how to better evaluate a building designed for disassembly.[15]

One technical paper was specifically helpful in terms of spelling out the concept of buildings changing over time and how that pertains to embodied energy and carbon. Raymond Cole and Paul Kernan's Life Cycle Energy Use in Office Buildings identifies scientifically how much embodied energy is in a building initially and them models the recurring energy in time. This experiment was repeated with variation in our LCA models. There were numerous other papers that were used to create more well rounded view of some of the more technical aspects of the research. Full listings of papers and books are located in the Bibliography.

02 Existing Buildings and their Importance to Environmental Impacts

Significance of Embodied Impacts

At the root of the built environment surrounding us daily are the buildings we occupy. These buildings are the result of a systematic construction process that started long before the first person began working within. If traced back to its source, the flow of materials is a journey that involves many people, machines and energy for production. Any building requires a great quantity of materials, all of which must be made from raw materials and processed with some form, or forms, of energy. This amount of expended energy can be *embodied* within the building and its materials as a representative amount. Embodied energy is the

[14] Kieran, Stephen, & Timberlake, James. (2004). ReFabricating Architecture: How Modern Methodologies are Poised to Transform Building Construction. New York: McGraw-Hill Companies, Inc.

[15] Kestner, D., Jennifer Goupil and Emily Lorenz, eds. (2010) *Sustainability Guidelines for the Structural Engineer*. American Society of Civil Engineers, Reston, Va.

amount of energy required to process and supply the material under consideration to the construction site.[16] This quantity, recorded for a material's primary energy used in production, is often given in either MJ/kg or kBTU/lb. This includes an accounting for the energy to extract, process and transport the materials to their place of use, as well as to demolish and/or recycle components.

The terms *embodied carbon* and *embodied energy* are often used interchangeably. Although similar, they are not the same. The amount of energy needed to bring a product through to installation will remain the same regardless of what form of energy was used to create it. If, for instance, renewable energy is the main power source for a factory there will be less carbon dioxide and other greenhouse gases embodied but the same amount of energy used.[17] The current state of US power indicates that around 83% of energy (BTUs) used is from fossil fuels as the primary fuel source; therefore, the amount of embodied energy and embodied carbon would be quite similar.[18] Projections show an increase in bio-based and renewables fuels in the coming years; however, for this report the terms will be used interchangeably to reduce confusion.

Embodied energy is generally regarded in two time sections: the initial embodied energy and the recurring. The initial embodied energy is the energy needed to get a material from cradle to gate, or from raw material through to installation in the building; it includes transportation. Over time, the building must be maintained, replacement parts must be brought in, and renovation must occur, all of which comes with the processing of new materials and some degree of re-construction. The energy expended for these tasks is referred to as recurring embodied energy. In a 1996 paper[19], researchers Raymond Cole and Paul Kernan evaluated a typical Canadian office building to ascertain the life cycle energy allocation in a building. They modeled a 50,000 ft^2 commercial office building (one with an averaged structure: wood, steel and concrete averaged together) and were able to show that it had an embodied energy of 4.82 GJ/m^2 or 424.4 kBTU/sqft. That data broke down into six categories: Envelope (26%), Services/Equipment (24%), Structure (24%), Finishes (13%), Construction (7%) and Site Work (6%). They go on to estimate the recurring energy within each of these categories over periods of 25, 50 and 100 years. What they found was that the Services/Equipment, Finishes and Envelope would have a dominant amount (93%) of the embodied energy over that 100-year period. Though the structure represented the heaviest investment of initial embodied energy, it never had to be maintained in their models; therefore, over the course of time its initial investment was diminished on a per-square-foot basis. Considering that foundation and other structural repair could have quite a high construction and site work burden, it would beneficial to build and protect a very strong structure as the building's core.

The concept of measuring energy embodied in materials first gained widespread recognition in the late 1970s. Not only was the Arab Oil Embargo focusing the attention of the nation on supply, it made us think

[16] Hammond, G. P. and Jones, C. I., 2008. Embodied energy and carbon in construction materials. Proceedings of the Institution of Civil Engineers - Energy, 161 (2), pp. 87-98.
[17] Hammond and Jones, 2008
[18] U.S. Energy Information Administration, US power supply chart for AEO 2012, http://www.eia.gov/forecasts/aeo/er/early_fuel.cfm
[19] Cole, R.J., & Kernan, P.C. (1996). Life-Cycle Energy Use in Office Buildings. *Building and Environment, 31* (4), 307-317.

about the efficiency of resource use.[20] It called into question the common feeling of utter abundance and our laissez-faire attitude toward waste. In 1967, a database inventory of the embodied energy of the materials used to construct new buildings was created.[21] Three different models were then devised to survey existing buildings with the hope that if we better understand the value of the existing, we will feel empowered to conserve. These models were used for years, with different degrees of accuracy, to determine the energy represented in any existing structure. In more recent times, similar studies have been undertaken. In the late 1990s, an Australian governmental group, The AU Greenhouse Office, part of the Department of Climate Change and Energy Efficiency, published a report that modeled the embodied energy of 60 case study buildings and used that inventory and model to project greenhouse gas emissions through 2010.[22] The findings of whether the embodied energy was significant with respect to the building's environmental impacts were consistent with other reports in that it is a small but growing part of the energy profile of buildings.[23] At the University of Bath another such research project is underway. Researchers there have created a modern inventory of over 200 common building materials to quantify their embodied primary energy and carbon.[24] This Inventory of Energy and Carbon (ICE) was developed to intentionally target the practices of the UK, although the data could be used elsewhere due to incomplete profiles specific to the UK and an energy mix there that is similar to mixes elsewhere in the world. The methods employed in the University of Bath's ICE are well described by Geoffrey Hammond and Craig Jones in their 2008 presentation to the Institution of Civil Engineers.[25] With most of the data coming from secondary sources, selection criteria was established with stakeholder input.

Possibly because there are no financial or regulatory ties to understanding or measuring embodied energy, the general public (including building owners) does not grasp the significance of embodied energy. Operational energy accounts for around 88% of the energy used during the lifetime of a building.[26] On the whole, it is wise to attack the larger problem first, and that is energy efficiency in operation. However, if embodied energy is not addressed with the same rigor of efficiency in mind, one day it will become a much more dominant fixture in the environmental profile of any building. As buildings become more efficient to operate, they become less environmentally impactful in their demands for electricity and gas/oil for combustion. Their embodied energy and its related environmental impacts, however, have not changed. This effect can be pictured as a pie chart divided into two uneven slices. The biggest slice (representing operational energy) grows smaller, forcing the other slice (representing embodied energy) to grow larger in proportion to it even as the overall pie is getting smaller. The embodied energy "slice" is playing a more dominant role than it once did. (Figure 06) In 2009 the United States used about 98 QBTUs of energy, half of that went into buildings.[27] Of that half, construction and materials amounted to only 5.6%. (Figure 07) That six percent is still about 5.5 QBTUS.

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[20] Smith, Baird M and Carl Elefante, "Sustainable Design for Historic Buildings: Foundations and the Future," APT Bulletin, Vol. 30, No. 3/4 (2009), pp. 19-26, Association for Preservation Technology International.
[21] The final report from Booz, Allen & Hamilton was: Advisory Council on Historic Preservation, *Assessing the Energy Conservation Benefits of Historic Preservation: Methods and Examples* (Washington, DC: 1979).
[22] "Australian Commercial Building Sector Greenhouse Gas Emissions 1990–2010," report, 1999
[23] "Australian Commercial Building Sector Greenhouse Gas Emissions 1990–2010," report, 1999 page 6
[24] Hammond, G. P. and Jones, C. I., 2008. Embodied energy and carbon in construction materials. Proceedings of the Institution of Civil Engineers - Energy, 161 (2), pp. 87-98.
[25] Hammond and Jones, 2008
[26] Architecture 2030, *The 2030 Challenge*, http://architecture2030.org/2030_challenge/the_2030_ challenge (graphs)
[27] Architecture 2030, graphs

However, based on the energy efficiency trends and the growing participation by firms in the Architecture 2030 Challenge, that ratio is poised to shift to nearly a 40:60 split over the next 20 years. (Figure 08) Embodied energy is growing to have a greater impact how building design should be considered.

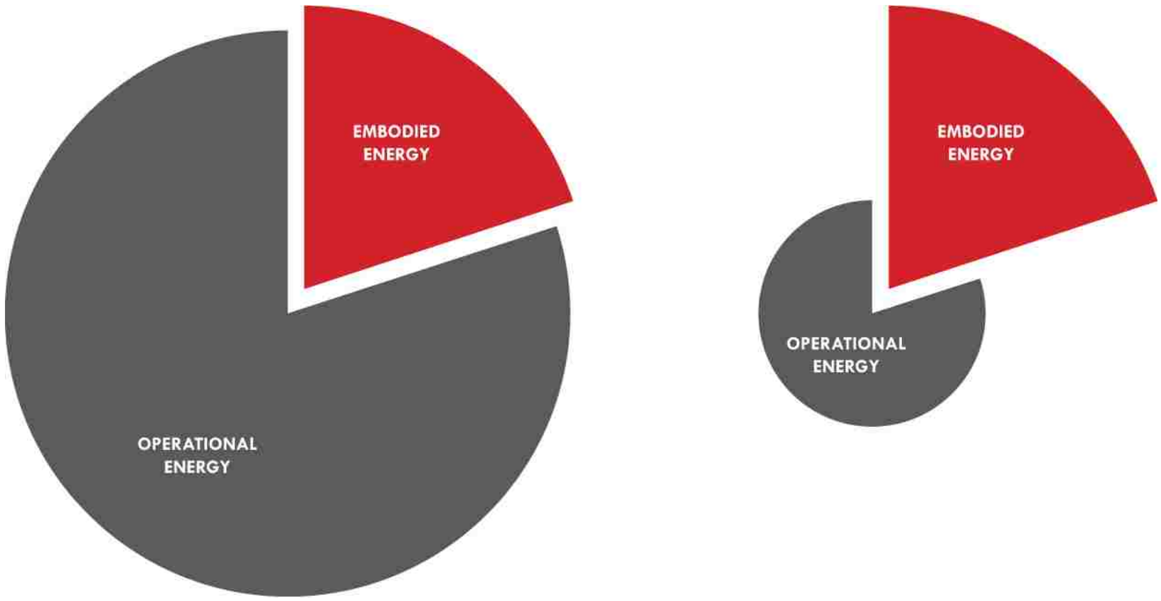

Image 06 – Total energy pie now; the future pie under increased energy efficiencies.

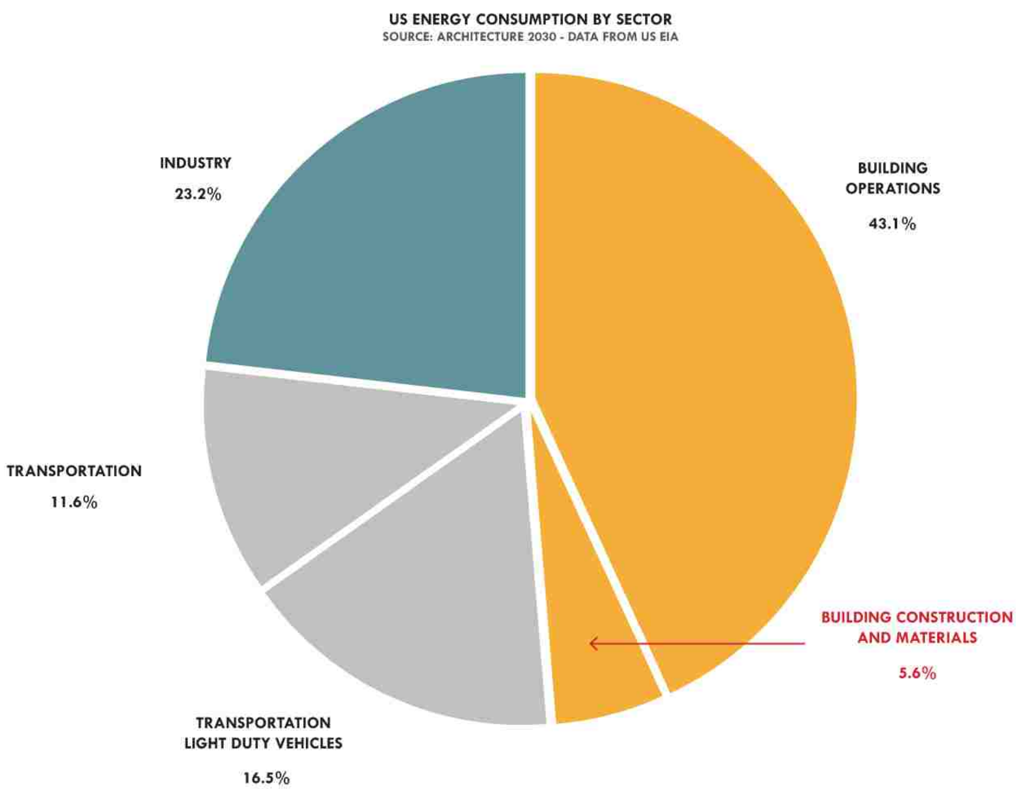

Image 07 – US energy consumption and embodied energy slice

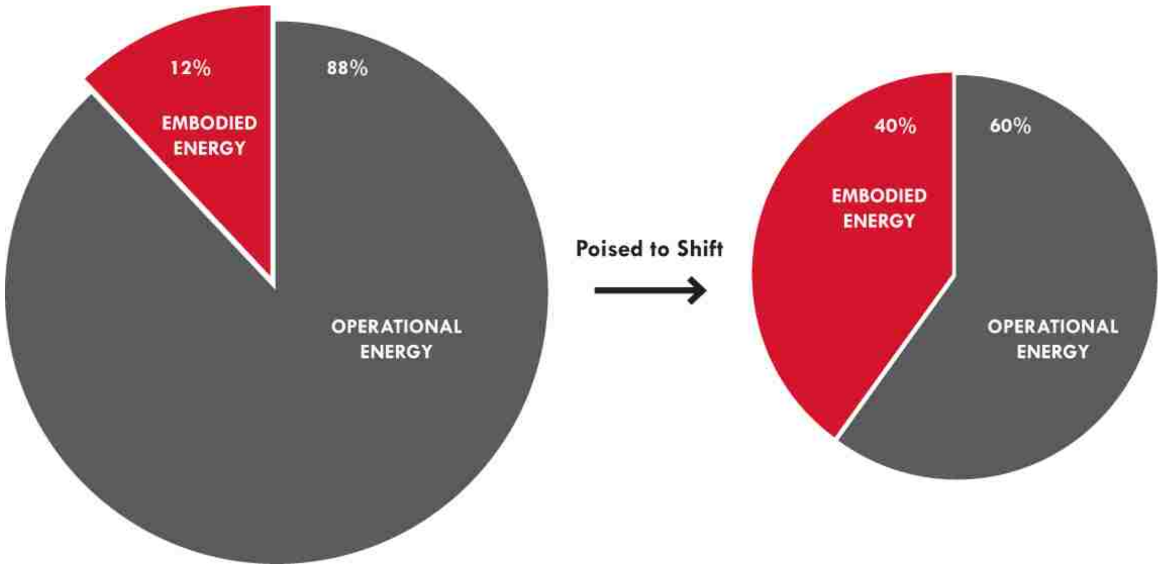

Image 08 – Energy pie poised to shift to include a more dominant picture of embodied energy

Potential consequences of disregarding embodied energy in existing building stock

Information such as this relating to embodied energy should lead us to reconsider the significance of existing buildings. Preservation Green Lab in Seattle, along with the National Trust for Historic Preservation, released a report recently documenting the avoided impacts associated with the reuse of seven different building types across four different climate zones within the US.[28] With LCA this report was able to show that if an existing building were to be torn down and replaced with a new building, it would take between 10 and 80 years for the added amount of energy to be "paid back."[29] They were able to show quantifiably that by reusing the existing materials in existing building the savings potential is between 4 and 46 percent in avoid impacts that would have occurred by rebuilding. As an example, the report demonstrates that if Portland, Oregon were to shift to a citywide policy incentivizing reuse over the next ten years, there could be approximately 230,000 metric tons of CO_2 saved. This represents approximately 15% of Multnomah County's goal toward total CO_2 reductions. If other cities and counties across the country were to install a similar direction there could be substantial savings generated.[30]

A building's materials are not going to gain or lose energy once created. Because of the energy necessary to manufacture them there is added value in avoiding the need to remake them. This line of logic continues at the whole building level in that by ignoring other potential uses of the materials, once the building is constructed the only value of it is in the avoided costs/impacts of not constructing another building to replace it. This is the "Avoided Impacts Approach."[31] The consequence to which this topic is

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[28] Preservation Green Lab Report (2012). "The Greenest Building: Quantifying the Environmental Value of Building Reuse." Accessible at http://www.preservationnation.org/information-center/sustainable-communities/sustainability/green-lab/lca/The_Greenest_Building_lowres.pdf

[29] Preservation Green Lab Report, 2012

[30] Preservation Green Lab Report, 2012

[31] "Avoided Impacts Approach" is outlined in The Greenest Building: Quantifying the Environmental Value of Building Reuse by Preservation Green Lab, pp. 20

referring has to do with those avoided impacts of demolition and reconstruction in building replacement. The National Trust for Historic Preservation points out that based on a 2004 report by the Brookings Institute, by 2030 we will have demolished and replaced 82 billion square feet of our current building stock.[32] This estimate is nearly 1/3 of our estimated 300 billion square foot of building stock.[33] Further, the Brookings Institute calculated that to demolish and reconstruct 82 billion square would require the same amount of energy needed to power the State of California for 10 years.[34] This is a dramatic amount of energy that could be saved by rehabbing and adapting these buildings for reuse. Considering that it would take an individual person recycling approximately 46 aluminum cans every day for 80 years to create the same savings in volume as the contents of a ten story building approximately 100' by 50' that is demolished.[35] As a society we should be moved to keep our buildings is use for as long as possible. Moreover, the constant replacement of buildings is more of a loss than just debris in a landfill as it has other tangibles uses such as energy conversion as burned waste, reusable value and many others. These effects can be measured in dollars saved or kBTUs produced. The intangibles are much harder to ascertain as that value does not have a price point. The loss of social fabric bound in buildings built a century ago is irreplaceable. To some people it could be the loss of a landmark; to others it could be a lost connection to their youth. No matter how it is measured there is a sense of loss bound in the razing of an old structure.

"Living Buildings (those certified by the Living Futures Institute under the Living Building Challenge) are a great thing but we can't build our way out of the climate mess that we're in. (Attributed originally to Richard Moe of the NTHP.) We MUST focus our attention on the improvement of existing buildings, operational efficiency and efficiency of use. We must keep and reuse every building that we can because there are too many resources that will go to waste."[36] This is absolutely true. However, Americans are a society of consumers. We save some but often we use once and throw away.[37] This is prevalent in our built environment, so much so that when a building is no longer good enough (value, size, aesthetic, non-structural condition, etc.) we tend to raze it to start over.[38] The advocacy of reusing old buildings is a paramount concern but using forethought in how we design and build the next buildings will determine how they can be dealt with in the future. This thesis does not go so far as to compare environmental impacts of newly constructed buildings with that of existing ones. That comparison is interesting and could be insightful information for use by architects and their clients. Opportunities such as this could be taken in further phases of this report.

Accounting for important data

Emissions from industrial processes are widely considered by scientists to contribute to climate change, acidification of water in the atmosphere and biosphere, eutrophication of lakes and oceans, low-lying

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

33 Green Halo News, website - https://greenhalosystems.com/?page=ghs/articles&ARTICLE_ID=53

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

35 Merlino, Kathryn R. Class Lecture. Building Reuse Seminar. University of Washington, Seattle, Wa. 06 April, 2012.

36 Allen, David. "Building Smarter Buildings," presentation to Environmental Innovation Practicum, University of Washington, Seattle, Wa. Oct 2012

37 WSU via The Associated Press, http://public.wsu.edu/~mreed/380American%20Consumption.htm

38 O'Connor, Jennifer. "Survey on Actual Service Lives for North American Buildings," *Woodframe Housing Durability and Disaster Issues Conference*, 2004

ozone (smog) and a host of other health-related phenomena. As a result of combustion for energy as well as chemical reactions involved industrial processing, gases and other pollutants are released into the biosphere. Some of these gases rise and are stored as greenhouse gases in the atmosphere while some particulates are deposited back over land. The creation of the energy needed to power buildings is an indirect contributor to this pollution.[39]

In the past fifteen years energy efficiency has come up as a central movement within architectural design. Increasing energy and water costs, along with price increases for labor and materials, have created a climate of demanding more for less. Owners and developers want more functionality with less energy use and thus less cost. Markets are showing strong returns for investments in energy savings.[40] Amory Lovins[41] at the Rocky Mountain Institute declares that the "Negawatt" is the world's great energy source in that it is not just the avoidance of using extra, unneeded energy, but that the energy saved reduces the need to build extra power plants and to supply extra coal or gas, and thus eases the burdens on the environment. A report by the New Buildings Institute in 2008 showed that LEED-certified buildings use less energy than their standard counterparts.[42] A standard small commercial office building (50,000 ft^2) in the US was estimated to use around 90 kBTU/ft^2/yr. The same building, LEED-certified, used around 70 kBTU/ft^2/yr, and one with a platinum rating used around 30 kBTU/ft^2/yr. These Energy Use Intensity (EUI) ratings by Energy Star[43] are a way to quickly understand operational energy needs for a particular building. Before LEED was a household concept and before Energy Star ratings were being used, energy use was not a large concern because the costs of energy ($/kWh) was so low. David Allen of McKinstry says that until energy costs were elevated to nearly 10 cents per kW (as a US average) no one took notice.[44] To accompany this trend, long-time environmental advocates are seeing the conversation broaden from the narrow focus on costs to a more holistic view of environmental degradation, pollution and stress.[45] "We are entering into a new era of sustainably minded development," David Allen exerts, "Buildings have to be smarter, more functional and more responsible than ever before."[46]

Lifecycle Management

How can we use metrics to create better buildings? It begins with understanding lifecycles. There are multiple layers to understand when approaching lifecycles. First there are the defining characteristics of what the lifecycle of a product is, second there is a need to understand the elemental aspects of materials and third there is a need to understand how lifecycle management can be applied to building design. The lifecycle of a product follows a path through the successive phases of a products life from the extraction of raw materials through their processing and manufacturing on to the product's use and maintenance

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[39] EPA, "Proposed Carbon Pollution Standard for New Power Plants," 2012

[40] Twill, J., Batker, D., Cowan, S., Wright Chappell, T. (2011). The Economics of Change: Catalyzing the Investment Shift Toward a Restorative Built Environment. Earth Economics, Tacoma WA.

[41] Lovins, Amory (2011) *Reinventing Fire*, Chelsea Green Publishing, White River Jct., Vermont

[42] NBI "Deep Energy Savings in Existing Buildings," Mark Frankel presentation to AIA at "Beyond the Green Dream," Seattle, Wa. June 2012.

[43] Energy Star is a joint venture of the US Environmental Protection Agency and the US Department of Energy is qualifying efficiencies of products and educates consumers through energy use labeling. – www.energystar.gov/index.cfm?c=about.ab_index

[44] Allen, David "Building: A Generation of Opportunity," presentation to Environmental Innovation Practicum, University of Washington, Seattle, Wa. 2011

[45] Wikipedia, "Environmental Movement," 2012

[46] David Allen, presentation, 2011

with a decision point coming at disposal. Along the way the product is picking up embodied energy as it moves through the cycle until disposal. The energy can at that point be recycle/reused, repurposed or lost into the landfill. (Figure 09)

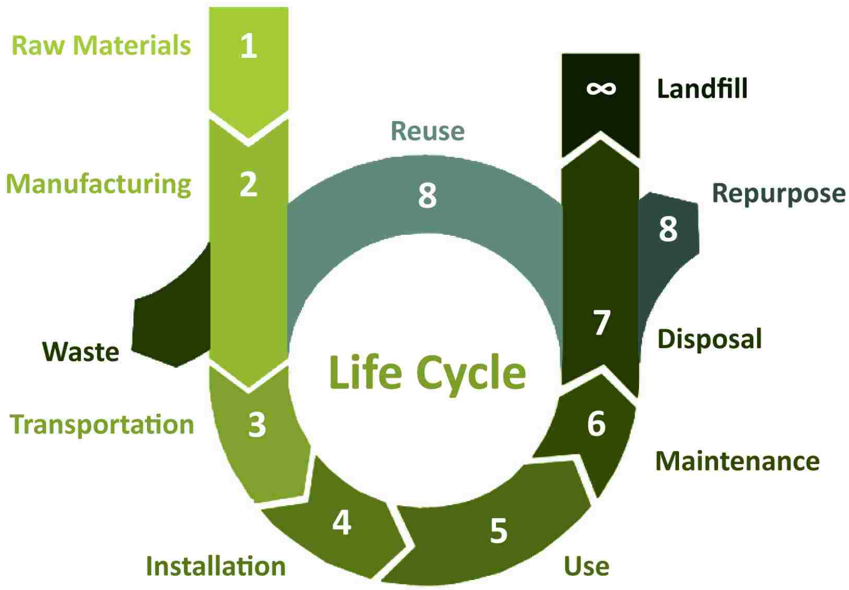

Image 09 – Lifecycle Diagram of a product (diagram reproduced from low quality internet source)

Inherent to every material are certain sets of enduring qualities, such as density, specific gravity, mineral composition, etc. These qualities give each of them unique characteristics that a designer can use to its fullest potential. For instance, engineer's of the Roman Empire recognized that mixing limestone, volcanic ash, stones of various sizes with a little water would yield a mixture that when cured took on some of the best qualities of natural stone. They could erect their buildings upon it or form them from it. They built temples and aqueducts of cementitious materials combined with stone that have lasted hundreds of centuries just like the stone cliffs of northern Alps. Concrete represents a material that is vastly different from wood or steel and each of them have qualities that lead them to be used for certain purposes. All materials wear within certain patterns of exposure, whether the case is natural exposure to rain and bad weather such as the siding of a countryside barn or to human interaction such as the rounding of the wooden tread nosing of stairs over years of use or car tires worn bald through extended periods of driving. A critical skill of any architect or engineer is to understand the limits of the materials there are specifying and working to get the best of them.

In spite of this our buildings often do not reach there full potential of use of materials.[47] Whereas the concrete foundation and steel superstructure could endure for hundreds of years, the roof decays in the sun and replacement cost rise too high, the whole building is razed because of non-durable material use in ill advised locations. All materials work on different lifecycles under different circumstances. It is up to the designer to locate them in positions to take advantage of their strengths, minimize their weaknesses and overall optimize their use. This matters because materials are often selected for the use of the

[47] O'Connor, Jennifer. "Survey on Actual Service Lives for North American Buildings," *Woodframe Housing Durability and Disaster Issues Conference*, 2004.

qualities they bring to a detail. These details are always a composition of materials as no single material can do it all. Moreover, they are also traditionally a combining of materials in such a way as to eliminate the option of disassociating them in the future. Stephen Kieran refers to this as entombing materials.[48]

Buildings need to last in good condition for a long time therefore building design needs to be thought of in terms of lifecycle management. The opportunity is needed to change or replace materials and assemblies when necessary. Lifecycle management is just that, understanding how to management potential change without expending too much time, energy, material or money to do so. Lifecycle oriented building design would not only have the typical information, e.g., drawings, material and finish schedules, cost calculations, etc., but also some mechanism for the designers and owners to understand how the building could progress over time.[49] Perhaps this takes the form of a better connection between the architect, the owner and the property management. This type of interaction could be transformational with regard to maintenance, facility updates, tenant improvement, aesthetic changes and many others. It could save the ownership money but also save society the added impact of unnecessary building debris. Thinking ahead will give a building or space the opportunity to be reborn with new components rather than destroyed only to have a similar mass of materials to be reconfigured again in the same location.

03 Lifecycle Assessment:

Lifecycle Assessment Overview

To determine the magnitude of impacts that embodied energy, embodied carbon and other potential impacts a product or material could have over its life, a method of accounting must be employed to measure and sum together each stage of the lifecycle.[50] Life cycle assessment (LCA) is a standardized method for the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle.[51] It is an accounting method by which to compile the inputs from industry (raw materials, energy, etc.) and outputs to nature (emissions, waste, co-products, etc.) to create a material or product. This accounting tracks through each stage of a product's lifecycle. Traditionally this began as a way of locating inefficiencies in products and material manufacturing. It has grown to look at larger assemblies of products and can now be combined to create whole building reports. For the profession of architecture this is where it needs to go, whole building LCA.

[48] Why Design Now?: Loblolly House, video presentation , 2010.

[49] Konig, H. Kholer, N. Kreissig, J. Lutzkendorf, T. (2010). A life cycle approach to buildings: principles, calculations, design tools. Radaktion DETAIL, Munich.

[50] Hammond, G. P. and Jones, C. I., 2008. Embodied energy and carbon in construction materials. Proceedings of the Institution of Civil Engineers - Energy, 161 (2), pp. 87-98.

[51] ISO (2006c) 14044:2006 Environmental management-Life cycle assessment-Requirements and guidelines. Geneva: ISO.

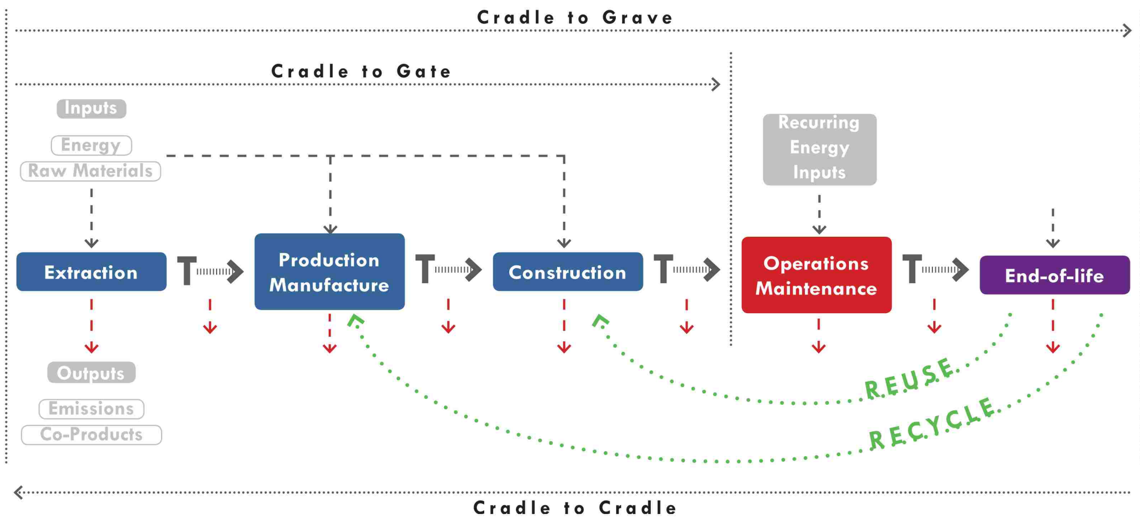

Image 10 – LCA diagram

LCA typically begins with the extraction of raw materials, continues through processing, manufacturing and construction installation (Figure 10). Operational energy is usually included but in the circumstance of our case study, which is a net-zero operational energy building it is not. The materials for maintenance, repair and replacement during building use are included. Finally, the scenarios for the building's end of life are examined—whether its components are to be recycled, reused or landfilled. Each of these life cycle stages consumes non-renewable energy and resources and generates emissions, which result in a number of environmental and health impacts at different levels. The burdens associated with each are included in the profile. Transportation is also included throughout, as products attained from a great distance require more energy than those attained locally.

Conducting an LCA can provide a range of information to designers and manufacturers. LCA can assist with locating the opportunities in a building's design to improve long-term performance through measuring the potential impacts of the energy consumption and emissions with the building's components. It can highlight where some of the greatest impacts are occurring during the product's life. For instance, the fossil fuel combusted to heat the limestone in Portland cement manufacturing has an overriding influence on the environmental burden associated with concrete. The other ingredients, though not negligible, pale in comparison.[52] This knowledge can lead the concrete industry to address the cement manufacturing process to find more efficient delivery paths, or look into mix designs with a greater amount of alternative cementitious materials made of industrial waste products such as fly ash or ground granulated blast slag. Another benefit of product LCA is that users can better understand the supply chain. By investigating options for suppliers with a lower environmental footprint, a manufacturer can potentially provide end users with a lower impact product. This is also an opportunity for those along the supply chain to create more efficiency—by better understanding their own process, they can better improve their overall procedure.[53] LCA can also be used in strategic planning for lifecycle management

[52] Marceau, M. L., Nisbet, M. A., and VanGeem, M. G. (2007) *Life Cycle Inventory of Portland Cement Concrete, SN3011,* Portland Cement Association, Skokie, Illinois, PCA.
[53] Supply chain transparency is one of the key drivers in the forming of the Sustainability Consortium by Walmart and other major retail companies, http://www.sustainabilityconsortium.org/why-we-formed/

and in the creation of Environmental Product Declaration (EPDs) and EcoLabels (similar to nutrition labels for products).[54]

Lifecycle Assessment Tools

A variety of tools have been made to support LCA ranging from very simple ones online to highly complex programs that are require a sophisticated knowledge of lifecycle assessment. These tools can provide a client with information ranging from a single number carbon footprint to a detailed environmental profile with multiple attributes. There are great challenges in creating a single tool that will satisfy LCA experts and non-experts alike. With the many tools available globally it is up to the user to decide what type of results they would like to see and gravitate toward a tool that will be commensurate. Tools have the potential to give a user a lot of usable information. A few things should be noted about any tool before a potential user needs to run an analysis.

- Some will contain regionally specific data (e.g. the Athena EcoCalculator and Impact Estimator) to reflect the regional power grid and local transportation distances.
- These tools do not typically permit manipulation of the data and therefore the results, while regionally specific, cannot be customized for a specific project with product specific data.
- The source of the tools data will come from a specific or from multiple sources depending on the tool being used.
- The data could be representative of the user's area or completely different, be sure to investigate which databases are being pulled from.
- Some tools allow the database to be changed based on the user's preference such as GaBi being able to switch from its professional database over to EcoInvent and others.

Tools have the ability to simplify the process of LCA investigations. They aspire to take care of both the data needed and the mathematics. They cannot fully replace a person in that there will need to be an interpretation of the results. As an assessment only, the tools listed below were experimented with by the author specifically for this report.

	Flexibility of program	Usability	LCA experience level required	Are all building components available
Athena Institute's EcoCalculator	Not flexible	Easy	Low	No
Athena Institute's Impact Estimator	Moderately	Moderate	Medium	No
BEES	Not flexible	Easy	Low	No
GaBi	Flexible	Complex	High	Yes

[54] Certifiable EPDs are compliant with a third party verified LCA, http://www.pe-international.com/topics/what-are-environmental-product-declarations/ and/or, http://www.environdec.com/en/Creating-EPD/the-epd-process/Collecting-LCA-data/#.UMabfqXUMTw

04 The Case for Endurance in Building Design:

Endurance as a strategy for designing with Climate Change

The pattern of continuous gains of carbon dioxide in the atmosphere reached a record of 391 ppm in 2012.[55] Scientists widely agree that in order to stave off the worst effects of climate change we must not exceed 450 ppm as this would keep mean global temperatures from rising more than two degrees Celsius.[56] In order to do this, radical shifts must be undertaken. Buildings contribute 39% of total greenhouse gas emissions in the US alone and thus provide a significant opportunity to reduce global impacts.[57] In addition to focusing on efficiently operating buildings we must consider the energy impacts associated with the materials embedded within and the construction process. Moreover, if buildings can function successfully for much longer, fewer will be constructed. This is the case for adaptability to be added into design schemes for new construction. If buildings are going to function well into the future they must be able to adapt to changes in exterior deterioration, internal program, aesthetic tastes and numerous other unforeseen circumstances.

Longevity in building service life

The Athena Institute released a report in 2004 titled, *Minnesota Demolition Survey: Phase Two* which revealed a series of interesting results. Most structures that are demolished are not done so because of structural deficiencies. Of the 200+ demolition permits taken out in Minneapolis between 2001 and 2003, only 3.5% recognized structural failure as the primary reason. 31% were demolished due to non-structural material failure with more than half of those citing a lack of maintenance as the lead in factor. [58] The study goes on to indicate that different structural materials used had little or no effect on the likelihood of teardown.[59] What it does indicate is that non-structural materials play a much bigger role in the longevity of life in buildings. The survey goes on to show that steel and concrete buildings were dominant in the areas of “Area Redevelopment” and “Not suitable for Anticipated Use.” A conclusion drawn by the authors of the survey stated that these two building types were too inflexible to be easily adapted to a new use and measures should be taken to provide for more flexible design and deconstruction in the future.[60] It would therefore seem that added focus should be applied to how these materials are used and how they are attached to the primary structure of the building.

Too often buildings are wholly demolished too soon, or the renovation is so complete, most of the original materials have ended up in the roll away dumpster. The US statistics of construction waste and demolition debris (C&D) that is tossed annually into landfills is staggering. General building demolition yields 155 pounds of waste per square foot while new construction yields 3.9 pounds per square foot of building area.[61] A 2008 report finds that an average of 1.7 pounds of C&D are generated per day per

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[55] Current readings posted at http://co2now.org/

[56] http://www.carbonbrief.org/blog/2012/12/can-we-still-limit-warming-to-two-degrees

[57] Energy Information Administration (2008). *Assumptions to the Annual Energy Outlook*.

[58] Athena Institute. (2004) “Minnesota Demolition Survey: Phase Two Report

[59]. O’Connor, Jennifer. “Survey on Actual Service Lives for North American Buildings,” *Woodframe Housing Durability and Disaster Issues Conference*, 2004.

[60] O’Connor, 2004

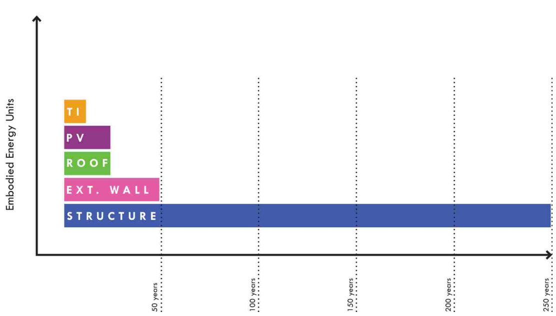
[61] Monroe, Linda. "Diverting Construction Waste," *Buildings* 2008.

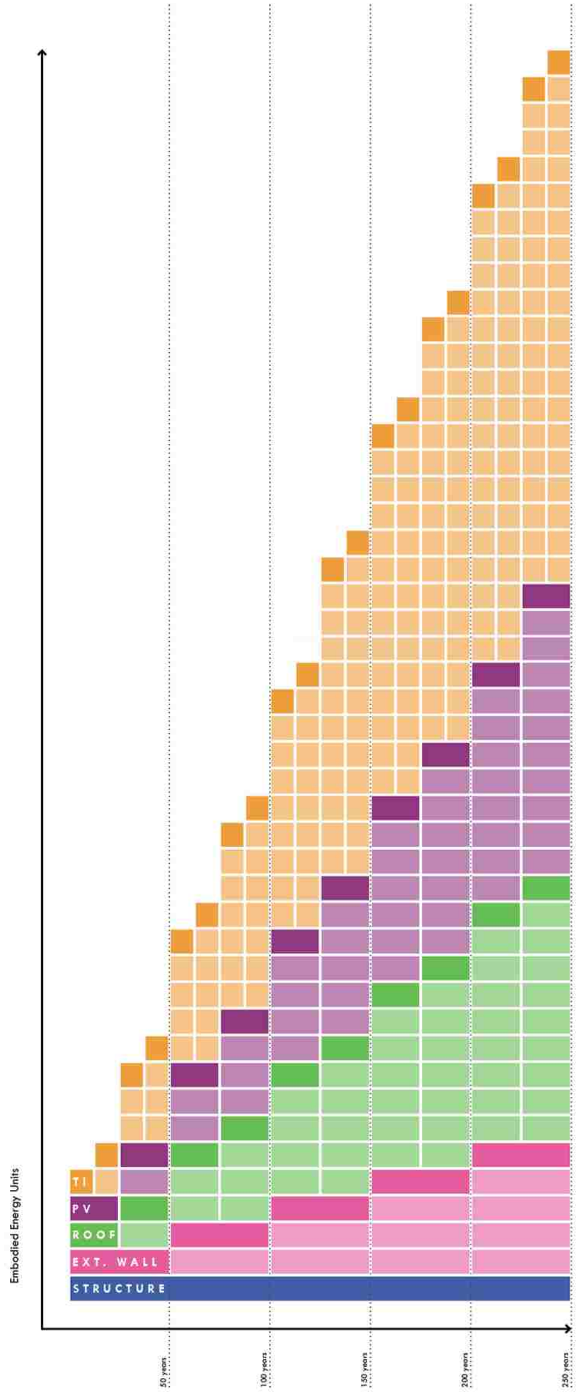
capita in the State of Washington's King and Clark counties alone.[62] With a combined population of 2.36 million, the approximate annual C&D waste is 4 million pounds. Seattle sends approximately 100 trains cars of garbage per day to OR, 25% of those are C&D.[63] 20M tons of debris could be diverted from landfills if 25% of the buildings demolished were deconstructed.[64]

Aside from some moving parts in systems, most of the materials buildings are made from will not move or change rapidly. It is a slow and contentious process of time and exposure to the elements to wear on a building. It will take many years before most materials wear down to a point of disintegration that requires replacement. Maintenance then becomes a point of concern, as it is the constant fighting back against aging in buildings. When presented with the culmination of high cost maintenance, sub-optimal working space, poor lighting (in many cases), and other such troubles with an aged building, it would be tough for the ownership to see the upside in keeping the building rather than razing and starting over. When buildings are design with little flexibility in mind, this is often the bind in which ownership will inevitably find itself. Poor planning for future realities will cut short the viability of a building long before the materials break down, this is a problem when seen in light of the environmental impacts of the building's life cycle. As designers and environmental stewards we must take into consideration the ramification of our material choices, design planning and construction detailing to better optimize the resources used. This is something that has been within the purview of the designer since the days of the medieval master builder.

As materials and assemblies wear out they need to be replaced. These materials (along with their excavation, transportation and manufacture) represent a diverse system of time, energy and effort to reach their points of installation and when they are not used until the end of their effective lives they represent a lost opportunity and lost potential. Each time a material has to be replaced it has to be remade through a long supply chain upstream of the point of installation. This recurring embodied energy adds up. It is therefore reasonable to consider not only how much embodied energy goes into the building but also how often those materials have to be replaced. Each time a component is replaced, a certain amount of energy is required upstream to create that replacement part. The continual making, replacing, making, replacing cycle represents the recurring embodied energy accruing. Images 13 and 14 is this this energy diagramed as a block of energy that with each additional replacement is "stacked up." Initially a building's embodied energy profile may look like Image 13 with materials that are more energy intensive holding a larger percentage of the overall makeup. The investment of energy into materials should not be disregarded easily as over time that cyclical nature of build and replace adds up. The figurative diagram in Image 14 shows that the energy embodied in materials is not lost only added as that material cannot be returned to the ground and that energy cannot be recovered easily or without adding more energy (i.e. in the recycling or waste-to-energy processes.)

[62] DSM Environmental Services (2008). 2007 Massachusetts Construction and Demolition Debris Industry Study.
[63] Mulady, Kathy. "Where your Seattle trash ends up." *The Seattle Post Intelligencer*, July 2007
[64] National Association of Home Builders, "Deconstruction: Building Disassembly and Material Salvage," 1998.





Images 13. Initial Embodied Energy Profile, 14. Embodied Energy Profile at 250 year (these diagrams are not to scale and are theoretical representations only, not real data points)

05 Case Study unpacked:

Bullitt Center – "Greenest Commercial Building in the World"
To begin studying how longevity can impact building design the Bullitt Center was selected as a case study. The building is a small office building, just over 50,000 ft^2, six stories in total, four structured primarily of wood frame over a two-floor concrete base. There is a basement containing the cistern, composting bins, server room and other such functions. The owners expect there to be between eight and twelve tenants including themselves. These tenants will have to share the available power supply year-round, and use means for commute as the will be no dedicated parking for the building. In addition to its performance goals, the Bullitt Center is to be a beacon of durability, evoking a strategy of longevity as a component to its vision of sustainability. Bullitt Center is designed to meet the Living Building Challenge, its highlights include:

- Net-Zero Operational Energy
- Net-Zero Water Use
- Zero Toxic Chemicals Used (Red Listed items)
- Zero combustion within systems use
- Its goal, "to change the use buildings are designed, built and operated to improve long-term environmental performance and promote broader implementation of energy efficiency, renewable energy and other green building technologies."[65]

Because it is planned as a Net-Zero operational energy building most of its environmental impact will be in its materials and construction. It has a planned service life of 250 years and to achieve this the architects have elected to go with a strategy of planned material obsolescence or what Stewart Brand called "Shearing Layers." The goals of the case study were to evaluate the building's design in two ways:

- Build an environmental profile using Lifecycle Assessment of the building's materials and construction, then project how this profile will look throughout its long life.
- Evaluate the detailing, configuration and infrastructural design to see how it is set up for adaptability and how can other buildings learn from it.

To create a metric support device for asserting endurance as a sustainability strategy, whole-building LCA work has been performed on the Bullitt Center as a case study. One goal of this exercise was to ascertain how much initial embodied energy there is in its materials and construction. The data compiled should be adequate to provide a profile of the environmental burden of each of the components under consideration. With adequate results it is possible to create any number of different scenarios for strategic planning for the future of the building's refurbishment procedures. These scenario models will show opportunities to reduce the long-term impacts of the building. One of the primary goals of the project is to create a building that has a long-term vision of sustainability and to understand what steps are need to be taken to achieve this goal.

Testing LCA on a low-energy, long life building, like the Bullitt Center should yield a clear picture of the impacts of a building without it being muddied down with indirect emissions from operating energy use. When a building is tested for potential environmental impacts, a net-zero operational energy building will

[65] The Bullitt Center - http://bullittcenter.org/building

help to isolate the embodied energy. Bullitt Center generates enough of its own electricity on site during summers to offset the energy it takes from the grid during the Seattle winters. Therefore the idea of it NOT having any operational impact is not strictly true. It is however a closer representation to the next closest building type, a LEED Platinum building that simply has dramatically reduced energy consumption. Moreover, the Bullitt Center is designed to have a long service life of around 250 years. This is counter to most privately owned buildings where ownerships tend to focus on short-term holdings and not the long-term viability of the building.[66] To achieve this goal of long-term viability, all of the materials used must be used to their highest potential. The strategy is one of planned obsolescence, whereby as components of the building reach the end of their useful lives they will be replaced in a systematic way to ease the reconstruction process.

The ownership behind the building is The Bullitt Foundation, which will be the anchor tenant, is an organization with aspirations of furthering the sustainability of human well-being and ecological balance by connecting grant funding with projects and individuals committed to making a difference in the sustainable development of the world. Their website characterizes this pursuit as looking "for high risk, high potential payoff opportunities to exert unusual leverage. It (the Bullitt Foundation) has a special interest in demonstrating innovative approaches that promise to solve multiple problems simultaneously."[67] It is a continuous supporter of like-minded entities, promoting their sustainability initiatives and bringing these ideas back to the Pacific Northwest as "ground zero for sustainable development." One such entity is the Cascadia Green Building Council. CGBC has been actively promoting programs to bring a healthier, more sustainable environment to the people of the Cascadia bioregion for nearly 15 years.[68]

Together with partners in the International Living Futures Institute, the CGBC launched the Living Building Challenge in 2006.[69] The Living Building Challenge (LBC) is a green building certification program similar to LEED, although substantially different in practice. The LBC is designed so that a building that achieves its benchmarks will be a fully self-sustaining building, creating all of its own power on site, containing and reusing all the water that falls upon its site, processing and reusing its waste, and containing no harmful chemical (per its "Red List"). Unlike most other green building certification systems, the LBC is performance based. There is no checklist for accumulating points, and the certification is only awarded after the building has been operational for one year. For design and construction teams, as its title suggests, the LBC is a challenge to not only create all of your own power on site but to create a sound, long-term infrastructure to accommodate water restrictions and material sourcing issues as well as vetting products for toxic chemicals, all while creating a beautiful building that is as inviting to occupy practically as it is theoretically.

Targets

The Bullitt Center is promoted by the media as "the greenest office building in the world."[70] Its owners and design team are staking a lot of time, energy and resources on this coming to fruition. The Bullitt Foundation's leadership decided early in the design process that their new headquarters would aspire to

[66] Ray Johnston, AIA, personal communication
[67] Bullitt Foundation, Website, http://bullitt.org/
[68] Cascadia Green Building Council, Website, http://cascadiagbc.org/
[69] International Living Futures Institute, Website, https://ilbi.org/
[70] Nelson, Bryn (2011), "The Self-Sufficient Office Building," NY Times online.

achieve "living building" status through rigorous adherence to the LBC.[71] In the interest of trying to solve multiple problems simultaneously, the LBC reaches for energy savings and production, water reuse, carbon neutralization, toxic material reduction and a characterization of "beauty," which no other green building certification can claim to achieve as a goal.[72] The Bullitt Center started construction in August of 2011 with a targeted completion date in the winter of 2012. Once complete and operational, the performance test will begin as a part of the certification.[73] As mentioned above, in order to be designated as a "living building" per the LBC, the building must operate with net-zero energy use, meaning that at the end of a one-year period, the energy it will have to take from the grid in winter (all power is electric and generated through photovoltaics) will be balanced to zero by the excess power it will create during the summer.

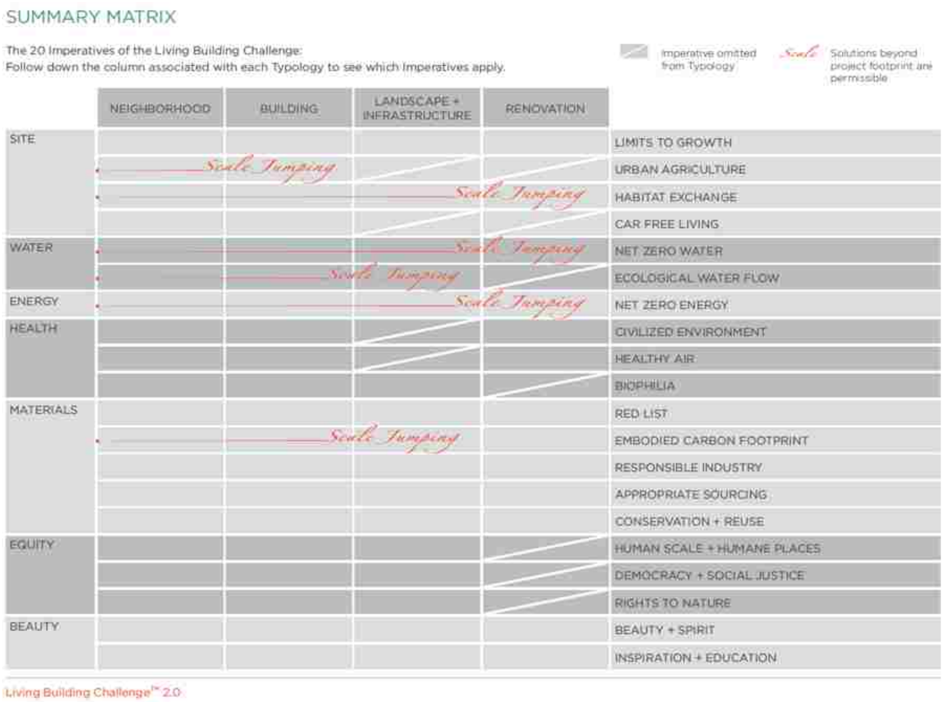


Image 15 – LBC Petal and Imperative Chart[74]

The Living Building Challenge is organized into seven performance areas or *Petals*. The *Petals* are further subdivided into twenty *Imperatives*.[75] Within the Materials Petal there is an imperative denoting that the building must become carbon neutral through purchase of offsetting carbon credits. Although it is not expressed this way, this section is the LBC's insertion of LCA in the design and construction field. *Imperative 12: Embodied Carbon Footprint* reads, "The project must account for the total footprint of embodied carbon (tCO_2e) from its construction and projected replacement parts through a one-time carbon offset tied to the project boundary."[76] To figure out the amount of carbon offsets to be purchased,

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[71] Denis Hayes, Presentation to NRMCA, Seattle, Wa., May 2012
[72] International Living Futures Institute, Website, https://ilbi.org/
[73] Interview with Brian Court and Casey Schuchart, Jan 2012
[74] Petal and Imperative Chart used from Living Building Challenge 2.0 standard
[75] Living Building Challenge 2.0 standard, https://ilbi.org/lbc/LBC%20Documents/LBC2-0.pdf
[76] Living Building Challenge 2.0 standard

the LBC offers two carbon calculators to ascertain the data.[77] One of these is BEES,[78] developed by the National Institute of Standards and Technology (NIST) as an online impact assessment tool that looks at the range of building products and generates both life cycle and cost analysis data weighted to whatever ratio is desired by the user.[79] The other calculator option is the Athena Sustainable Materials Institute's EcoCalculator,[80] which is a downloadable Excel workbook into which the user inputs the square footage of materials within various constructed elements in the building. For the Living Building Challenge these tools are used as a de facto lifecycle assessment mechanism. The data garnered from the use of either of these calculators is the amount of carbon offsets to be purchased to balance the initial embodied energy within the project. The architects chose heavy timber (glue-laminated timber) as the primary structural material for the upper four floors of the building with an intuition that wood would have the lowest embodied energy and thus be less expensive in terms of carbon offsets.

Evaluation

In light of this thesis, the Bullitt Center represents a pivotal turning point in how buildings for the future can be designed. Aside from the challenges presented by the LBC, the owner's brief to the architect was at the outset to design a building that would last for 250 years.[81] Considering that most commercial office buildings of this type are considered viable for 60 to 75 years, this benchmark reaches three to four times beyond the status quo. This meant that the design scheme had to be radically re-thought with every conventional detail examined. Along with a team of environmental, energy modeling and daylighting consultants, the designers were able to create a scheme that can operate at a presumed comfortable level in line with their photovoltaic electricity generation cap.[82]

"Almost immediately" in the pre-design phases the architects realized that there needed to be a strategy of planned lifecycle management and took inspiration from Stewart Brand's "Shearing Layers."[83] This layered conceptual design for the Bullitt Center is one promoted in his 1994 book, *How Buildings Learn*. In it he explains how buildings can 'shear' away layers. Brand's Six S's explain that a building is made of sub-components layered upon one another. A building sits on a *Site*, its *Structure* is set in place, its *Skin* is wrapped around the structure, the *Services* are inserted, the plan for *Spaces* inside is laid out, and the *Stuff* is brought in to accommodate the occupants.[84] That said, the Bullitt Center is conceived as a structure of concrete, steel and timber, to be protected by the exterior skin of wall panels and curtain wall. The structural elements should last the full 250 years, while the wall panels will need to be systematically changed out every 50 years. This scheme continues with a 25-year roof, 25-year photovoltaic panels and tenant improvement that the owner will hope to change not more often than every 15 years. Because the goal is for the whole building to be viable for the long term, these systematic replacements must be made in a way that will protect the building (the structure and other sub-components) from the periodic refurbishment deconstruction.

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[77] Interview with Brian Court and Casey Schuchart, Jan 2012

[78] http://ws680.nist.gov/BEES

[79] Simonen, K and Liv Haselbach (2012). "LCA for WA: Life Cycle Assessment (LCA) and Buildings Research for WA State." The Carbon Leadership Forum.

[80] http://www.athenasmi.org/our-software-data/ecocalculator/

[81] Personal communication with Brian Court, Jan 2012

[82] Personal communication with Brian Court and Rob Pena, 2012

[83] Personal communication with Brian Court, Nov 2012

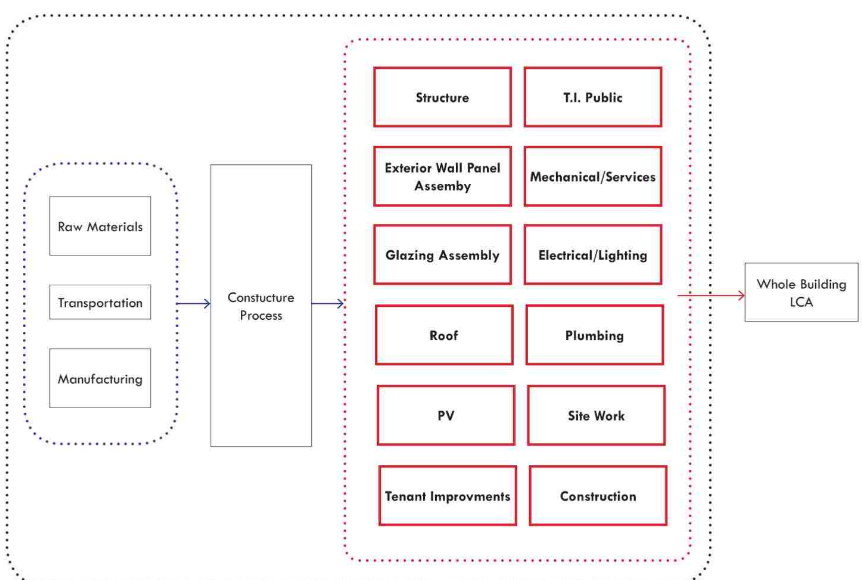
[84] Brand, Stewart. (1994). *How Buildings Learn: What Happens after They're Built*. Penguin Books, New York.

Exposure to the elements is a major factor in the long-term durability of all buildings. No matter the climate, no material, and therefore no building, can survive indefinitely without refurbishment. James Douglas characterizes refurbishment as a series of events born from the first occupation of a new building, consisting of maintenance, repair, replacement—anything to keep the elements out and the building standing.[85] He goes on to say that a building's materials are always breaking down with time and we should therefore accept it as fact and expect it to happen. The architects of the Bullitt Center accepted that not only would the materials break down far sooner that the projected long-term duration, but also at different rates. Intuitively they recognized that a "layered" approach could allow for a controlled obsolescence of component assemblies and could thereby preserve components that are much more long lasting.

The Process of LCA

In order to perform an LCA one has to first identify the goal and scope of the investigation. Within the scope a functional unit is also defined, for the LCA preformed on the Bullitt Center a functional unit of one long lasting building for a 250 year duration was used. Also within the scope a boundary has to be drawn to indicate what is and what is not included in the study. This is referred to as the system boundary. Twelve components have been selected to evaluate, they are highlighted in red in Image 16. For clarity this diagram has been simplified to a "big picture" framework. An attempt was made to account for each phase of the project's life tracking from raw materials through construction of each component. Each of the component parts has had a reasonable assumption made about how long they may be expected to last on the building over a 250-year duration. Additionally, three assumptions were made. Each component will be replaced:

- Continuously
- On schedule
- With an identical component each time



85 Douglas, James (2006). *Building Adaptation*. Elsevier Ltd. Oxford, UK.

Image 16 – Big Picture System Boundaries

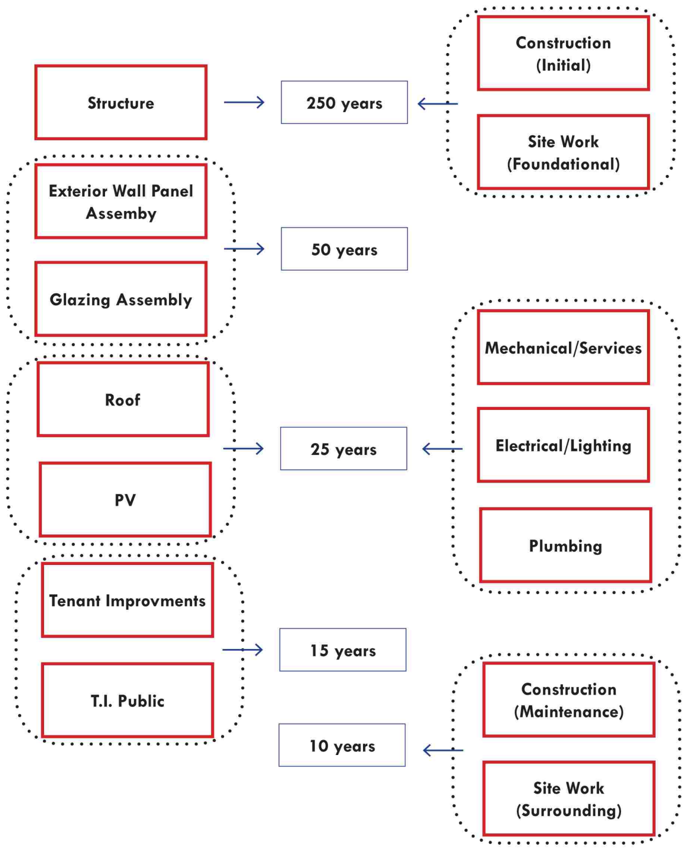


Image 17 – Time Assumptions of Components
Note: A more detailed Bill of Materials is located in the Appendix.

Feeding into each component are sub-components, highlighted in Image 18 in blue. These sub-components are the material components of each assembly such as concrete, steel and timber combine to become the building's structure. Each of these sub-components is an individual lifecycle inventory (LCI). An LCI is gathered data for a product that is organized to create an understanding of all the unit processes that have gone into the creation of the product. These individual unit processes tracks the raw materials through its manufacturing. An apt visualization of this would be the Russian Nesting Dolls or Matryoshka Principle. Much like Matryoshka Dolls, it was conceived that there would be a high-level system boundary to which the LCA would adhere followed by other LCA within each of the components followed by another LCA within each sub-component. See Figures 19 below. The theory is that if by combining together multiple LCAs an accurate picture of the whole building's environmental profile will emerge.

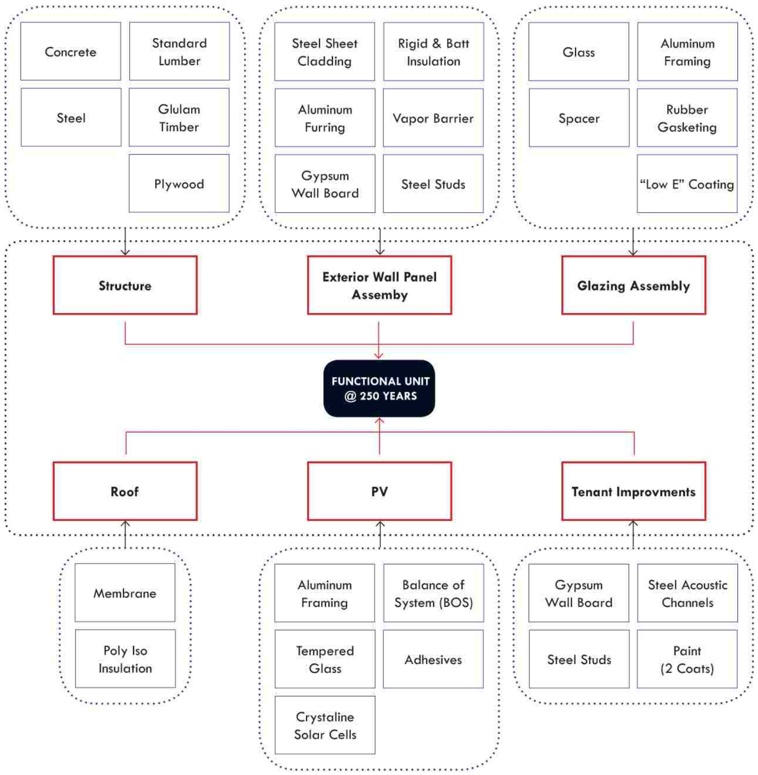


Image 18 – Sub-Components

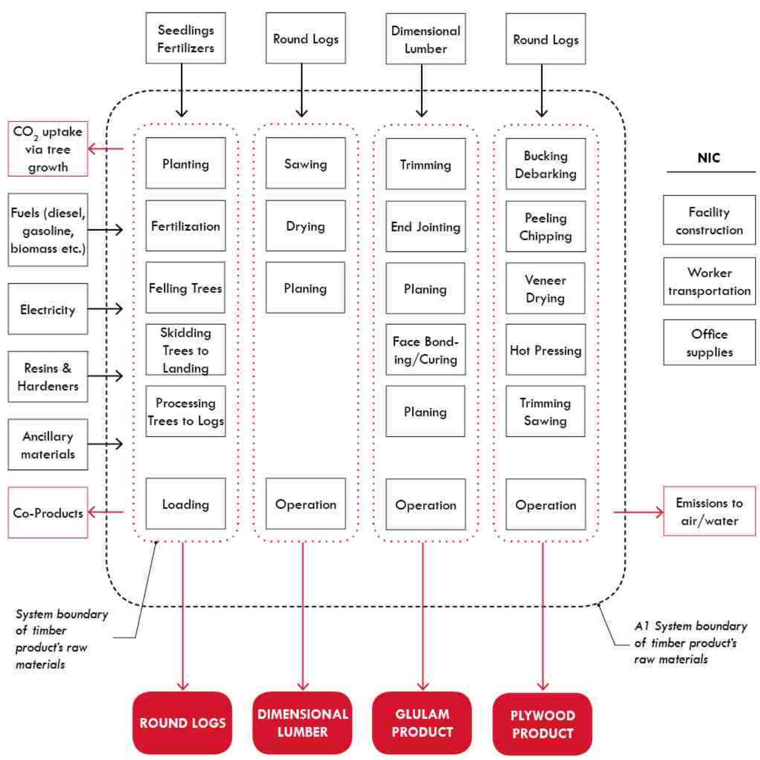


Image 19 – Unit Processes

Within this scheme is an investigation structure of how a building functions, physically, over time. Each sub-component has a theoretical time horizon, or expected duration of use before replacement. Most products have expected durations of wear, even if they are combined into larger assemblies. A module-based approach is becoming common in the pre-fab industry, but the Bullitt Center does not fall into the modular category. Even though it is being constructed in a relatively normal process, steps are being taken to allow for an easier systematic removal of the sub-components when their time has come. This in and of itself is quite a departure from the traditional construction technique, where most points of connection are entombed and irreversibly linked until demolition.[86]

After compiling the lifecycle inventory characterization factors are applied to understand the magnitude of the data. A characterization would be where, for instance, the emissions of 5,000 tons of methane (CH_4) would be described as having a climate change potential (GWP) of 115,000 tons of CO_2e. At this point an interpretation of the results would be written up as an expert opinion and conclusions from it would be drawn. For the Bullitt Center we wanted to understand how the environmental impacts of a building are affected by different time horizons of portions of the building.

Comparative views of LCA modeling and results

The goal of this Bullitt Center LCA case study was to build an initial profile of the building's environment impact and then project that impact into the future. This LCA contributed to evaluations of LCA methods and tools prepared for the 'LCA for WA: Life Cycle Assessment for Washington State' research project funded by the Washington State Legislature.[87] Six different LCAs versions of the Bullitt Center were performed over the past year using different tools, methods and databases. These methods include:

01. EcoCalculator: An easy, straightforward tool but is not flexible enough to closely match the Bullitt Center's assembled components. It also lacks all MEP systems data, photovoltaic data, construction and other aspects found to be important.

Pros	Cons
Easy interface, quick to use	Few Inputs = Inflexible
Requires little LCA knowledge	Missing Data: PV, Systems, Construction
Fewer input fields	Transport is embedded, cannot be adjusted

02. Computational Model: Is infinitely flexible as all of the parameters are built up in an Excel spreadsheet. It becomes highly complex quickly as it requires that all of the inventory data be collected and entered properly and all of the mathematical structure be computed correctly.

Pros	Cons
Highly flexible	Highly Complex
Can be robust and powerful	User is responsible all data
Very transparent, no hidden calculations	Two worries: Data and Calculations

03. Economic Input/Output (EIO): Equates emissions to dollars spent on any certain industry sector using the North American Industry Classification System (NAISC) where US economic census data

[86] Kieran, Stephen, & Timberlake, James. (2004). ReFabricating Architecture: How Modern Methodologies are Poised to Transform Building Construction. New York: McGraw-Hill Companies, Inc.

[87] Simonen, K and Liv Haselbach (2012). "LCA for WA: Life Cycle Assessment (LCA) and Buildings Research for WA State." The Carbon Leadership Forum.

is housed. Modeling with EIO data is complex within the scope of a whole building with industry sector overlap.

Pros	Cons
Flexibility to choose applicable sectors	Can be complex in whole building evaluation
Quick to use (if using Carnegie Mellon's online tool)	Infrequent Updates (e.g., 2002, 2007)
Based on US Census Economic Data using NAICS	

04. Hybrid Model: Contains data from multiple source types including EcoCalculator results, technical paper data, EIO numbers and others. Is flexible following closely the structure of the computational model, requires mathematic computational arrangement and has proven to be tricky to combine data types.

Pros	Cons
Greater flexibility over LCA tools	Still fairly complex to organize
Can include whole building data	Tricky to combine different data types
Fairly transparent	

05. Impact Estimator: A more robust version of EcoCalculator allowing users to dictate what their modeled assemblies are through establishing wall and floor types, foundation wall sizing and others. Still lacks systems data and other vital components, as did EcoCalculator.

Pros	Cons
LCA of Assemblies	Limited by frequency of updates
Does not require extensive LCA background	Missing Data: PV, Systems, Construction
Fairly flexible	Transport is embedded, cannot be adjusted

06. Impact Estimator (Bill of Materials version): Within Impact Estimator a user can list the extra materials used if the program does not have it native as an assembly option. This version attempts to add all materials per the Bullitt Center's BOM and compare against the standard version of Impact Estimator's results.

Pros	Cons
Benefits of Assemblies plus adds extra materials	Limited by frequency of updates
Requires extensive BOM	Missing Data: PV, Systems, Construction
Increased completeness	Transport is embedded, cannot be adjusted

Included within are the results of these LCAs, performed either by myself or other members of the research team. The following is a table that summarizes the methods used. For more information about the methods, tools and data see content extracted from the LCA for WA report and included in the appendix.

	Complexity	Flexibility	Not modeled	Cost	Notes	Modeled by:
EcoCalculator	Low	Low	MEP Systems, PV, Construction	Free download	Transport data embedded per region	David Fish
Computational Model	High	High	N/A	Uses MS Excel	Enables site specific data to be included	David Fish
EIO	Low	Moderate	N/A	Free online	Carnegie Mellon online version is free	Kate Simonen
Hybrid Model	Moderate	Moderate	N/A	Uses MS Excel	Difficult to rectify the difference in magnitude of EIO and process data	Kate Simonen and David Fish
Impact Estimator	Moderate	Moderate	MEP Systems, PV, Construction	Free download	LCA of assemblies	Kyle Boyd
Impact Estimator (BOM)	Moderate	Moderate to High	MEP Systems, PV, Construction	Free download	Extra materials added per BOM	Kyle Boyd

Each of these analyses computed the initial embodied impacts of the building. This author compiled and analyzed the preliminary LCA results of the six studies to evaluate the relative importance of embodied impacts of materials and components of a long life building. The author integrated the basic LCA data into an analysis model to account for the changing out of different lifespan components.

Image 20A shows a comparison chart of each model's results of Climate Change (in Global Warming Potential, GWP). Looking at the variation in results from model to model we realized that totals are less meaningful than the relative portions of the parts. What is more meaningful are the relative orders of magnitudes and consistencies of the parts between them. All versions were modeled to show results per a certain year requested.

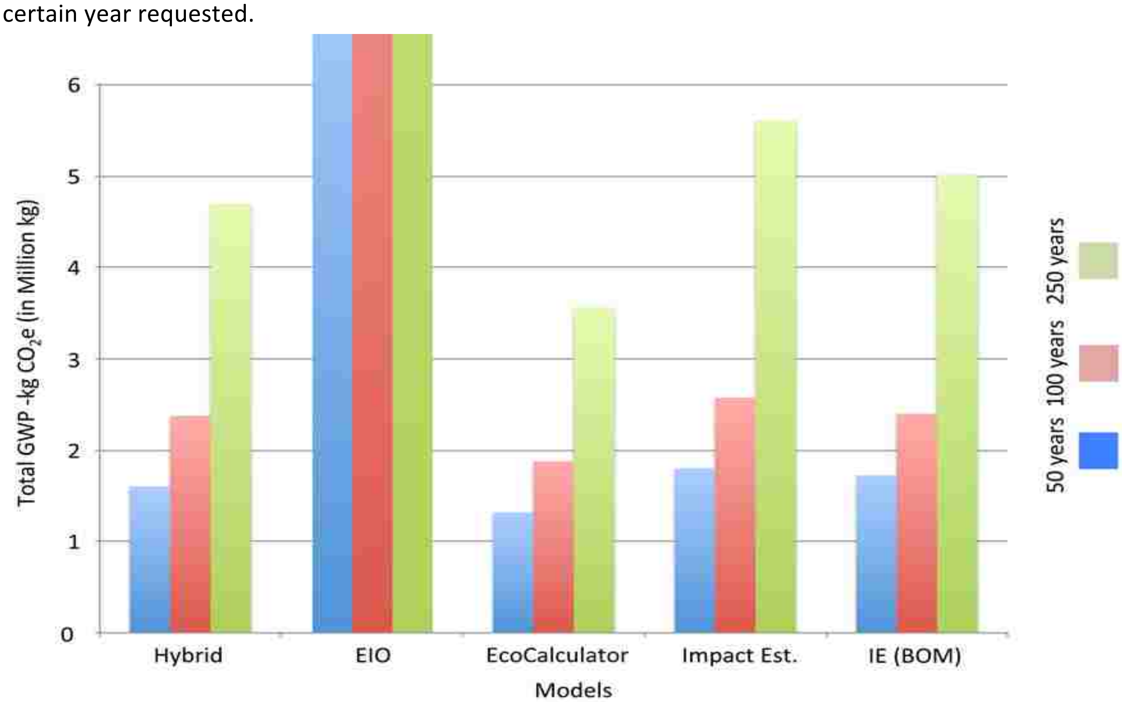


Image 20A – Five modeled results comparison chart

As the chart indicates that EIO results were much higher in absolute figures than any of the other versions attempted. This was reconciled within the Hybrid Model (which uses three points of EIO data) by applying a weighted factor to the data points. Even though the absolute figures in EIO are much large, the relative portion per component is similar to other models and therefore remains relevant to this study. Image 20B below shows the same data that the axis scaled to accommodate the total absolute figures on the EIO modeling.

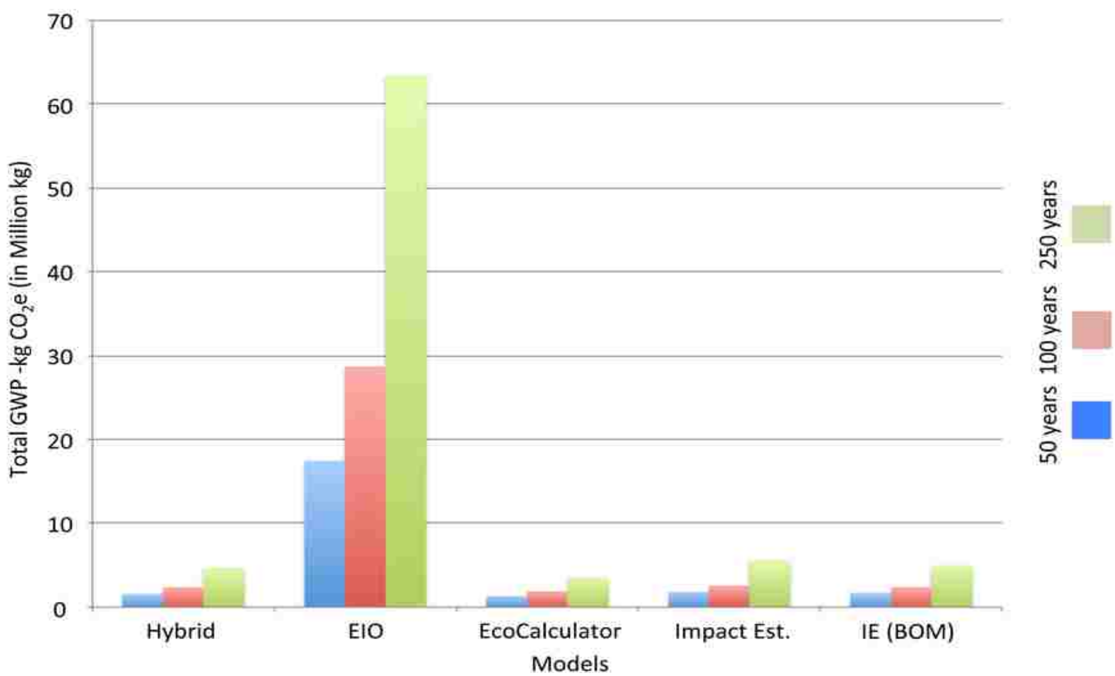


Image 20B – Modeled results comparison chart scaled to show absolute figures from EIO method.

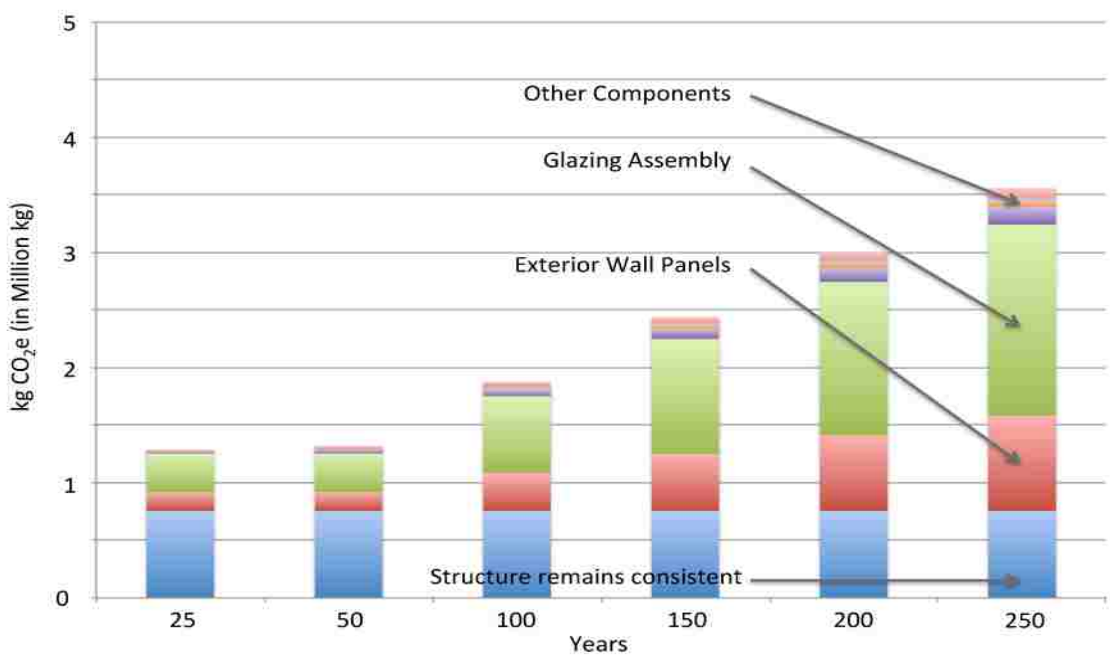


Image 21 –EcoCalculator results – GWP

When viewing these results charts remember which components change and how often. For instance, the structure component does not change over the 250 year duration, glazing changes every 50 years, roof 25 years, etc. (Image 21) In the hybrid model the impacts of adding MEP systems and transportation can be seen. (Image 22) And again, the absolute figures for the EIO method are tremendously large but the components' portions look very similar to the other results. (Image 23)

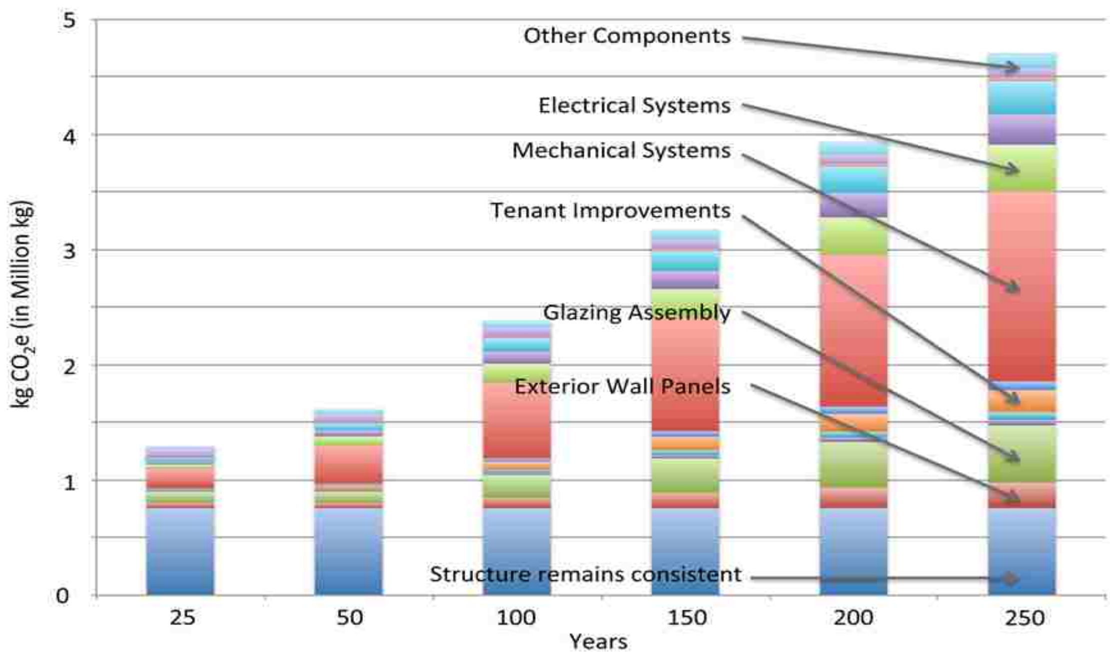


Image 22 – Hybrid Model results – GWP

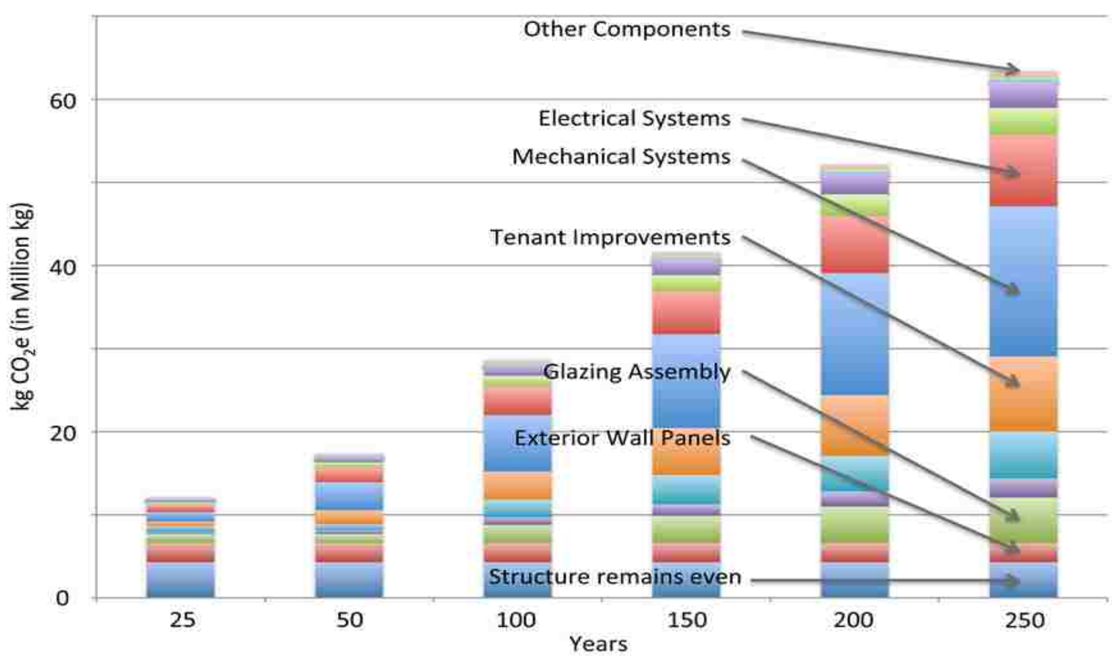


Image 23 – EIO results – GWP

The interpretation espoused here this is that a building lasting 50 years (Case 01) torn down and replaced five times over 250 years will have over three million more kg of CO_2e (equivalent) emissions than the single 250 year building (Case 03). The same can be said for a 100 year building (Case 02) replaced two and a half time emitting more. (Image 24)

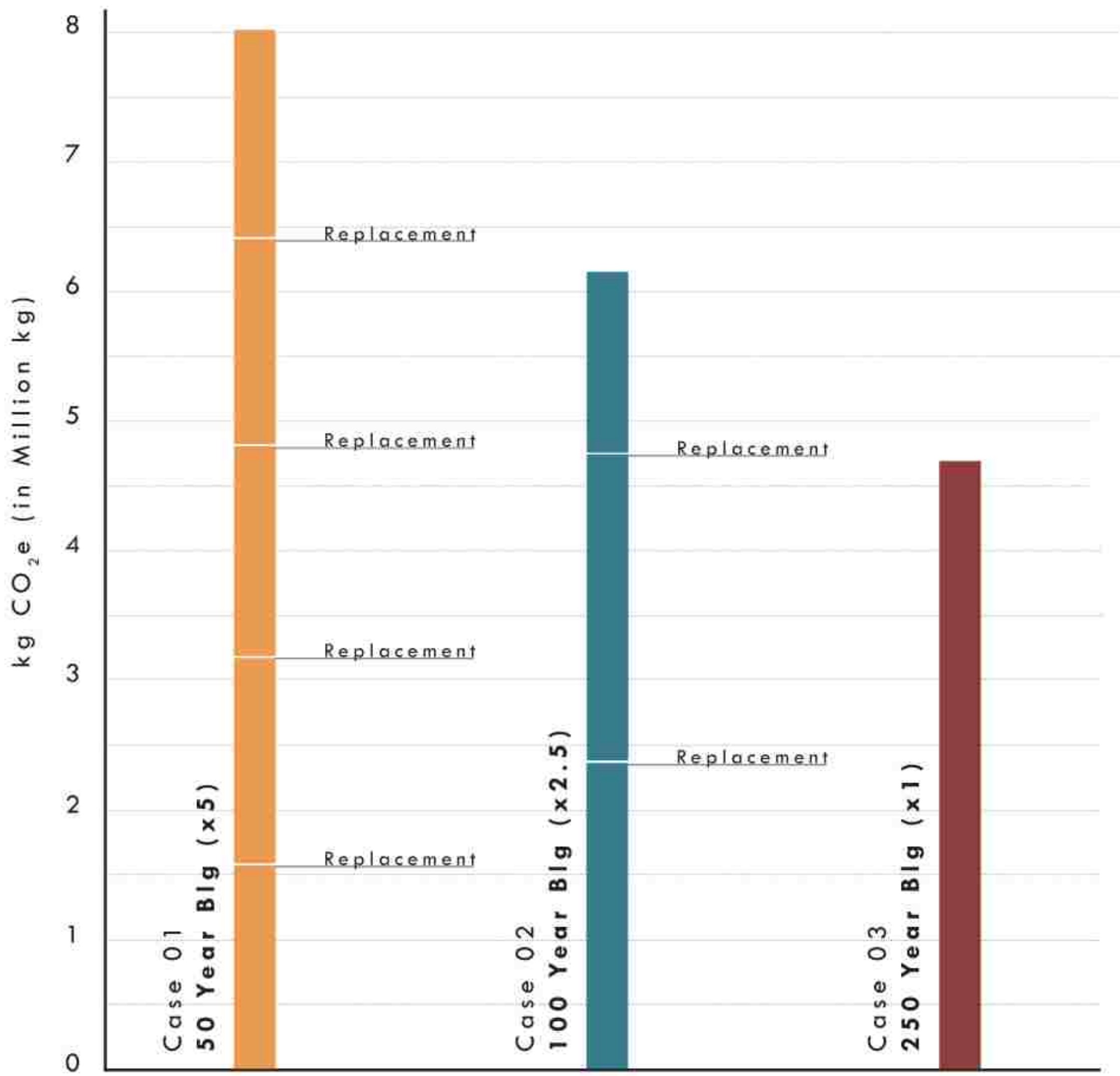


Image 24 – caption reiterating the case evidence

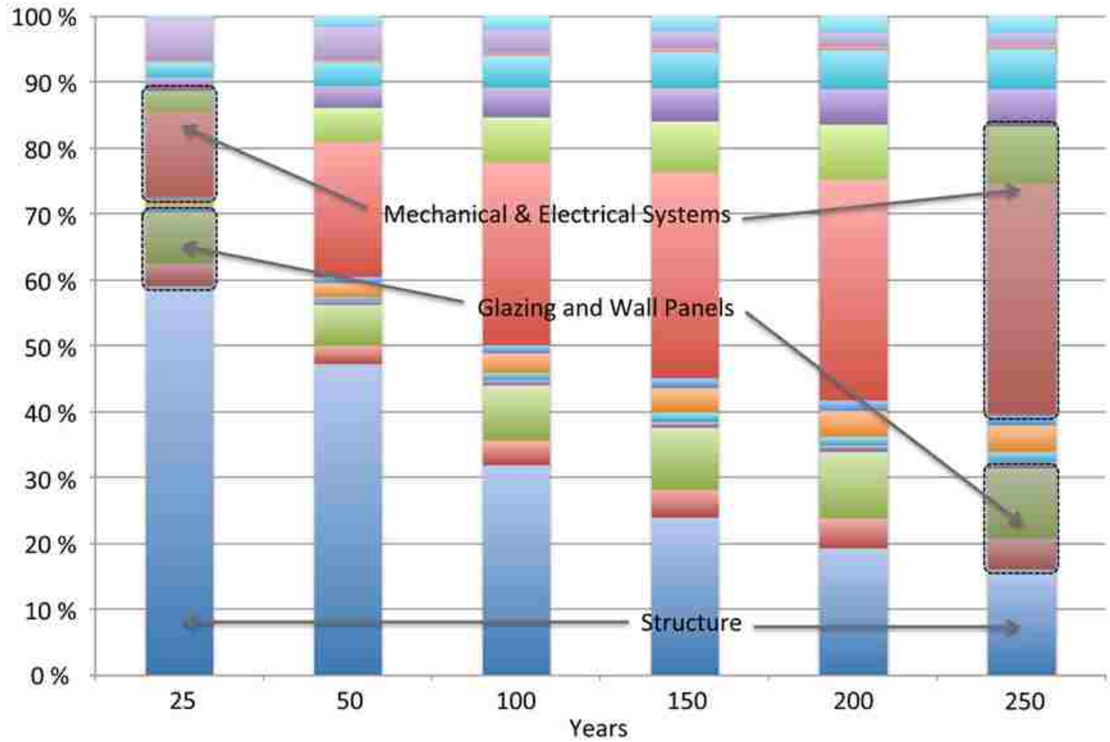


Image 25 – LCA used in locating areas of focus

To be able to identify where one should focus their attention, consider that over time the amount of embodied energy will change for the building based on Ray Cole's research into recurring embodied energy. In the beginning structure could account for as much as 60% (looking at the Hybrid Model as example results). Without it changing, over time it will have less impact then other components. Looking ahead to the 250 year market it is evident that the systems components and exterior skins should get more attention in lifecycle management as to how often they are replaced and from what materials they are made. Energy embodied in high repeat items such as mechanical systems and exterior walls are more significant than non-changing structural materials over the long term and should therefore receive more focus than they currently do. These numbers represented here are based on assumptions by the author, the research team and the project design team. Because it is parametric in nature we can change these to see how sensitive the models are. The way to best use this information is to create different scenarios during the design's development. If the assumptions used indicate that the mechanical systems will have a big impact long-term then use this as an indication that perhaps it would be wise for the owner to select a system that has a proven track record of being durable. If the assumed lifespan of that equipment can move from 25 to 40 or 50 years there could be a total savings of ~920,000 kg of CO_2e. If the glazing and wall systems could move from 50 to 75 years in life an additional savings of ~540,000 kg of CO_2 could found. These models do not represent an exact science they are merely to be used as guides.

Life cycle assessment is challenging and complex even for a single product such as a glue-laminated beam. When the task is scaled to encompass an entire building the challenge is greatly magnified. Throughout the past year of graduate study, this author has been investing what LCA is, how it can be a useful tool and how it can be integrated into architectural practice. The interconnected nature of the world of products (and by extension construction of buildings) creation and transportation makes it very difficult to pin down specifics with regard to where environment impacts occur.

Key principles that have been learned throughout these investigations that we think are key to both the future of LCA and its integration into average practice:

- Good data is hard to find and we need to encourage the creation of more of it
- Limiting the system boundaries is critical
- Results totals are less meaningful than the relative portions of the parts

06 Analysis of Detailing:

Endurance is in the Details
The way in which a building is put together matters just as much as how it operates or from what it is made. The details of how materials are connected to one another will speak to the durability and weather tightness, how the infrastructure is laid out sets up the future of its adaptability to new programs and flexibility to learn (be updated) and the configuration of spaces and materials will help the building optimize its resources' efficiencies.

Edward Allen and Patrick Rand assert that a good architectural detail must be satisfactory in three separate categories: Function, Constructability and Aesthetics.[88] Any detail that is executed without the consideration or review regarding of one or more of these perspectives could suffice as long as the building is in use. The quality of the design however, will not necessarily be regarded as astute. Good detailing is one of the moments in the practice of architecture where form and function merge with artistry and imagination, it is where good buildings become great and mediocre ones become pandered. Mies Van Der Rohe famously penned the phase, "God is in the details[89]," which stands in contrast to his minimalist architecture. Regardless of style, buildings are a series of material connections, gaskets and flashings, bolts, nails and other such pieces. The ways that these items are combined is the essence of what the building is and possibly more important, how the building will be (wear, deteriorate) over time.

Many books have been written over the years demonstrating how good detailing is done. Some speak to the fundamentals, the "tried and true" combinations that have evolved through construction practice over the centuries.[90] Some are technical journals chronicling detailing and assembly methods around the world to inspire and aid designers.[91] Others speak more toward the poetic nature of them such as *On Weathering* where the author recalls Victor Hugo's assertion that books are more durable than buildings, saying "dominant idea(s) of each generation will be embodied in the book of paper rather than the book of stone."[92]

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[88] Allen, E and Patrick Rand (2007). *Architectural Detailing*. 2nd edition, John Wiley & Sons, Inc. Hoboken, NJ.
[89] Mies Van Der Rohe, "On Restraint in Design." *The New York Herald Tribune* (28 June 1959).
[90] Frances Ching (1991). *Building Construction Illustrated*. 2nd edition, Von Nostrand Reinhold, NY, NY.
[91] Gatz, Konrad, ed. (1967). *Modern Architectural Detailing. Vol 3*. Reinhold Publishing Corp., NY. and Details (Magazine) "Not Just Building: Sustainability." Oliver Lowenstein, Jan 2012.
[92] Mostafavi, Mohsen and David Leatherbarrow, (1993). *On Weathering: the life of buildings in time*. Cambridge, Mass, MIT Press.

Part of evaluating the detailing at the Bullitt Center for adaptability is to understand what it takes to make a good detail and how to determine what is a good detail. Detailing is critical in creating a good thermal envelope and helping to slow material deterioration. Generally speaking, the knowledge of how to execute a good detail is built up over time and not learned anew with each new building. Norman Wienand describes the steps to be taken in this design process as following a number of different routes:[93]

- The adoption of standard solutions
- The adaptation of existing solutions
- The production of completely new methods

Architects want solid, functional and constructible details that minimize their risk while at the same time demonstrates their artistry in the creation of signature building designs. For this they need innovative solutions. These innovative solutions, however, come with both added risk and added reward. Image 26 diagrams the target bravery for architect in designing innovative details. [94]

Wienand also points out that attitudes today have shifted from focusing narrowly on a single project as an isolated event to a more holistic understanding of designing as a part of the built fabric of cities or towns and specifically incorporating sustainability into those designs.[95] This includes how detailing can effect the long-term viability of the project. Poor detailing can lead to premature deterioration and non-structural materials failure, both can hamper the owner with added maintenance, restoration and replacement costs. Buildings that have high infiltration (via poor connection details) rates will have to balance that air loss with additional energy to heat and cool the interior. This indirectly increases emissions via fossil fuel fired power plants. Material deterioration leading to replacement means the new material or assembly will be created, transported and installed, all of which builds upon the environmental profile of the building.

Configuring the building to take advantage of the resources of its site, e.g. harnessing the sun's energy to passively heat and cool the interior spaces, is not only good operational design but also good material design. Limiting the amount of materials and services needed to operate reduces the risk of breakdown and replacement. Open bay layouts will aide daylighting schemes meaning fewer lighting fixtures and less electrical wiring needing to be run. Configuration and infrastructural spaces go hand in hand for how a building will develop through the years. Changes in spatial needs will probably happen during the building's use and the ease that will happen goes directly to preventing additional waste of materials being removed and subsequently replaced.

[93] Wienand, Norman (2008). *Materials, Specification and Detailing*. Taylor & Francis, NY, NY. Pg. 32
[94] Chart adapted from Norman Wienand's in *Materials, Specifications and Detailing*. Pg 8
[95] Wienand, 2008

Image 26: Risk/Reward Chart

Technical strategies: Infrastructure, Configuration and Detailing
Because a designer cannot predict the future changes needed in a building, it must have enough flexibility built in to allow it to be updated as needed. Three areas of focus in the design of any building can offer more endurance for that building's life:

- *Infrastructural* – Accessibility to interstitial spaces including vertical and horizontal chases or between assembly components, accessibility to systems for service and replacement, etc.
- *Configuration* – Spatial layout, column spacing and positioning, floor to ceiling heights, floor plate size, material assembly compositions, etc.
- *Detailing* – Component connections to structure, disassembly potential, durability, etc.

Infrastructural
When speaking about adaptability in design, two principal architects (at a firm that specializes in healthcare) explained that the first rule must be that "work is be able to continue when anything is happening on the floor (referencing a suite of patient's rooms in a hospital setting) whether its maintenance, equipment replacement or the redesign of a large portion of the suite."[96] In their view a building or space that is adaptable will be able to be maintained without interruption of everyday business. Having access to chases and raceways provides relatively easy access to replacing electrical, plumbing and mechanical systems. Redesign of interior spaces is aided when it is less hampered with additional costs of relocating service items such as electrical devices or supply boots. Moreover, with less material having to be torn out during the renovation process, waste is diminished and the remaking of those items not needed. This has become common practice at Miller Hull Partnership within commercial building design to use a raceways and trunk and branch systems for distribution of system supply lines. Most often this is seen running along the ceiling corridor, sometime hidden above a dropped ceiling, sometimes exposed.

Because Bullitt Center has a smaller footprint it has a single centralized chase for systems and exposes its limited amount of branching per floor. When buildings are designed to perform at a higher level of efficiency, sometimes these raceways are relocated to be under floor to "clean up" the ceiling and allow

[96] Interview with Duncan Griffin and Ross Leventhal, June 2012

greater stretches of uninterrupted ceiling space for reflective daylighting. This is the case at the Alley24 development project in the Cascade neighbor in Seattle. These floating floor systems allow a great amount of flexibility from the aspect of repair and replacement but also flexibly to relocate workstations above, walls and whole rooms as needs.

Infrastructural advantages:

- Wiring: Flexible replacement or updating of communication/internet wiring
- Wiring: Easy relocation of work stations
- Plumbing: Centralized toilet facilities help to minimize additional branching which increases pressure needed.
- Plumbing: Vertical piping systems create an ideal gravity drainage situation bettering the odds of long-term use also minimizing the need for branching (decreasing clog potential).
- Mechanical: Access to ducts for repair, replacement or addition future branching
- Centralizing systems decreases branching needs, minimizes turns in the system, helping in its efficiency and longevity.

Configuration

Configuration design should be looked as twofold:

- How the material assemblies are put together.
- How material resources can be optimized.

Configuration can be composition of material assemblies not just spatial configuration. In order for a building to take full advantage of the materials it must harness the elemental properties and balance that with what it took to get that material in place. Concrete may be a difficult material to form and prepared and it may have a high content of embodied energy and carbon, but it will last for the ages in a pure, unchanging form. A good architect will take advantage of its thermal properties as well to aide heating and cooling and will possibility use it as an opportunity to be aesthetically expressive. Engineering and engineered products have developed to the point of allowing architects the freedom to routinely open up spaces that just 25 years ago were unheard of. Post and beam rhythms at 8-foot intervals have been replaced with 24-foot spans in timber and twice that for steel.[97]

The placement and spacing of these bays can play a great role in how future adaptations of the building can go. Discussion at one architecture firm revealed that this is a critical decision in how to align the spaces vertically within buildings. “If the grid is too restrictive it narrows the opportunities for adjustment. At the same time we (the architects in the firm) should not get too attached to any one module, say a 24 by 24 bay, as the building type and ownership can give you a clue to the building’s future.”[98] This “clue to the building’s future” is a reference to possible ownership changes. For instance, a university or hospital could be considered a stable ownership model whereas a developer owned building is most typically a short-term hold. Other configuration strategies could be to consider how useful the floor plate size would be for other program types, how daylighting could effect workspace interaction or how compact floor-to-ceiling heights would translate to other uses.

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[97] Based on the author’s field experience in residential and light commercial building.
[98] Interview with Cima Malek-Aslani and staff, September 2012

Spatially a building can be set up for success by configuring the space to pull double duty. Dan Watch of Perkins + Will writes about laboratory designs trending to "flexible spatial arrangement allow for different types of experiments and different user groups to occupy the same spaces."[99] These are "social spaces in team-based lab" that need open spaces, inflexible and accessible infrastructure that can be reconfigured temporarily. Will Macht, writing for the Urban Land Institute, mentions that when considering newly constructed retail space, "if the space does not lease as expected, its double-height spaces allow the addition of mezzanines to create live/work units, with ample light and air provided by tall windows. Or it could be configured to provide more office space to enlarge net rentable space, increase income, and reduce effective rent per square foot."[100] It is clear that the configuration of space can play a big role.

Bullitt Center is a straightforward core and shell commercial office building awaiting tenant infill. Beyond the intent of maximizing open floor space to lease, the only program elements provided are restrooms, shower facilities and janitorial closets in the central core. The "irresistible" stair has been pushed out to a far wing of the space with the secondary stair and elevator tucked into the rear. Keeping the restrooms and showers in the core helped with centralizing all of the systems including plumbing. Minimizing branching saves extra materials used (plastics, sheet steel, piping, etc.) and saves on pumping and fan use. Also by narrowing the footprint on levels 3-6 natural light can get deeper into the spaces saving electrical lighting needs. The footprint reduction also reduces beam depth limiting material quantities needed (both in GluLams and standard sawn lumber) and provided more insulative exterior wall area because of the reduced need for a higher window to wall ratio.

Configuration advantages:

- Optimization of material resources allows for reductions in material use while allow the material to do more
- Proper column spacing can allow for changes of use or program beyond TI changes.
- Easily added program can enhance the value of space, the structure needs to be accommodating for these changes.

Detailing

Two thoughts to consider when designing a building detail should be, how will this hold up to daily wear and tear and environmental conditions and how accessible is it to modification, maintenance and disassembly? It is the position of this thesis that designing details that are not only durable but also modifiable is a key strategy to a building sustaining its high functionality for many decades. In terms of risk and reward it would push the architect toward a position of moderate risk because historically buildings have adopted an entombing layering approach. One material is attached to the next and the assembly is thus built up without the thought of needing to break it back down. It should be considered however that it will have to be broken back down at some point and provision should be taken to acknowledge this. The advantage of building in this manner is clear, the entombed tightness of pulling together multiple materials into a single unit is a way to assure that the materials will fully integrated. Pre-fabrication or "Design for Disassembly" could be viewed as the opposite of this concept. A building that is fully designed and constructed to be de-constructed may rely to heavily upon attachments and fillers to contain infiltration, water vapor, etc. Either method is subject to lose construction practices and poor quality but

[99] Watch, Dan "Trends in Lab Design." Whole Building Design Guide, National Institute of Building Science. 12 Sept. 2012.

[100] Macht, Will. "Building Flexibility into Mixed-Use Projects." Urbanland, Urban Land Institute, 31 May 2012.

both contain great opportunity to make wonderful buildings To help minimize the risk in more innovative detailing, this author proposes a hybrid approach to building assemblies and building construction. Combining the best techniques of traditional detailing with pre-fabrication strategies (assembling units into a collective whole) there is reason to suspect a positive long-term relationship.

These three are seen here as the key to unlocking the potential long-term benefits on material utilization and durability. Moving from entombment schemes to designing for disassembly will change how buildings are maintained and repaired and eventually reused. Mark D. Webster writes that sustainability is using only renewable resources for materials and using them no faster than they can be renewed. Short of that reusing resource materials that are already made are the next best thing in that they can be considered renewed resources.[101] Buildings can become a source of renewable resources with details designed to take advantage of the situation.

Advantages of detailing for endurance:

- Replaceablity
- Repairability, ease of maintenance.
- Harnessing a great potential in the materials ability to perform.

Designing for Endurance

Three strategic categories for maximizing materials lives in buildings include advanced connections of assemblies, planned obsolescence of components and management of material replacement. All of these are supported with innovative detailing. The 'connection of assemblies' observation comes from studying the Bullitt Center. It is designed as a literal interpretation of Stewart Brand's idea of "shearing layers."[102] The strategy for the building to endure for 250 years is to maximize individual component's lifespans and then "shear" them away to be easily replaced with another similar component. This is here regarded as a planned scheme of obsolescence. The critical junction then becomes the connection between the exterior component and the structural component. How these entities coexist will determine the success of the long-term venture. This recalls the risk level of detailing and thus is the case of the Bullitt Center it was decided that this more module approach was not satisfactory due to a variety of reasons.[103] It was designed, however, that even though the exterior wall panel components were stick built in place the seat of "trays" because they are outboard of the structure where there would be minimal if any damage to the structure, intermediate floor or surrounding materials if they needed to be replaced.

Listed here have been a few ways buildings can come to have more durability. These are general ways to think about spatial design. Future building design should always consider these:

- Do not embed high repeat items such as mechanical systems and exterior wall sections within long cycle components such as the building's super structure.
- Infrastructure = flexibility and repairability, take advantage of it by using it as the building's nervous system.
- Find a way to optimize material use and composition by letting them to do two or more things at once.

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[101] Webster, Mark D. (2010) "Design for Adaptability and Deconstruction," *Sustainability Guidelines for the Structural Engineer*. American Society of Civil Engineers, Reston, Va.,

[102] Brand, Stewart. (1994). *How Buildings Learn: What Happens after They're Built*. Penguin Books, New York.

[103] Conversation with Brian Court, Nov, 2012

With designing for endurance the overarching theme is that the designer should recognize that the building can be a viable workspace for many decades and how the building is configured can go a long way to supporting its continued versus its potential obsolescence. Adaptable design must be a holistic approach. It is not enough to consider just one of these as THE strategy but to adopt a mantra of adaptability with them all. Other industries have been doing this for decades and their products exemplify their process. The awareness of designing for adaptability is the key first step to transforming the ways in which the building professions have come to understand design and construction. Shifting slightly the way components attach will increase the long-term performance of the building without excessive additional cost. This was the tenor the architects and engineers of the Bullitt Center had to grapple with.

"Just because the building is suppose to last 200+ years doesn't mean that it can cost four or five times as much as one lasting 50. Costs had to be controlled. We saw the subtle shifts (in detailing) as not increasing costs. In fact, the only thing the contractor has only said is that we should have laid out the column spacing at 10' on center not 10'-6" because it causes more drops. Sitting the walls (exterior wall panel components) on angles and not on the slab has made no different in costs at all."[104]

Lessons from other industries: Automotive and Airplane building

If lessons learned from the automotive and shipbuilding industries are of any precedence, building designer could take notes on their maintenance and assembly processes.[105] Kieran and Timberlake dissect the process of automobile and airplane construction with the assertion that "smart modules" that are the assembly of many parts can be assembled into a building in a more efficient manner than single parts built up one at a time. Automobiles that are damaged in operation are generally not scraped just because of a dent in the quarter panel or a leak in the sunroof. The door can be replaced efficiently in a garage bay as can the leaking sunroof. These are usually new components plugged into the existing car's infrastructure. Although true that the car can come to the garage where specialized tools stand waiting but the message in this statement is not the mobility of the car but the garage bay where the tools are. If a building is an assembly of component parts, ones that are tightly assembled in a garage-like setting and meticulously attached on site. A similar process can happen in reverse to correct a problem. Although the Bullitt Center does not employ this as a technique, it is detailed in such a way that de-construction of separate components is not only possible but also expected.

***Future proof* details to be easily understood by future generations**

Buildings also have to be designed in logical straightforward ways. Looking again to the automobile industry as it has evolved over time we see this precedent. Though the rebuilding of a 1918 Ford is not exactly the same as rebuilding one from the 1960s, there is a link that is indelible. Professional mechanics and backyard amateurs alike understand the fundamentals of the interplay of the components. Even if a novice can follow the processes to their logical conclusions and put the car together. Building science must gravitate toward this trend thinking first, how do we deconstruct this, instead of just using a crane to tear it apart. Although there are many parts, if the parts are put together in a simple process that can be replicated easily, though tedious there is a means to an end.

[104] Conversation with Brian Court, 19 Nov 2012

[105] Kieran, Stephen, & Timberlake, James. (2004). ReFabricating Architecture: How Modern Methodologies are Poised to Transform Building Construction. New York: McGraw-Hill Companies, Inc.

With the world of architecture and construction changing as rapidly as it has, projecting ahead, what will it look like in 50 or 200 years? Will there be a means to or the need to pull up drawings from decades earlier to figure out how to deconstruct buildings or portions there of? As we do with many buildings today that are too costly or difficult to renovate, will they simply raze them to make the process quicker? How will buildings designed today with adaptable solutions in mind be construed in the future? In short, how can details of our high performing buildings be 'future-proofed?' Two ways to do so is to begin to culturally shift the ways in which design is conceived and construction is preformed so that it is the norm rather than the exception. The other is to get back to first principles, simple details that are straightforward and easily understood. This all begins with thoughtful consideration and awareness; buildings designed today will be those that are renovated tomorrow.

Study of details

Although it is a very advanced building, conceptually many of the Bullitt Center's detail's strategies are meant to be straightforward and simple.[106] This simplicity is its greatest advantage in having its components endure over time and be changed appropriately. Simplicity in this case is easier to understand and is equal to ease of replaceability. Also thinking in terms of Function, Constructability and Aesthetics[107], how do the details at the Bullitt Center stack up?

Two details were chosen to study in depth at the Bullitt Center. They will be characterized here as *Exterior Cladding attachment to Intermediate Floors* and *Timber Column to Timber Beam Connection*.

Exterior Cladding attachment to Intermediate Floors

There are two exterior cladding conditions (components) at the Bullitt Center. One is that of the glazing assembly (curtain wall) and the other are the exterior wall panels. The glazing assemblies are mostly "stick framed" on site with operable components pre-fabricated in Everett, Washington. All are attached to the building via clips screwed into the perimeter beams. The other condition is the opaque exterior wall panel composed of steel studs, gypsum wallboard, batt and semi-rigid insulation, vapor barrier and steel cladding. In commercial building design exterior walls typically sit on the edge of the intermediate floor's supporting slab and is also aligned with the column line.[108] These alignments in timber-framed buildings allow it to be carried by the beam structure between columns.[109]

The Bullitt Center architects have instead pushed the wall panel out beyond the edge of the floor's slab and column line into a more "true" curtain wall-like situation. A structural angle is bolted (plus back up welding) to a steel angle anchors to the beam that also acts as edging to the topping slab. The wall panel sits on this angle out-board of the floor so that it moves independently of the structure. This move pairs the exterior wall panels together with the glazing assemblies in a symbiotic relationship to reduce friction between them enhancing their preservation.[110]

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[106] Conversation with Brian Court, 19 Nov 2012
[107] Allen, E and Patrick Rand (2007). *Architectural Detailing*. 2nd edition, John Wiley & Sons, Inc. Hoboken, NJ.
[108] Conversation with Brian Court, 19 Nov 2012
[109] Gatz, Konrad, ed. (1967). *Modern Architectural Detailing. Vol 3*. Reinhold Publishing Corp., NY.
[110] Conversation with Brian Court, 19 Nov 2012

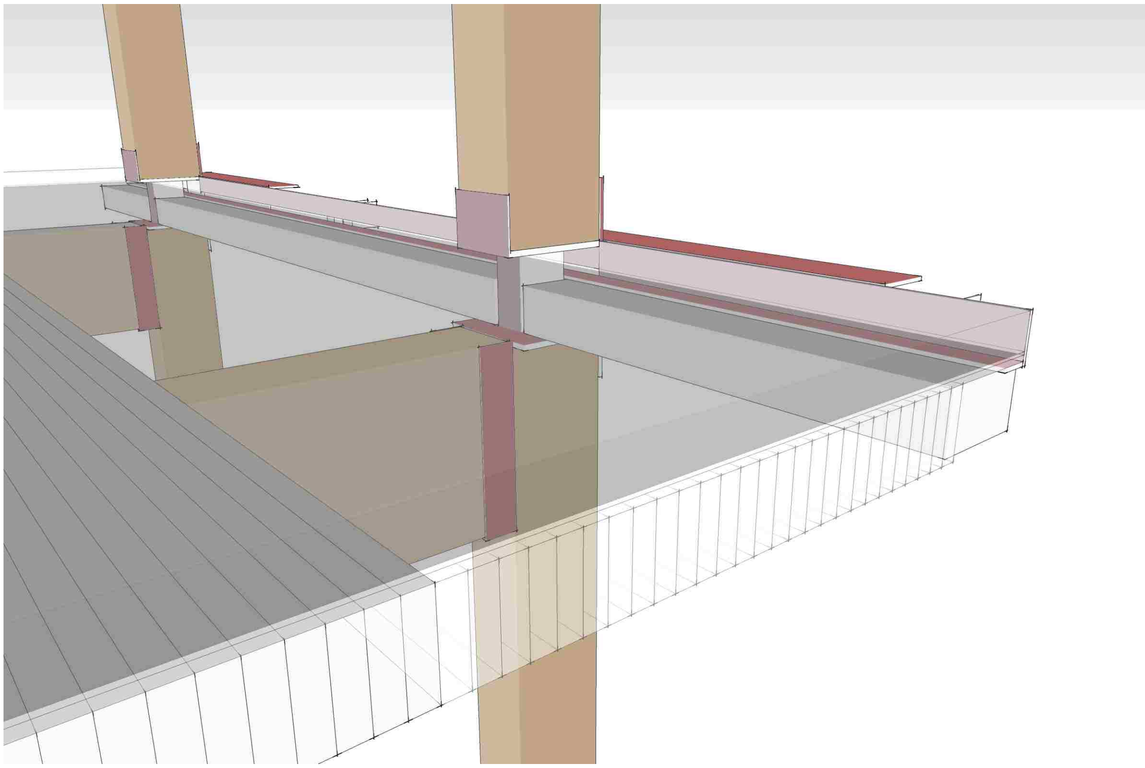

Image 27. Cutaway detail of Floor assembly. Steel angle in distance carries exterior wall panels.

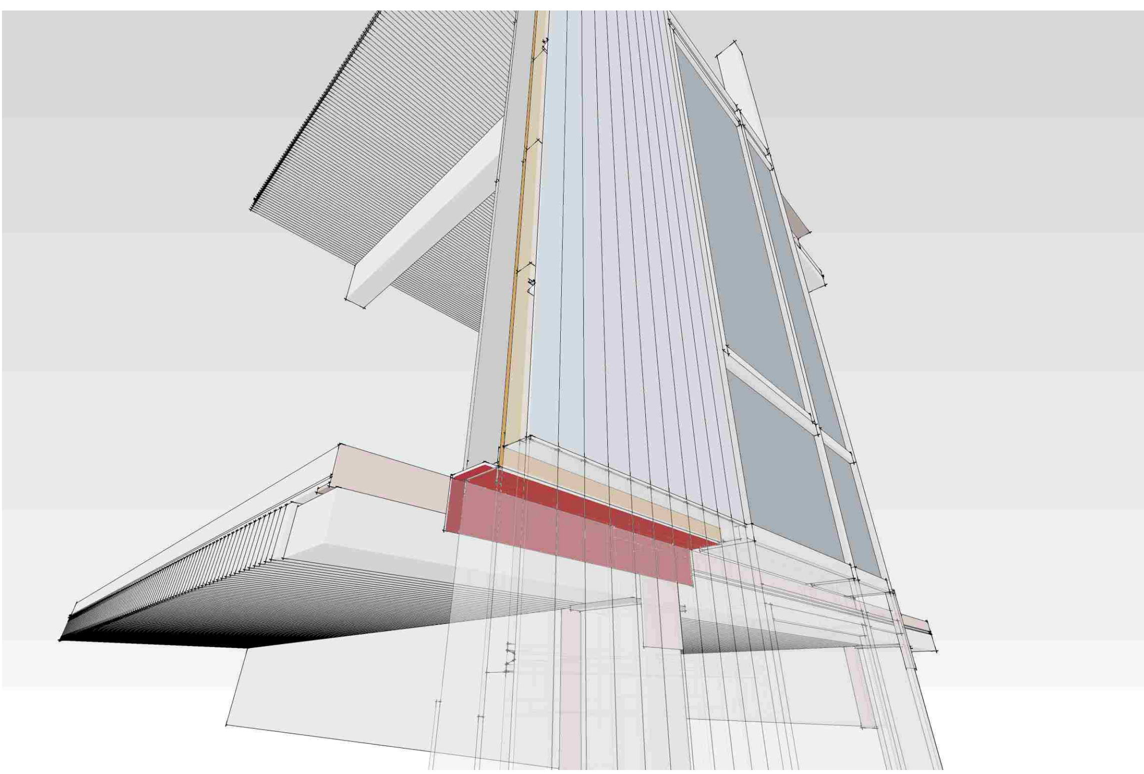

Image 28. Exterior Wall Panel (sitting on steel ledger) and Glazed Curtain Wall companion

Advantages of attaching curtain wall outside of structural elements:

- Closer symbiotic relationship between Wall Panels and Curtain wall, movement as one unit.
- Provides a thermal separation of skin to structure.
- Curtain Wall and Wall Panels are NOT tied into structure in the event of change or replacement, minimum reconstruction of intermediate floors or super structure needed.

Function, Constructability and Aesthetics:

- Functionality of better aligning the exterior wall panels with the glazed curtain should prove beneficial to both durability and thermal performance. Unifying them as a skin takes long-term stress in building movement and expansion & contraction away helping to preserve the integrity of the thermal envelope and the materials.
- Constructability was not an issue as it remained a typical construction sequence. The composition of the wall panel itself could be more difficult. Using the reformulated water barrier was actually challenging as it was more dense and viscous than the other formulation. Constructing the panels off set could have been easier but adding a crane to install them would have been a wash.[111]
- Aesthetically the building did not suffer a change in appearance from any other high performance building that Miller Hull has design of late. One could argue that flushing out the plane of wall panel and curtain wall brought uniformity to the composition to help balance the wall massing with the solar sombrero.

Timber Column to Timber Beam Connection

When considering how to design a modern timber structured building the project architects took into consideration that strength of the frame is in the connections and dissimilar materials do not always work perfectly together. Even if timber elements were to be considered a weaker material choice for vertical loading over concrete or steel, because they employ fabricated steel connections the overall structure is as durable and flexible. With taller multi-story heavy timber structures there is typically a lot of cross grain crushing of a horizontally positioned beam beneath a vertical column. To alleviate this a steel tube connects a base plate of the column above to a capitol plate on the column below (Image 27). Two advantages arise from this move, one, there is little compression along the columns in the structure and two, this standoff clears the columns from being embedded within the structural cavity, clear of all materials surrounding it at the floor and ceiling levels. This clearance will allow any single column to be removed and replaced in the future should the need arise through localized fire or water damage.

[111] Conversation with Brian Court, 19 Nov 2012

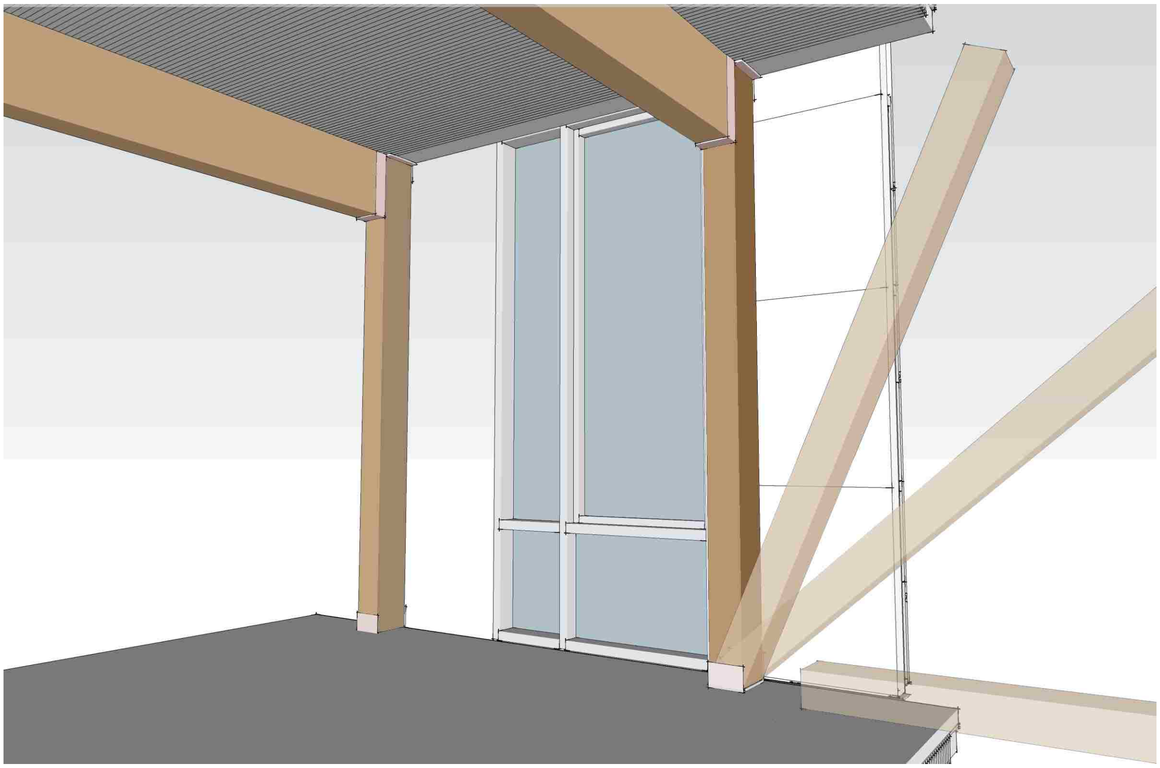

Image 29. Imagined replacement sequence of column

Advantages of columns and beams attached via fabricated steel connections:

- Columns can be replaced without detaching other structural elements.
- Steel connectors preserves cross grain crushing by limiting direct contact with column.
- Separation of combustible materials affords one additional fire protection

Function, Constructability and Aesthetics:

- Functionality of connecting the timber members should be an unquestioned gain. Using the steel connectors in a lot of ways leveled differences between using steel or concrete members to do the same job. Having the allowance to change members if needed is essentially a bonus.
- Although an extra step and expense to design and fabricate the connectors, the benefits exceed the costs. Installation was efficient and improved over standard notice and saddle procedures.[112]
- Timber structures can be beautiful and because the connectors did not require fireproof, the purity of the warm wooden aesthetic was preserved.

07 Analysis of Alternatives:

Opportunities taken by the design team of the Bullitt Center

Intuitively the architects understood that if protected the structure could endure and that the skin and roof would be the points of fallibility. As described in the previous chapter, they took this opportunity to design a building with individual components that when installed together would create a building that was highly efficient, thermally comfortable, sensibly constructible and exuded an aesthetic of a building

[112] Conversation with Brian Court, 19 Nov 2012

built for tomorrow as much as today. Pairing the goals of high thermal protection (because high energy efficiency levels were critical) with the ability to change components, the designers were more easily able to take greater advantages of the materials properties and location. Although the separation of envelope and structure should be seen as an immediate energy saver this is often not the case. Here they were able to couple energy savings with building endurance strategies potentially giving long life to it.

Potential improvements

What are possible improvements upon this system as designed? What would the designers and contractors done differently in retrospect? According to lead designer Brian Court, there could be several small things tweaked in the design but he pointed to only a few that could make a difference. Items such as the handling of transporting rainwater in leaders from the roof to the cistern, how the mechanical exterior blinds work in their coverage and finally the attachment method of the components. They explored the idea of prefabricating much of the building offsite and site assembling. At the scale of the building there would not have been enough savings to justify going this route, however there is now proof of concept that the out board structural ledger system works and the curtain walls sections could have easily been bolted on.[113] Had it been available at the time they would have used cross-laminated timber as the timber flooring infill instead of laminating 2x6's. This could have saved time but not money at the Bullitt Center but on a larger building where time is a more critical path item this could have been a financial savings as well.

Scenario Planning

Because this is a new way of thinking about building design, one that is proactively anticipating the changes the building will encounter, the initial design is only the first phase of addressing potential improvements. It is projected that tenants will change at least every 15 years or so, the exterior wall panels will last only 50 years and the photovoltaic technology will be outdated in 25 years. Understanding this the current and future owners will do well to planning for how these and other components will change. What will future materials be like in terms of cradle to gate emissions and embodied energy, what thermal properties will new insulations hold, how much recycled content could the next round of cladding hold, etc.? The future cannot be predicted with precision but would could be done is to offer scenario planning.

Applying different life span options to the hybrid LCA model created for this case study could offer planning scenarios. For instance, if a user input all needed data to create an initial environmental profile, one that specifies the building operating from years one through the first expected component turn over (in this case study the first turn over component expected is tenant improvements at 15 years). Changing that to represent at least two lifecycles of one component one can see the additional environmental impacts associated with a one to one replacement of said component. However, if one were to anticipate a 20% reduction of the embodied energy with each lifecycle exchange the overall profile will also change, being lessened in this scenario. As LCA data becomes more readily available and reliable, this type of planning will compliment both material palette design and material performance specification. Owners that are interested in the legacy of their environmental footprint would do well to think in these terms.

[113] Conversation with Brian Court, 19 Nov 2012

Importance of material optimization

Durability and optimization go hand in hand. Durability reduces environmental impact by decreasing the amount of resources and energy needed to replace or repair. Optimization is about getting the most from the material, its longevity, its thermal properties, its conductivity, etc. Used in the correct way materials can aide the building in many way and therefore it is responsible to protect that investment in a durable way. Material optimization is about using a material's properties in a dynamic way. Within a façade most individual material types will have different thermal qualities, expansion rates, moisture contents, flexibility, etc. Coordination of these elemental properties is necessary to harnessing their true abilities to endure. Traditional construction methodology layers the materials of any detail or configuration one upon another entombing one behind the next. A better utilization is systematic grouping of these same materials into component then attaches them one by one. It is inherent that larger groupings/components will not be completely entombed but remains free enough that they can be accessible. This subtle shift will aide the durability and preservation of the materials, thus the building, to perform at an equally high level up to the time of the natural end of each component's lifecycle. Accessibility allows the component to be repaired and not the *whole* building theoretically lowering recurring costs, eliminating larger one time fixes and permitting the building to endure.

Future of Enduring Building Design

The Bullitt Center could represent a change in direction of building design for many reasons related to its strategies for low energy use but what is more compelling is how the designers coupled material performance to time horizons. This is a stark difference in conventional thinking. Stewart Brand's examination of how buildings learn is a commentary on how buildings react to changes brought upon it without the forethought of anticipating the changes. The Bullitt Center knows that it must change and uses that to its advantage. Other building designers can learn from this.

When thinking about the future built environment as a whole, what building types should be long lasting? Should all buildings be? If not, which should, which should not and what are the difference between them? How could this be decided and what incentives could be created to encourage this behavior in owners? The full depth of this discussion will not be explored here only prompted. Should only ownership groups that have vested long-term interests in a structure push for long lasting buildings such as universities or municipalities? Should typical businesses in stand along buildings do the same such as the developer of a movie theater or drive-thru restaurant? It could be argued that all building's materials are worth preserving and if a building has a predictable short life as temporary warehouse or fast food chain restaurant, the materials should be able to easily be disassembled only to be reconfigured as needed elsewhere.

One could look at any building in a less permanent way and remark that it is NOT a building at all but a storehouse for materials. These materials are to be assembled, used appropriately and then relocated along to another building of the same type or mixed back into the systems to be used by the next lessee, aka *buyer*. Any building could be viewed in this way not just one meant to be temporary. For it to be financially viable however, steps most be taken by the designers to anticipate disassembly in a reasonable manner. As discussed with the detailing at the Bullitt Center, tweaking typical details should cost no more than typical construction practices especially if detailing for endurance becomes the more typical way of building.

Will the Bullitt Center mark a turning point in building design? This remains to be seen however the principles involved are already being applied again. Coupling design strategies for endurance with energy efficiency is the best way to further this cause at present. Recording the benefits and raising awareness will be the next and future challenge.

08 Discussion:

Tying LCA and Endurance to better building design

This thesis project began as a way to explore the intricacies of designing buildings that were easier to change and maintain. This is a way of making better buildings, ones that will endure in viable ways for generations longer than a typical building, buildings that can mature, buildings that have the longevity to endure the marathon of life as we need them to. Better building design is not about style. Better building is intelligence. A better building is smarter; an extension of what is becoming more apparent to society as needed, a more sustainable building environment.

LCA provides metrics to better understand the impacts of buildings throughout their life cycle. Better buildings will be built when designers can intelligently integrate life cycle thinking and life cycle data within the fast timeline of building design and construction. Integrating LCA into the design process is not something that has been done traditionally. It is not something that clients have typically asked for nor is it something that building code or building policy have required. However, a first step is to raise awareness of the need for this information and to create a dialog with those closely linked to the creation of building projects. Designers can learn from the process and the demand for better data might increase. Drivers for integrating LCA could include designers, builders, clients, the financial counterparts on a project, local and regional governmental figures connected to industry, industrial representatives of material manufacturers, and many others.

Armed with information that is relative and useful, architects can make a significant difference in the direction of *what happens next* with their buildings. Although there can be no dictation of how long an owner will have control over the facility or what the next change of use will be, giving the building the allowance to be modified is the best hope for the building surviving and thriving. Finding methods to integrate endurance into ALL buildings at no added cost should be a measure of good architecture.[114]

The following are general recommendations appropriate for architects and engineers looking to integrate endurance, lifecycle management practices into their practice.

- Understand that LCA at a practical level is not about precision but overall orders of magnitude and that is enough because it inspires designers to think in whole life cycles – this is a more holistic point-of-view on building design.
- Integration of LCA into practice will probably come in combination of regulation and incentives – they will work in tandem though the regulatory side will only come after the building community begins the grassroots effort of using it.
- The use of EPDs in architectural specifications can be used as an additional pre-qualification of product performance – this is an opportunity to display transparency for the owner (marketing),

[114] Kate Simonen, personal communication

to locate a better product, help in the rating system certification process and navigate future regulatory hurdles.

- The insertion of lifecycle thinking into mainstream thought will get a boost with its inclusion into rating systems such as LEED v4 and LBC – architects need to frame this as a value-adding proposition and as an investment for ownership, not as a barrier.
- Balance the data-driven aspects of design with practical mechanisms for repairability – the models cannot project actualities only possible scenarios, so make it easier on the client to maintain and update the building over time.
- Bring the aspect of longevity into the conversation by outlining the three current financial qualities of a building: first costs of construction, the cost of energy use, and cost of maintenance and repair– then add in the costs of externalities and use that savings as a marketing arm to demonstrate its deeper *green* nature.
- Think on a multitude of scales from small (residential, light commercial) to the mid sizes to district and urban planning scales – longevity and durability is a changing notion for each though it is rooted in making better buildings with less wasteful practices.

09 Future Research Needs

Through this research, the following questions were identified for future research.

- Explore how LCA can link to the social and economic aspects of building design and how this can stretch from the scale of a single building to a community and beyond.
- This thesis evaluated and modeled the Bullitt Center as a case study. A next step could be to compare it's modeled results to existing buildings and other typical office buildings of the same size.
- Taking some of the premises from this thesis; explore how we can learn from existing buildings methods of longevity in terms on their infrastructure, configuration and detailing.
- The models presented here do not account for potential recycling of components as additional avoided impacts nor does it account for carbon sequestration before and after construction. These aspects would be interesting to how scenario planning and time assumptions can be made.
- What does this look like at different scales? How can single-family dwellings use metrics and design details to promote durability and longevity? How does this different from the urban planning level?
- How can this be translated to clients and public at large? Can we create visualization campaign tools to quickly reach a broader audience?
- Compare more models and methods to results found here. Is there one that is a "best fit" for different levels of users, i.e. architects, engineers, LCA experts, etc.

10 Conclusions:

The title of this thesis, (by)Metrics (by)Design, suggests the two avenues of recommendations, that *metrics* can be a useful aid in the creation of more enduring buildings and that architects and engineers can give them *by design* greater longevity. Perhaps there will be regulations and incentives that one day compel design teams to be more transparent about carbon footprinting or hold them to minimum standards of environmental impact. Perhaps the negative externalities of emissions and pollution that are currently hidden will one day be a transparent part of us paying a more true cost of materials. Part of getting to that place is in education on a variety of levels, education among the professional community, education of the client and education in schools. We need to learn to design with intention.

Better buildings not just last longer, they endure. They do not grow obsolete quickly with a change of technology; contrarily they thrive for generations because they are adaptable to new needs. They are comfortable and affordable to operated and maintain. They understand their true impact on the planet and make decisions accordingly. It is fairly obvious that sustainable design has grown in stature over the past 15 years. One could also pick out that energy efficiency has been one of the key drivers of this. As demonstrated in this thesis, as buildings become more energy efficient their environmental impact will shift from operational energy use as the primary source to material efficiency. It is doubtful that all or even most buildings will become net-zero energy operators in the coming generation but a lot will and a lot more will show drastic reductions from efficiency. It is therefore imperative that we begin to understand material sourcing and its associated impacts, transportation impacts, construction, maintenance and rehabilitation impacts and those coming at the end of the building's life. Thinking in whole life cycles will be the key to furthering sustainable design.

11 References:

Advisory Council on Historic Preservation, Assessing the Energy Conservation Benefits of Historic Preservation: Methods and Examples (Washington, DC: 1979).

Akashi, O., Hanaoka, T., Matsuoka, Y., Kainuma, M. (2010). “A projection for global CO2 emissions from the industrial sector through 2030 based on activity level and technology changes.” Elsevier Ltd.

Allen, E and Patrick Rand (2007). Architectural Detailing. 2nd edition, John Wiley & Sons, Inc. Hoboken, NJ.

Architecture 2030, The 2030 Challenge, http://architecture2030.org/2030_challenge/the_2030_challenge

Athena Institute. (2004) “Minnesota Demolition Survey: Phase Two Report

“Australian Commercial Building Sector Greenhouse Gas Emissions 1990–2010,” report, 1999

Azari, R and Kim, Y.W. (2012). Comparative Assessment of Life Cycle Impacts of Curtain Wall Mullions. Building and Environment, Vol. 48, February 2012, pg. 135-145.

Bare, J. C. (2011). “TRACI 2.0 - The Tool for the Reduction and Assessment of Chemical and other environmental Impacts. CLEAN TECHNOLOGIES AND ENVIRONMENTAL POLICY.” Springer-Verlag, New York, NY, 13(5):687-696.

Bayer, C., Gamble, M., Gentry, R., Joshi, S., (2010). “AIA Guide to Building Life Cycle Assessment in Practice.” Accessible at *www.aia.org/aiaucmp/groups/aia/documents/pdf/aiab082942.pdf*

Brand, S. (1994). How Buildings Learn: What Happens after They’re Built. Penguin Books, New York.

Brandão, M. and Levasseur, A (2010). Assessing Temporary Carbon Storage in Life Cycle Assessment and Carbon Footprinting: Outcomes of an expert workshop. JRC Scientific and Technical Reports, JRC European Commission.

Bribián, I.Z., Capilla, A.V., Usón, A.A. (2010). “Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential.” Elsevier Ltd.

Brown, L. (2006). Plan B 2.0: Rescuing A Planet under Stress and A Civilization in Trouble. W.W. Norton & Co., New York.

Brown, L. (2009). Plan B 3.0: Mobilizing to save Civilization. W. W. Norton & Co., New York.

Bowyer, J (2011, Sept). “Green Building Programs – Influencing Positive Change, But Fundamental Flaws Inhibit Effectiveness.” Paper presented at the Structural Engineers Association of California (SEAOC) Convention 2011, Las Vegas, Nevada.

Bowyer J., Bratkovich S., Lindburg A. and Fernholz K. (2008). “Wood Products and Carbon Protocols – carbon storage and low energy intensity should be considered.” Dovetail Partners, Inc.

Buchanan, A., John S., Nebel, B. & Perez N. (2008, update 2009). “Environmental Impacts of Multi-Storey Buildings Using Different Construction Materials.” Unpublished report commissioned by the Ministry of Agriculture and Forestry under proposal POR/7811.

Busby, Perkins + Will, “Life Cycle Assessment, Buchanan Building-D,” University of British Columbia (2006).

Chang, Y., Ries, R.J., Wang, Y. (2011). "The quantification of the embodied impacts of construction projects on energy, environment, and society based on I–O LCA" Elsevier Ltd.

Ching, Frances (1991). Building Construction Illustrated. 2nd edition, Von Nostrand Reinhold, NY, NY.

Cole, R. J. (1999). "Energy and Greenhouse Gas Emissions Associated with the Construction of Alternative Structural Systems," Building and Environment, v. 34, pp. 335-348.

Cole, R.J., & Kernan, P.C. (1996). Life-Cycle Energy Use in Office Buildings. Building and Environment, 31 (4), 307-317.

Denniston, S., Frankel, M., Hewitt, D. (2010) "Outcome-based Energy Codes on the way to Net Zero." White Paper. New Building Institute.

Department of Energy and Climate Change (U.K.) (2008). Impact Assessment of the Climate Change Act. Accessed on 27 April 2012, Retrieved from:
http://www.decc.gov.uk/en/content/cms/legislation/cc_act_08/cc_act_08.aspx

Douglas, James (2006). Building Adaptation. Elsevier Ltd. Oxford, UK.

DSM Environmental Services (2008). 2007 Massachusetts Construction and Demolition Debris Industry Study. Accessible at http://www.mass.gov/dep/recycle/reduce/07cdstdy.pdf

EPA, "Building Savings: Strategies for Waste Reduction of Construction and Demolition Debris from Buildings." http://www.epa.gov/osw/nonhaz/municipal/pubs/combined.pdf

EPA, "Proposed Carbon Pollution Standard for New Power Plants," 2012 Accessed at http://www.epa.gov/air/tribal/pdfs/carbonpollutionstandardnewpowerplants032712-1030am.pdf

Gatz, Konrad, ed. (1967). Modern Architectural Detailing. Vol 3. Reinhold Publishing Corp., NY.

Golden, Jay (2010). "An Overview of EcoLabels and Sustainability Certifications in the Global Marketplace."

Grant, J. & Moonen, P. (2011). "Leadership Standards & Disclosure Tools: Raising the Bar for ALL Materials Used in Green Building." White Paper. Retrieved from,
http://www.jasongrantconsulting.com/wp-content/uploads/2011/06/Leadership-Standards-Disclosure-Tools.pdf.

Hammond, G. P. and Jones, C. I., 2008. Embodied energy and carbon in construction materials. Proceedings of the Institution of Civil Engineers - Energy, 161 (2), pp. 87-98.

Hannon, B. M.; Stein, R. G.; Segal, B.; Serber, D.; Stein, C. Energy use for building construction Progress Report, 1 Mar. - 1 Aug. 1976 Illinois Univ., Urbana. Center for Advanced Computation.

Hindle, Tim. (2008). "Guide to Management Ideas and Gurus," The Economist, The Economist Newspaper Ltd., Accessible at http://nashaucheba.ru/docs/8/7500/conv_1/file1.pdf

Horne, R., Tim Grant and Karli Verghese (2009), *Lifecycle Assessment: Principles, Practice and Prospects*, Csiro Publishing, Collingwood VIC, (Australia).

Hunt, R.G., Franklin, W.E., Welch, R.O., Cross, J.A. and Woodall, A.E. (1974). Resource and Environmental Profile Analysis of Nine Beverage Container Alternatives. EPA/530/Sw/-91c. United States Environmental Protection Agency, Office of Solid Waste Management Programs, Washington, D.C.

ISO (2006c) 14044:2006 Environmental management-Life cycle assessment-Requirements and guidelines. Geneva: ISO.

Kestner, D., Jennifer Goupil and Emily Lorenz, eds. (2010) Sustainability Guidelines for the Structural Engineer. American Society of Civil Engineers, Reston, Va.

Kieran, Stephen, & Timberlake, James. (2004). ReFabricating Architecture: How Modern Methodologies are Poised to Transform Building Construction. New York: McGraw-Hill Companies, Inc.

Konig, H. Kholer, N. Kreissig, J. Lutzkendorf, T. (2010). A life cycle approach to buildings: principles, calculations, design tools. Radaktion DETAIL, Munich.

Lane, T (2010). Embodied energy: The next big carbon challenge. Building.co.uk. Retrieved April 26, 2011, from http://www.building.co.uk/technical/embodied-energy-the-next-big-carbon-challenge/5000487.article

Lane, T (2007). Our dark materials. Building.co.uk. Retrieved April 26, 2012, from http://www.building.co.uk/analysis/our-dark-materials/3099435.article

LeVan, S.L. (1995). "Life Cycle Assessment: Measuring Environmental Impact, Life Cycle Environmental Impact Analysis for Forest Products." Paper presented at the 49th Annual Meeting of the Forest Products Society, Portland, Oregon.

Lippke Bruce. (2006). Building Materials and Climate Change: The Unseen Connection. California Forests (California Forestry Assoc.), Sacramento, CA. Winter 2006. Vol. 10 No. 1. p12-13.

Lippke B., Wilson J., Meil J. and Taylor A. (2010). Characterizing the importance of carbon stored in wood products. CORRIM's special issue of Wood and Fiber Science

Lomborg, B. (2007). Cool it: The Skeptical Environmentalist's Guide to Global Warming. Vintage Books, Random House Publishing, New York.

Lovins, Amory (2011) Reinventing Fire, Chelsea Green Publishing, White River Jct., Vermont

Macht, Will. "Building Flexibility into Mixed-Use Projects." Urbanland, Urban Land Institute, 31 May 2012. Accessible at http://urbanland.uli.org/Articles/2012/April/ul/MachtFlexibility

Manning, A., Nisbet, E., Keeling, R.F. & Liss, P.S. (2011). Greenhouse gases in the Earth system: setting the agenda to 2030. The Royal Society, Mathematics and Physical Sciences, Accessed on 27 April 2012, Retrieved from: http://rsta.royalsocietypublishing.org/content/369/1943/1885.ful

Marcea, R.L., & Lau, K.K. (1992). Carbon Dioxide Implications of Building Materials. Journal of Forest Engineering, 37-43.

Marceau, M. L., Nisbet, M. A., and VanGeem, M. G. (2007) Life Cycle Inventory of Portland Cement Concrete, SN3011, Portland Cement Association, Skokie, Illinois, PCA.

Martin, Sadie (2009) *Constructing a Carbon Conscience*, Master's of Architecture Thesis, WSU.

Mazria, Ed. "It's the Architecture Stupid." Solar Today Magazine, May/June 2003.

McDermott, C.P. (2009). "The future of the construction industry and the implications for construction project management and education." Iowa State University, Dept. of Construction Engineering and Management, Master's Thesis, Accessible at http://publications.cce.iastate.edu/bitstream/123456789/74/1/C%20McDermott%20MS%20Thesis%202009.pdf

Miettinen, P., Hamalainen (1997). "How to benefit from decision analysis in environmental life cycle assessment (LCA)" European Journal of Operational Research 102 (1997) 279-294. Elsevier Ltd.

Millennium Ecosystem Assessment (various authors) (2003). Ecosystems and Human Well-being. World Resources Institute. Island Press, Washington, D.C.

Monroe, Linda. "Diverting Construction Waste," Buildings 2008. Accessible at http://www.buildings.com/ArticleDetails/tabid/3334/ArticleID/5758/Default.aspx

Mostafavi, Mohsen and David Leatherbarrow, (1993). *On Weathering: the life of buildings in time*. Cambridge, Mass, MIT Press.

Mulady, Kathy. "Where your Seattle trash ends up." The Seattle Post Intelligencer, July 2007

National Association of Home Builders, "Deconstruction: Building Disassembly and Material Salvage," 1998. Accessible at http://www.epa.gov/osw/conserve/imr/cdm/pubs/decon_br.pdf

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

Nelson, Bryn (2011), "The Self-Sufficient Office Building," NY Times online.O'Connor, Jennifer. "Survey on Actual Service Lives for North American Buildings," Woodframe Housing Durability and Disaster Issues Conference, 2004.

Oregon Department of Environmental Quality, "Prioritizing Green Building and Waste Prevention Practices with Life Cycle Assessment: Systems Thinking for Residential Buildings" (2010).

Ortiz, O., Castells, F., Sonnemann, G. (2008). "Sustainability in the construction industry: A review of recent developments based on LCA." Elsevier Ltd.

Pinto, I. (2011). LCA comparison of structural frame alternatives for office buildings. Unpublished report commissioned by the Canadian Institute of Steel Construction with funding from the Steel Structures Education Foundation and MITACS Accelerate.

Preservation Green Lab Report (2012). "The Greenest Building: Quantifying the Environmental Value of Building Reuse." Accessible at http://www.preservationnation.org/information-center/sustainable-communities/sustainability/green-lab/lca/The_Greenest_Building_lowres.pdf

Puettmann, M. and Wilson J. (2005). Gate-to-gate Life-Cycle Inventory of Glued Laminated Timber Production. Wood Fiber Sci. Vol 37 Dec. 2005: p99-113.

Puettmann, M. and Wilson J. (2005). Life-Cycle Analysis of Wood Products: Cradle-to-gate LCI of Residential Building Materials. CORRIM's special issue of Wood and Fiber Science

Roberston, Adam (2011). "A Comparative Life Cycle Assessment of Mid-rise Office Buildings Construction Alternatives: Laminated Timber of Concrete." University of British Columbia, Dept. of Forestry, Master's Thesis, Accessible at https://circle.ubc.ca/bitstream/handle/2429/36433/ubc_2011_fall_robertson_adam.pdf?sequence=1

Sabol, Louise. "Technology, Change, and the Building Industry." Real Estate Review, Vol. 36, No. 3, December 2007.

Sjostrom, C., Chevalier, J.-L., Trinius, W. (2005). Life Performance of Construction Materials and Components. Accessed on 27 April 2012, Retrieved from: www.pebbu.nl/resources/allreports/downloads/05_D1_finalreport.pdf

Simonen, Kathrina (2011). "Motivating Low-Carbon Construction: Opportunities and Challenges, A road map for rapid and significant impact." White Paper. Carbon Leadership Forum. Peer Reviewed.

Simonen, K and Liv Haselbach (2012). "LCA for WA: Life Cycle Assessment (LCA) and Buildings Research for WA State." The Carbon Leadership Forum.

Smith, Baird M and Carl Elefante, "Sustainable Design for Historic Buildings: Foundations and the Future," APT Bulletin, Vol. 30, No. 3/4 (2009), pp. 19-26, Association for Preservation Technology International.

State of Washington General Administration (WA GA), (2005). Energy Life-Cycle Cost Analysis: Guidelines for Public Agencies in Washington State. Washington State Department of General Administration Engineering and Architectural Services. Accessed December 28, 2011 from http://www.ga.wa.gov/eas/elcca/ELCCA.pdf.

Target Zero. (2011) Cost Effective Routes to Carbon Reduction (Supplement, 16 March). Retrieved from http://www.targetzero.info/news/release/the_target_zero_supplement/

TRADA Technology Ltd. (2009). Timber Carbon Footprints: Calculated Values (version 1, Dec 2009). Buckinghamshire, U.K. Retrieved from *www.trada.co.uk/downloads/.../CO2%20Calculated%20Values.pdf*

United States Department of Energy (2008). Energy Efficiency Trends in Residential and Commercial Buildings. Accessed on 27 April 2012, Retrieved from: http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/bt_stateindustry.pdf

Twill, J., Batker, D., Cowan, S., Wright Chappell, T. (2011). The Economics of Change: Catalyzing the Investment Shift Toward a Restorative Built Environment. Earth Economics, Tacoma WA.

U.S. Energy Information Administration, US power supply chart for AEO 2012, http://www.eia.gov/forecasts/aeo/er/early_fuel.cfm

U.S. Energy Information Administration, Commercial Buildings Energy Consumption Survey (CBECS) (Department of Energy, 2003)

U.S. Energy Information Administration, Green Building Facts (Department of Energy, 2009).

U.S. Energy Information Administration (2008). Assumptions to the Annual Energy Outlook. Accessible at http://www.eia.gov/forecasts/aeo/assumptions/pdf/0554(2012).pdf

U.S. Department of Energy, Building Energy Data Book (2010).

USGBC Press Release (2012). "LEED-Certified Green Building Projects Hit 12,000 Mark." Accessible at *https://www.usgbc.org/ShowFile.aspx?DocumentID=18681*

USGBC Green Facts Sheet (2012). Accessible at *www.usgbc.org/ShowFile.aspx?DocumentID=5961*

Van Der Rohe, Mies. "On Restraint in Design." The New York Herald Tribune (28 June 1959).

Victor Olgyay and Cheryln Seruto, (2010). "Whole-Building Retrofits: A Gateway to Climate Stabilization," ASHRAE Transactions, vol. 116(2)

Watch, Dan “Trends in Lab Design.” Whole Building Design Guide, National Institute of Building Science. 12 Sept. 2012. Accessible at http://www.wbdg.org/resources/labtrends.php

Watson, Rob. (2011). “Green Building Market Impact Report: 2011” Accessible at www.greenbiz.com/sites/all/themes/greenbiz/doc/GBMIR_2011.pdf

Webster, Mark D. (2010) “Design for Adaptability and Deconstruction,“ Sustainability Guidelines for the Structural Engineer. American Society of Civil Engineers, Reston, Va., pg 85

Wienand, Norman (2008). Materials, Specification and Detailing. Taylor & Francis, NY, NY. Pg. 32

Wright-Chappell, Theddi and Chris Corps (2009). “High Performance Green Building: What’s it worth? Investigating the Market Value of High Performance Green Buildings.” Accessible at http://www.sustainablebuildingcentre.com/wp-content/uploads/2011/11/GBValueStudy.pdf

Appendices:

A. Lifecycle Assessment Tools and Databases - Overview

Performing a lifecycle assessment can be a tedious process depending on experience, complexity, length, etc. Better LCAs will inevitability have a greater level of detail and depending on the subject of focus, the shear amount of detail and data can be mindboggling to a practicing architect. The procedure of collecting data, building spreadsheet models and running calculations can become quickly overwhelming in volume and time expended, and edge on disaster if there is an unseen error embedded within. Fortunately for professional LCA analysts, tools have been developed to aid in the production and computation of lifecycle assessment. These tools fit within a sequence of events. Tool, which holds the computational structure, references the database for its data. The use of these two allows the user to estimate the environmental impacts of the subject under review. These impacts are reported in the LCA's results and interpretation, which can be refined into an Environmental Product Declaration and other eco labels. Without using these tools, the persons performing the LCA would have to construct the lifecycle inventory (LCI) manually using the data collected and stored in any one of the many databases around the world and compute the data by hand. Although not impossible, the sheer volume of data would be so cumbersome and time consuming; the LCA would not be created quickly enough to be of real use to a manufacturer or specifier. This pace has been one of the hampering features associated with the use and integration of LCA in to mainstream use.[115]

The goal of any LCA tools is to provide its user complicated information in a way that is organized and understandable. Ralph Horne and Karli Verghese describe and explain the "Quick LCA Tool."[116] The 'quick tool' they assert must carry six qualities while balancing its output. They consider those qualities to be design requirements for any tool that is to be used to assist in the performance of a lifecycle assessment. A quick LCA tool must:[117]

- Assist designers and manufactures to make early design and manufacturing decisions based on LCA information
- Assist environmental managers to control the environmental impacts of organizations by providing quick LCA information to help them meet environmental objectives and targets
- Provide information in clear, simple, accessible ways for use by consumers, purchasers or specifiers
- Engender or contribute to a system of trust and independence in the supply of information about environmental performance
- Provide businesses with the means to comply with regulations and codes of environmental development

The most difficult aspect of using or designing an LCA tool is to balance the sophistication needed in the outputted data with the necessary simplicity of use by a user that may or may not have training in the intricacies of performing a lifecycle assessment. The term 'tool' is used to denote a computer program that will assist is categorizing and computing the data entered. These tools are not meant to perform the

[115] Horne, R., Tim Grant and Karli Verghese (2009), *Lifecycle Assessment: Principles, Practice and Prospects*, Csiro Publishing, Collingwood VIC, (Australia).
[116] Horne, Grant and Verghese, 2009
[117] Horne, Grant and Verghese, 2009

LCA in the stead of the user but rather to facilitate and streamline the process. It is generally recognized that LCA tools can be separated into two categories, more complex tools and softwares, and the easier to use, simpler online tools or 'calculators.'[118]

The 'databases' referenced above are the depository of primary data associated with a particular unit process that is within the user's boundaries of study. Their fundamental make up is that they are a grouping of inventories that are listed based on what the inventory is referring to, such as, bituminous coal at mine. Within this listing of bituminous coal at mine, there is primary data collected as samples to quantify the resources used to extract a single unit of bituminous coal (one kg) and the emissions associated with that same unit of coal. See Image below from a screen shot of Bituminous Coal at Mine. Moreover, this particular inventory does not tell the user the emissions when this unit of coal is burned to make electricity or heat, which is in another inventory. To most effectively use these inventories to gain a full picture of the lifecycle process of a material, several of these inventories would have to be viewed, cross-referenced and computed to ascertain a range of environmental input and output. This is the point where an LCA tool would be of great value to someone attempting to create a lifecycle assessment.

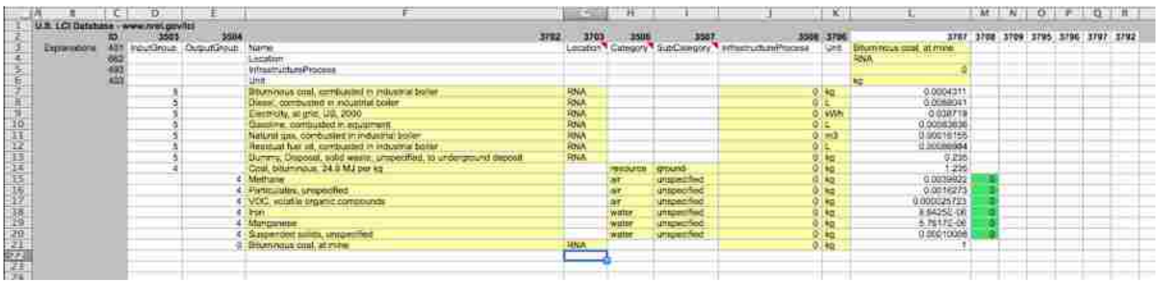

Image. Bituminous Coal at Mine[119]

These databases exist as a wide variety of contexts. Some are privately held and privately populated by companies that hold subscriberships for data access. The companies that maintain them have dedicated resources to gathering and updating the inventories with privately commissioned studies, with partnerships in data sharing with companies or gather data from other sources. Examples of these databases are *Eco-Invent* from the Swiss Center for Life Cycle Inventories[120] or the *GaBi Professional* databases from PE International.[121] Some databases are free to access. For instance, the United States Lifecycle Inventory (US LCI)[122] has been collected, processed and hosted by the US National Renewable Energy Lab (NREL) for many years. The funding coming in starts and fits, it does not have the resources to actively seek out new contents nor to be continuously updated. Unlike the subscription-based systems, the US LCI relies upon lifecycle researchers around North America to provide their data to be formatted and uploaded for free, on-demand dispersal. To date there are 593 separately listed inventories. Of those listings, 169 of them are transport related data from the US EPA, 52 listings are related directly to electricity generation via power plant with the data coming from US EPA's eGrid and 154 listing related to timber products, fuels or other, from a single research body, the Consortium for Research on Renewable Industrial Materials (CORRIM) based at the University of Washington in Seattle. This is illustrated that

[118] Simonen, K and Liv Haselbach (2012). "LCA for WA: Life Cycle Assessment (LCA) and Buildings Research for WA State." The Carbon Leadership Forum.
[119] US LCI Database screen capture.
[120] Swiss Center for Life Cycle Inventories - http://www.ecoinvent.org/database/
[121] PE International - http://www.gabi-software.com/international/databases/gabi-databases/
[122] US LCI Database Project, NREL - http://www.nrel.gov/lci/

nearly 40% of the database is governmental agency supplied data and not private research, while a single research institution has provided over 25% of the database. Whereas there are thousands of listing within the 'for-profit' world of LCI database creation, those that are not heavily funded lag behind in content.

The following excerpt from LCA for WA elaborates of the methods of LCA modeling.[123]

METHODS

LCA analysis is typically conducted using one of the following methodologies: process based LCA, Economic Input Output LCA (EIO-LCA) or Hybrid LCA. Each of these methods is different in how they characterize the system and allocate emissions and environmental impacts to the different materials used and processes performed. Therefore, while all of these models are respected methods of conducting LCA, the results of analysis completed based on different modeling assumptions will have different results. Review of LCA results must thus carefully consider the models and assumptions used in creating the LCA. Analysis and impact models must be identical if results of LCAs are to be compared. Good texts, which provide more detailed information on LCA methodology, include (detailed references at end of document):

1. *The ILCD Handbook: A General guide for Life Cycle Assessment-Detailed Guidance. European Commission Institute for Environment and Sustainability (2010)*
2. *A life cycle approach to buildings: principles, calculations, design tools. Konig, H. Kholer, N. Kreissig, J. Lutzkendorf, T. (2010)*
3. *The Computational Structure of Life Cycle Assessment. Heijungs & Suh (2002)*
4. *Environmental Life Cycle Assessment of Goods and Services: An Input-Output Approach. Hendrickson, Lave & Matthews (2006)*

DATA

The underlying LCI data used in an LCA can either be specific (data collected at the manufacturing site) or generic (based on data from another study). The Swiss government has supported the development of the most comprehensive LCI database currently in use, eco-invent. Data thus represents Swiss manufacturing processes and Swiss electrical energy consumption. The US LCI database needs to be expanded. However, within it are the unit process LCI data for US-specific manufacturing.
Most of these databases model energy generation and use, and the tools provide methods to change the energy source of a manufacturing process to model different production methods. Tools to model the operational energy use in buildings have not been reviewed as part of this study. For more information on this topic see the US Department of Energy's Building Energy Software Tools Directory at: http://apps1.eere.energy.gov/buildings/tools_directory/software.cfm/ID=347/pagename=alpha_list (accessed July, 2012).

Life cycle inventory and assessment (LCIA) tools are in a state of continuous improvement. Figure X5.1 is provided to show how the tools use databases that provide materials, water and energy use, and waste data to create a product (or process or material)-specific life cycle inventory (LCI). The life cycle inventory is a detailed accounting of all of the 'flows' (quantities of materials, chemicals, etc. that are both taken from and released to nature. For example, an LCI would typically quantify items such as combustion of a quantity of coal and emissions of items such as $C0_2$, methane and mercury as well as resource use (e.g.

[123] Simonen, K and Liv Haselbach (2012). "LCA for WA: Life Cycle Assessment (LCA) and Buildings Research for WA State." The Carbon Leadership Forum.

water). LCI databases exist that quantify the input and emissions for different 'unit processes'. In this section we will review the extent and scope of the primary existing LCI databases.
A comprehensive LCA analysis must carefully account for all of the materials and processes (e.g. iron ore and coal combustion) that are required to manufacture a specific product (e.g. steel). Thus multiple LCIs (unit process data such as coal combustion, iron ore mining and transportation by truck) are combined to get an aggregated LCI for a specific product (e.g. steel wide flange beam). The list of emissions in an LCI from manufacturing a product can include more than 100 different chemical and physical releases. In order to simplify the interpretation of these emissions, LCI results are typically aggregated into an environmental impact category such as climate change or acidification.

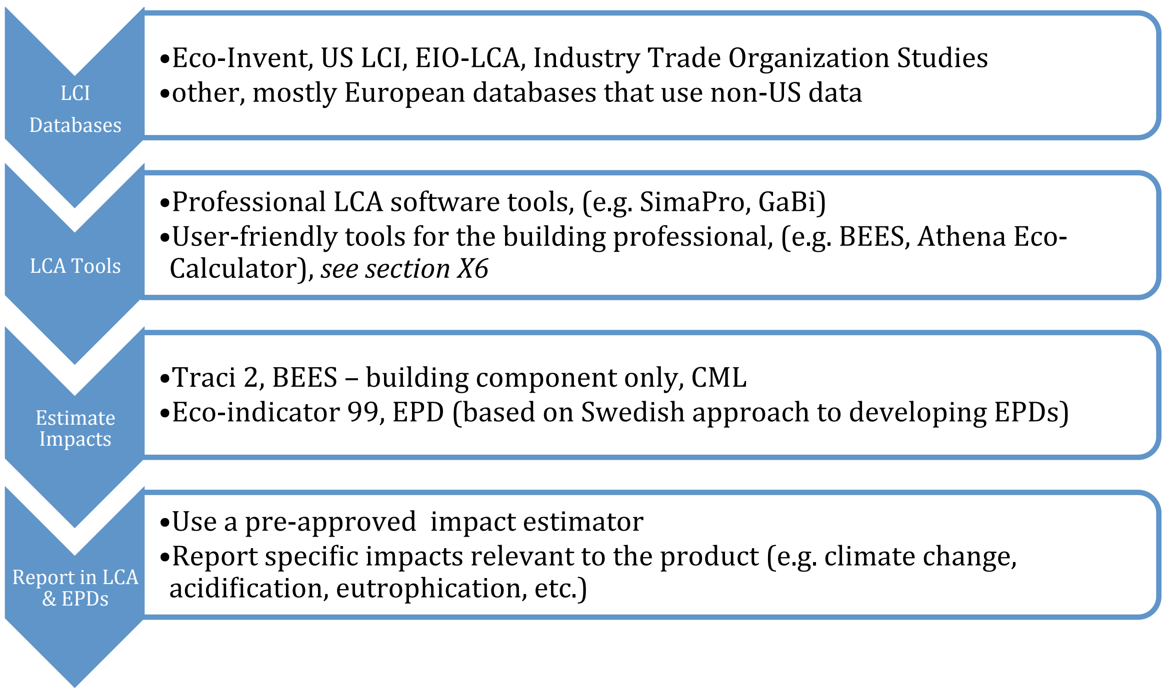

Figure X5.1: *Links between LCA databases, tools, impact estimators, and their uses.*

IMPACTS

Scientific studies have evaluated the impact of different emissions on specific environmental impacts, such as climate change. These studies enable the creation of characterization factors to model the relative influence of different emissions on the noted environmental impact. For example, as multiple greenhouse gasses (GHG) have been determined to impact climate change, the combined impact of all of these GHGs is reported by multiplying each of the GHGs by a characterization factor (the Global Warming Potential/GWP). The characterization factors can be used to translate multiple emissions into a single environmental impact category (such as equivalent Carbon Dioxide (CO_2e) to represent the climate change impact category). Some of the environmental or resource impacts are well understood by the scientific community and accepted by the public. Other impacts are not as well understood, and impact estimators for them are in their infancy. See discussion in the Introduction to this project for additional information about different environmental impacts and characterization models.

There are additional impacts directly related to resource use (water, non-renewable resources). Often the total LCI for these resources are published as a resulting LCA impact. Of note, methods, databases and tools for estimating the following impacts are still developing and are less uniformly reported: the contribution of direct and indirect land use to climate change or other environmental impacts, impacts on human health, bio-diversity, social impacts, and water use.
The reported results from standard impact categories are the foundation of interpreting results of an LCA and form an integral component of environmental product declarations (EPDs) designed to showcase the environmental and resource footprint of a given product in an understandable format using metrics that are consistent across product categories.

DATABASE TOOLS
Given the complexity of tracking LCI data and combining the unit processes to develop LCA impacts for specific products, LCA tools have been developed to manage (and expand) LCI databases and facilitate the creation of LCAs. These comprehensive LCA tools designed for LCA practitioners are reviewed in this section. Simpler, building industry specific LCA 'calculators' are reviewed in the next section of this document.

B. Lifecycle Assessment Tools and Decision Support
One method of using LCA is to aid in material selection and with decision support. There are many tools available globally to architects, engineers and lifecycle assessment experts with a wide range of levels of user knowledge of LCA. Tools have the potential to give a user a lot of usable information. A few things should be noted about any tool before a potential user needs to run an analysis.

- Some will contain regionally specific data (e.g. the Athena EcoCalculator and Impact Estimator) to reflect the regional power grid and local transportation distances.
- These tools do not typically permit manipulation of the data and therefore the results, while regionally specific, cannot be customized for a specific project with product specific data.
- The source of the tools data will come from a specific or from multiple sources depending on the tool being used.
- The data could be representative of the user's area or completely different, be sure to investigate which databases are being pulled from.
- Some tools allow the database to be changed based on the user's preference such as GaBi being able to switch from its professional database over to EcoInvent and others.

Tools have the ability to simplify the process of LCA investigations. They aspire to take care of both the data needed and the mathematics. They cannot fully replace a person in that there will need to be an interpretation of the results. The author experimented four tools specifically for this report.

	Flexibility of program	Usability	LCA experience level required	Are all building components available
Athena Institute's EcoCalculator	Not flexible	Easy	Low	No
Athena Institute's Impact Estimator	Moderately	Moderate	Medium	No
BEES	Not flexible	Easy	Low	No
GaBi	Flexible	Complex	High	Yes

C. Summary of Tool Assessment:
Two tools in Figure 01, BEES and EcoCalculator, require little LCA expertise to get started using outside of the building's data such as material quantities. In addition very few input opportunities are given the user making the experience easy and quick. There are few opportunities to manipulate the inputs, reducing inadvertent error if one is not familiar with the complexities of LCA computation. In the case of EcoCalulator, the user has a variety of common assembly types to choose from but if those do not match closely the building assemblies needed to investigate there is no flexibility to alter the tool. BEES is more of a dropdown selection menu style online interface. Both tools will give results that are interesting but not quite the depth needed to really investigate WHY those results were found. Because architectural and engineering staff members will probably not use more robust tools that have a greater level of detail and flexibility frequently, these quicker, more compact online and downloadable tools can still serve a purpose.

Athena's Impact Estimator and Gabi reflect a more robust version of LCA tool. They have more opportunity to be manipulated by the user thereby getting more in depth results. However, with more user interface a higher level of LCA knowledge is needed because there is now a greater chance of messing up the potential results. For instance, in Impact Estimator the user can specify building assemblies by picking the materials to build up, e.g. a wall type. If a certain material is not available under "Walls" and the user decides to add it in under "Extra Materials," it the quantities are then on the user to specify correctly. Major errors could lead to equally major errors in the results. GaBi is a very different type of interface where the user is asked to link together individual unit processes to "build up" the products chain. With so many products in any single building, it is easy to imagine a missing something important or not linking some unit processes correctly. For this reason among others, GaBi falls under the category of expert level of LCA knowledge needed to navigate successfully.

LCA tools are only as good as their underlying data because the tool is just an interface to allow computations to be done with users of varying levels of LCA sophistication. The toolmakers want consultants and architects to be able to choose materials based on their results. Currently, because the LCA data for U.S. building materials and products is of varying quality and completeness, the best use of these tools appears to be to gather a sense of the order of magnitude for each potential material selection. Because of underlying assumptions and a vast amount of variation from tool to tool made the tool creators, using the tools to support detailed decision-making is not reliable. If the selection criteria for a client called for a material with a low global-warming potential, two materials can be quickly compared, but there is a lot of background to that data that the specifier is not privy to. This is both the tools' greatest strength and greatest weakness.

D. Methods of gathering data

The data that populates these databases come from sources around the globe. Often an LCA practitioner is looking for data that is regional in nature. In order to be more geographically accurate, thereby creating a more accurate account of the subject, looking for data sets that are specific to the local energy mix and local material sourcing is preferred. Data such as this is not always available. In fact, most often there has to be a mixing of data sources, sometimes a mixing of databases. In no way does invalidate the LCA although the one performing the LCA would be clear to list and evaluate their sourcing.

As mentioned, those that collect and format the data housed in these databases have different resources available to expand the database volume. Those that are subscriber-based take many routes to do so. Data is gathered from either primary or secondary sources. Primary sources are collected at the point of emission, sampled directly from the process. Secondary sources could be in the from of data collected by the one gathering the data (a recreated experiment for instance), it could be found from other reported locations, journals or technical reports, etc.[124] The further from the primary sources the less credible the data will be when held up to scrutiny.

As an observation by this author into gathering data and using these databases, most of the primary data collection comes in the form of industry survey. Survey in this case is specific to a grouping of producers, manufacturers or processers, which have the capacity to divulge the information requested. Three cases of this can be found within the wood, steel and concrete industries. CORRIM has spent a considerable amount of years gathering data via survey from saw mills, forest managers and the like to create a wealth of data related to the timber industry. Their data generally is representative of a significant portion of the total production of a localized region thereby establishing a big enough sample to from which they can draw some conclusions. For instance in the 2004 report on the gate-to-gate lifecycle inventory of Glue Laminated Beams (glulam), authors Maureen Puettmann and Jim Wilson reported products and emissions accounting for 70% of all glulam production in the Pacific Northwest.[125] Even though there were only three plants participating, they held a large regional market share. This is similar to the other industries mentioned.

E. Data Modeling within Tools

Those creating tools have taken them in a variety of direction. They therefore exist in an assortment of forms and operate at varying degrees of complexity. Depending on which tool a user has selected to model LCI data, different levels of expertise will be required. Online calculators generally have fewer inputs required; often the data is available as a selection on a 'drop-down menu.' Although little input is needed, little data is thus conveyed and what could be worse, there is little in the way of tweaks that can be performed to vary the output received. In the case of very rough comparisons between a few products with a wide range of variation this could be acceptable. If two products are closely related however, there would be little or no distinction.

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[124] Joyce Cooper, PhD, "ME515 Lifecycle Assessment (LCA): Compiling Lifecycle Inventory Data," 2012

[125] Puettmann and Wilson, "Glue Laminated Beam – Pacific Northwest and Southeast," 2004

Spreadsheet-style programs can be slightly more robust. The EcoCalculator from Athena is an example of one of these. It has many more features and a greater depth to explore leading to great variation. This variation can allow a user to 'dial in' closer to what the product is, in the case of EcoCalculator the product is a whole building. These spreadsheet style programs can also be limiting because of preset parameters from which a user must choose as inputs. This leads the user to be hampered by restrictions and thereby potentially not building the best product profile possible.

These online calculators and spreadsheets represent a brave attempt to bring LCA to a mainstream audience in that it is free, quick and requires little in the way of LCA expertise. In light of their limitations they can facilitate a service for understanding the orders of magnitude of impacts regarding a possible assembly selection. They will not, however, be sufficient in profiling a building's environmental footprint nor evaluating its ecologic burden. In order to build a more reliable LCA more rigorous models must be employed. Categorically, two avenues can be taken. One is for the user to build their own spreadsheet in a program like *Excel* or *MatLab* by 'manually' assembling the data into matrices and using that programs computational structure to generate the needed data outputs. The second is to employ a more sophisticated LCA tool such as *SimaPro* or *GaBi*.

Developed by the European sustainability consulting firm PRé Consultants, SimaPro is a highly intelligent software that has built in access to Eco-Invent's database. Similarly, GaBi also employs Eco-Invent but also a suite of other optional databases like their private database, GaBi Professional and the US LCI. When using these programs it is up to the user to correctly construct the order and flow of the processes in the study. The unit processes (a single listing of an lifecycle inventory) must be engaged in a logical order and connected by appropriate means of transportation and power supply in order to effectively model the lifecycle condition. To this extent knowledge of LCA practice and principles are required to be successful.

F. Bill of Materials

Using an issued set of drawing provided by the Miller Hull Partnership, a detailed review of the Bullitt Center's bill of materials was performed. The designated components (bold) and sub-components are:

Structure

- Concrete
- Steel
- Glulam Timber
- Standard Dimensional Lumber
- Plywood

Exterior Wall Panels

- Sheet Steel Cladding
- Aluminum Furring Channels
- Gypsum Wall Board
- Semi-Rigid & Batt Insulation
- Water Pressure Barrier
- Steel Studs

Glazing Wall Assemblies

- Glass
- Spacer
- Aluminum Framing
- Rubber Gasketing
- Low "E" Coating

Roofing

- EPDM Membrane
- Poly Iso Tapered Insulation

Photovoltaics

- Aluminum Framing
- Glass
- Multi-Crystalline Solar Cells (Silicone)
- Adhesives
- Balance of System

Tenant Improvement

- Gypsum Wall Board
- Steel Studs
- Steel Acoustical Channels
- Paint (2 Coats)

Public Space/Owner Improvement

- Gypsum Wall Board
- Steel Studs
- Steel Acoustical Channels
- Paint (2 Coats)

Mechanical/Services

Industry Sectors

- Air conditioning, refrigeration, and warm air heating equipment manufacturing
- Heating equipment (except warm air furnaces) manufacturing
- Iron, steel pipe and tube manufacturing from purchased steel

Electrical/Lighting

Industry Sectors

- Electric lamp bulb and part manufacturing
- Lighting fixture manufacturing
- Wiring device manufacturing
- Copper rolling, drawing, extruding and alloying

Plumbing/Fixtures

Industry Sectors

- Plumbing Fixture Fitting and Trim Manufacturing
- Valve and fittings other than plumbing
- Plastics Pipe and Pipe Fitting Manufacturing
- Pump and pumping equipment manufacturing

Sitework

Earthmoving Equipment

- Caterpillar (CAT) 375 excavator
- Caterpillar (CAT) 315 excavator
- Caterpillar (CAT) 416c Backhoe Loader

Construction

- kWh usage on site
- Diesel usage converted to kWh output

G. Comparative views of LCAs of the Bullitt Center

Life cycle assessment is challenging and complex even for a single product such as a glue-laminated beam. When the task is scaled to encompass an entire building the challenge is greatly magnified. Throughout the past year of graduate study, this author has been investing what LCA is, how it can be a useful tool and how it can be integrated into architectural practice. The interconnected nature of the world of product (and by extension construction of buildings) creation and transportation makes it very difficult to pin down specifics with regard to where environment impacts occur. Several key principles have been learned throughout these investigations that we think are key to both the future of LCA and its integration into average practice:

- Good data is hard to find and we need to encourage the creation of more of it
- Limiting the system boundaries is critical
- Results totals are less meaningful than the relative portions of the parts

Iteration 01 – Fall 2011

Using Athena's EcoCalculator we wanted to see how well we could model the Bullitt Center with a free program as well as make an assessment of how effective it would be for an architect (a non-LCA expert) to use it on the average in-studio project. The idea was that the architectural profession is not going to become LCA experts nor are they going to invest in expensive LCA software. They will possibly use a free download but how effective and useful would the results be? Athena's EcoCalculator is limited in that it has generic, pre-described assemblies in which a user must choose for each category of the building such as the structure, exterior walls, columns & beams, etc. These assemblies may be far from matching their project's exact detailing. For our experience, it seemed as though the environmental impacts were underestimated based on what was left out. Further, we surmised that when understanding the Bullitt Center as a 250-year building, we needed to multiple the results four times as EcoCalculator assumes a building life of 60 years. These results were unsatisfactory in their data acquisition but did begin to create a discussion of the relevance of using such a tool in practice. Our recommendation was to not rely on EcoCalculator to decide which assembly is better but to better gage what order of magnitude of impact a material selection could make.

Pros	Cons
Easy interface, quick to use	Few Inputs = Inflexible
Requires little LCA knowledge	Missing Data: PV, Systems, Construction
Fewer input fields	Transport is embedded, cannot be adjusted

Iteration 02 – Winter 2012

Following closely the mathematical concepts put forth in Heijungs and Suh's *The Computational Structure of Life Cycle Assessment*[126], we took the charge of creating our on Excel spreadsheet models, investigated the individual processes of making each component in the building and attempted to find data that was more transparent than that of Athena's EcoCalculator. The principle investigation was to compare the structural systems as designed (timber and some steel over a concrete base) versus an early option of constructing the building entirely of reinforced concrete. The structure of the experiment was to create two Excel models that could be directly compared to ascertain any measurable differences in impacts. The results of this experiment were also mixed. Modeling such complex material flows within an eight to ten

[126] Heijungs, R and Suh, S (2002). The Computational Structure of Life Cycle Assessment, Kluwer Academic Publishers (now Springer-Verlag), New York.

week period was problematic. We relied heavily upon databases such as US LCI and industry data such as that published by CORRIM[127] and PCA,[128] however the results generated were much higher in magnitude than we were expecting to receive. One principle of the investigation was achieved, a thorough understanding of the mathematics should drive a user to appreciate good data and demand more of it.

Pros	Cons
Highly flexible	Highly Complex
Can be robust and powerful	User is responsible all data
Very transparent, no hidden calculations	Two worries: Data and Calculations

Iteration 03 – Summer/Fall 2012

Armed with an array of knowledge reaped from the first two passes, the third LCA attempt was much more aimed at reaching "whole building LCA" status. It is a hybrid of the first methods this time taking the custom modeling principles from Heijungs and Suh's book and populating it with data from the tools and databases used previously. Additional we expanded the unit processes to include MEP systems, sitework and the construction process. The significance of the systems addition is that no database holds data that will fully encompass an entire service system, say that of the mechanical or plumbing. This hybrid model uses Economic Input/Output (EIO) data that is a linking association of economic expenditures to environmental impacts. This "impact per dollar" is based on US federal census data and give our model the opportunity to include major portions of the building which had be excluded until now. Moreover, this model also includes the functionality of allowing the user to specify the building's life expectancy to see the affects of repeated building renovation (component replacement) over the decades. This accounting of the "lifetime demand" of any one component is based upon an assumed duration of a particular component assembly in the building. This model thus has before modeling control than any other experimented with so far. Assuming that the underlying data populating the model is accurate, this model could be used to examine any building design to estimate its potential lifecycle environmental impacts as well as plan strategically for component replacement schemes.

Pros	Cons
Great flexibility over LCA tools	Still fairly complex to organize
Can include whole building data	Tricky to combine different data types
Fairly transparent	

Iteration 04 – Fall 2012

To check our work in the hybrid model we developed a study model using only EIO data. This model was originally went to clarify if the three segments of data used in the hybrid model were in line with the order of magnitude that the other disparate data point were. It was found was that no, the EIO data in absolutes are much large totals, i.e. the 250 year total for the structure when modeled by EcoCalculator is 757,549 kg of CO_2e, with EIO at 250 years it was 4,293,845 kg of CO_2e. This was typical of each component yet we needed data to represent the MEP systems. Through consultation with Rick Betita at Climate Earth (consultant representative to CEDA) we determined that our numbers and model was correct and EIO data is perhaps more inclusive therefore resulting in large absolute totals. To reconcile EIO data with others we calculated a weighted average factor that could be applied. This experiment led us to consider

[127] Consortium for Research on Renewable Industrial Materials (CORRIM) - www.corrim.org
[128] Portland Cement Association – www.cement.org

what and entire EIO model would result in and the fourth version of this LCA study was thus able to be performed.

Pros	Cons
Flexibility to choose applicable sectors	Can be complex in whole building evaluation
Quick to use (if using Carnegie Mellon's online tool)	Infrequent Updates (e.g., 2002, 2007)
Based on US Census Economic Data using NAICS	

H. Final LCA review

(This LCA report is incomplete here as it tracks from introduction through Lifecycle Impact Assessment. The results are presented in the main document above.)

Introduction

The most recent iteration of a life cycle assessment of the Bullitt Center has been the most introspective. The model is shaping up to be able to deliver information that could be seen a valuable, even if the underlying data is not perfect. The exercise to engage in this discussion has been fruitful in other ways that just a nailing down of the amount of embodied energy and carbon in the building. It has opened the door to many discussion of why we, architects, engineers and the public, should think about what goes into the products in buildings that surround us daily. This is possibly the most valuable insight found. As for the actually LCA report, the highlights of it are as follows:

In Chapter 2, it was discussed that if the Bullitt Center is able to achieve net zero operational energy use it's lifelong environmental profile will be dominated by its material's impact. Therefore it is important to begin to understand what builds that profile today and track its evolution over the years. Using LCA as the tool for this we have built a working model simulation to view those potential impacts. While considering the best approach to performing an LCA on the Bullitt Center, several aspects of this unique building had to be contemplated. Tackling first, aspects of the Living Building Challenge, particularly the Materials Petal, had to be thought through with relation to deciding which lifecycle inventories would be most appropriate to use. The other major aspect has to do with the life expectancy of the building and its constituent parts, their replacements and end-of-life scenarios.

The Living Building Challenge's Materials Petal sets out rather specific guidelines from distance radii in which materials for a project can come. For instance heavy materials such as concrete and steel are restricted to distances of 500 km or less while lightweight products such at the liquid applied vapor barrier can be source within 2000 km. More specifically this measured distance can be to the source of extraction or to the manufacturing facility in some cases[129,130]. To use specific distances to locations specific to a product would be atypical for most generic LCAs. These would use data averages to achieve national or regional pattern understanding. If using federal data, averages are the normal type and to understand how to best blend and specific location data with this aggregated national data is complex. Nevertheless, the goal is to be as specific to the Bullitt Center as possible and therefore aggregated data was used only when needed.

[129] Personal communications with Joe David, Point 32 Developers
[130] LBC Standard 2.0, pages 32 & 33

Life cycle assessment work is difficult and complex. It is an attempt to open up a view into a world of interconnectivity and a apply quantitative analysis. The difficulty in interpreting impacts is that it is very hard to isolate material flows expunging all direct or indirect drivers that would have influence at some point along the path of a single product's lifecycle. If one were to be specific in the goal of investigating a small segment of a single product's material flow there is reasonable assurance that appropriate numbers could be found because the breadth of information needed to be found or calculated is more manageable. As the scope expands, as more materials are added and as more specificity is require the task become exponentially more complex. This is not to say that it is impossible but only that more time and resources are needed to explore the full depth of the requirement.

LCA modeling

The basic structure of this LCA model was devised following the "Basic Model for Inventory Analysis" detailed by Heijungs and Suh's book *The Computational Structure of Life Cycle Assessment* (2002). The goal was to create a parametric model capable of being updated with new information as it because available regarding the Bullitt Center but also that it could be used with any other building that was in need of investigation. The basic model consists of two matrices, one, Matrix A or Technology Matrix, is an accounting of the necessary input amounts of the parts required to create the functional unit. It this case our functional unit is one Bullitt Center building therefore it would take x square feet of exterior wall panels, glazing assemblies, roof, etc. The second, Matrix B or Environmental Matrix, is an accounting of all the outputs (emissions and products) to nature or the environment. Included in this matrix is CO_2 eq., N eq., PM_{10} eq., etc. These input and output numbers are derived using methods described above for each component and sub-component. Using the bill or materials established during takeoffs of the building, the quantities attained were referenced by the model to compute results.

This model has a few departures and additions to Heijungs and Suh's basic model. In order to understand how the building is to have some components endure 250 years while others change out every 25 years, another set of parameters were needed. It was determined that a "lifetime demand" calculation was needed which would multiple the amount of a component by the number of expected iterations throughout the building's 250 year projected endurance. For example, it is assumed that the roofing materials will last for approximately 25 years. The materials cover about 7,600 sqft and will thus be replaced 10 times in 250 years. The model therefore recognizes the environmental impact of not just 7,600 sqft of materials but that of 76,000 sqft of material in the total time line.

The benefits of modeling parametrically for this building is that a determination of the potential embodied energy and emissions can be calculated for both the initial profile of the building and for the whole life of the building. This is unique in regards to typical LCA modeling. A typical whole life building model as an assumed duration that all parts as subject too simultaneously. Multiple time horizons of material assemblies are thereby rendered obsolete categorically saying that the foundation's potential is the same as that of the windows or roof. In reality this is far from the truth and this model attempts to recognize this fact.

Carbon sinks and recycling benefits modeled

Two other factors this model has not yet been able to incorporate are that of recycling and carbon uptake. The uptake and sequestration can act as an offset to additional emission outputs and the offset of impact due to carbon uptake and storage in the form of heavy timber (and to a lesser degree in other materials). Factoring recycling into the equation recognizes mathematically the savings, or the avoided impacts, of fully creating materials from virgin materials. The inclusion of carbon uptake in the model would recognize the commitment of the owners to sequestering carbon within the timber materials as their building's commitment to offsetting emissions caused by the built environment.[131]

The reason for advocacy of recycling to be embedded into the model is so the modeled results recognize that virgin sources are not always being consumed, therefore less impactful and that there are avoided impacts in using materials with high-recycled contents. Recycling those materials when finished is also a way of avoiding impacts, which is more a part of scenario planning, but considering this model aims to profile the 250-year life should be included. The recycled content of the materials initially installed in the building are not taken into account by this model. US data currently does not do a good job of displaying in data points the inputs and outputs of recycling for various materials. It is a known fact that the steel and aluminum industry rely heavily upon the use of recycled content but the recycling rates of buildings have high levels of uncertainty.

Per conversations with the owners and design partners, timber was chosen as a major structural element for more reasons than cost and structural attributes. A part of that choice was in the believe that because trees uptake carbon dioxide as a building block of their structure it is held or sequestered within. This CO2 will remain sequestered until release via combustion or decomposition. Therefore having heavy timber and other wood materials 'locked up' in the building for 250 years is an effective storage device. Most LCA models do not recognize carbon uptake as a part of the narrative. The reasons for this are varied and will not be discussed here. It is sufficient to say that if other buildings are using this model in the future, the lines contain carbon uptake can be zeroed out or computed at the users discretion.

Matryoshka Principle

Whole building LCAs are complex. With a larger scope of work to plow through, there are too many parts to the building to track them all down completely. In order to appropriately build a model for the Bullitt Center it was determined that the building components listed above would be used to represent the whole. It is unclear what percentage of the whole building is represented and how fully that representation is. What is clear is that a structure of investigation was needed to carry out the research and modeling. Much like Matryoshka (Russian Nesting) Dolls, it was conceived that there would be a high-level system boundary to which the LCA would adhere followed by other LCA within each of the components followed by another LCA within each sub-component. The theory is that if by combining together multiple LCAs an accurate picture of the whole building's environmental profile will emerge. This is the direction that this LCA has taken and is reflected in the modeling.

Data and Sourcing

The data used for this LCA comes by way of multiple sources. In all instances it was collected from a store of data whether from database or technical paper. This is typically referred to as secondary data. There is no use of primary data, which would be adding new data to the store.[132] The two primary sources of data came from Athena's EcoCalculator and from Climate Earth's Comprehensive Environmental Data Archive (CEDA). For the structure, exterior wall panels, glazing wall assemblies, roofing and tenant improvement,

[131] Personal communication with Denis Hayes and Steve Whitney of the Bullitt Foundation, August 2012

[132] Hox and Boeije (2005). "Data Collection, Primary vs. Secondary", *Encyclopedia of Social Measurement*, Elsevier, Ltd.

EcoCalculator was used. Within EcoCalculator the following are listed as being already factored into their calculations:

- Resource extraction and processing;
- Product manufacturing; on-site construction of assemblies;
- All related transportation;
- Maintenance and replacement cycles over an assumed building service life of 60 years;
- Structural system demolition and transportation to landfill of those materials that are currently landfilled. (Athena EcoCalculator for Assemblies: Inner Workings Synopsis, 2011)

Athena's EcoCalculator uses two databases to construction calculations, the US LCI and their own privately funded database. It is unclear how the calculations are performed or from which database the data is pulled. Based on review of a few studies funded by the Athena Sustainable Materials Institute, the data collected seems to be of sound merit.[133,134,135]

For MEP systems CEDA was used. Climate Earth's Comprehensive Environmental Data Archive (CEDA) is created via mathematical compilation of "publicly available economic data (from the Bureau of Economic Analysis) and U.S. environmental data (primarily from federal agencies)." The industry sector data and commodity sector data are then harmonized so that the emission/dollar flows associated with each sector are congruent.[136] This allows a user to input any dollar amount spent in a certain industry sector, i.e. #333415: Air conditioning, refrigeration, and warm air heating equipment manufacturing, and receive various outputs accounts per 2002 US dollar spent. For the purposes of this LCA the outputs used were the greenhouse gas emissions per dollar spent.

Public spaces improvement data is a mirror of the tenant improvement numbers from EcoCalculator with different material quantities via Point 32's BOMA lease form. Point 32 provided the author with their BOMA calculations to accurately reflect the distribution of all spaces within the building.

Photovoltaic data was pulled from four technical papers:

- Held (2006) Sustainability Evaluation of Solar Energy Systems LCA Analysis,
- Stoppato (2006) Life cycle assessment of photovoltaic electricity generation,
- Laleman (2010) Life Cycle Analysis to estimate the environmental impact of residential photovoltaic systems in regions with a low solar irradiation,
- Fthenakis (2010) Photovoltaics: Life-cycle analyses.

The two that held the most directly applicable data points were Held's LCA of solar energy systems were profiled the CO_2 eq of multiple PV panel types along with quantifiable evaluations of NO_x, SO_x, O_3 and

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[133] Meil, Jamie (2006). A Life Cycle Perspective on Concrete and Asphalt Roadways: Embodied Primary Energy and Global Warming Potential, submitted to Tim Smith of the Cement Association of Canada.

[134] Meil, Jamie for Athena Sustainable Materials Institute (2002). Cradle to Gate Life Cycle Inventory: Canadian and US Steel Production by Mill Type.

[135] Venta, George (1998). *Life Cycle Analysis of Brick and Mortar Products*. Submitted to Athena Sustainable Materials Institute.

[136] CEDA user guide

primary energy used during the manufacturing of multi-crystalline panels, and Fthenakis's LCA of mostly European manufacturing. In his report he surveyed 11 European plants and 2 US plants with little data difference between the two continents. To conform the data to be useful for this LCA quite a bit of conversion was needed. There was quite a bit of difference from report to report (probably based on collection methods and manufacturer process differences) and it is unclear as to which data sets are "better." In addition, the pace at which the PV industry is growing and changing, data relevant to today will certainly be outdated within the year as it is a quickly evolving industry.

Transportation data was found by mapping generic (shortest distance) routes in Google Maps (http://maps.google.com/) combines with data from US LCI (ES Transport, diesel truck, long-haul, 2010). Additional transport impacts were found in the US Commodities Flow Survey (CFS).

Cutoff Criteria

The building and construction industry is built upon a complex system of interconnected networks of manufacturing, transportation, extraction, etc. To that extent, when tracing any material flow upstream to its source can prove difficult and frustrating. Generally speaking, no one single actor along the supply chain is privy to all other aspects of the chain. The transparency that is needed to do so has never been the priority of the industry. That said one attempting to trace these materials flows should set a limit to how far to proceed before the data become too vast to keep accurate tracking. System boundaries set the first of these limits. These boundaries set what is to be included in the study and that which falls outside of the study. The next layer of cutoff criteria could be in the weight of the mass in terms of the overall component or sub-component. Again, if the mass is small enough not to have effect on the system there could be time lost attempt to attain the data unnecessarily. Of course this line should be debated as to where it falls but it must be located somewhere. For this LCA no strict rules for cutoff were established because of the wide variation with the makeup of the components. The initial selection of components was the real level of cutoff, not mass or others. These components were selected for their coverage in EcoCalculator or because of their high-profile nature, i.e., the photovoltaic array.

Accuracy through continuous refinement

With each iteration of this LCA there has been a refining of the technique, data use and modeling. Within this third version there was also a continuous refining process that began with a quick pass to populate the model with data for evaluation of interworking. As time went by the owners provided more information, the underlying data improved and the model reflected a better result. This work should be seen as a begin point to be continued and improved. Although the data derived from the building itself will reach a conclusion, ancillary data that supports it will be advanced as others work on it. Additional observations and approaches should be explored. Can this and other buildings be modeled in other ways to yield environmental profiles? Other elements that have not been included that are important to recognize such as recycling of component assemblies and carbon sequestration should be modeled. This is further research that time would not allow for in this report.

Life Cycle Impact Assessment

This study has attempted to quantify the upstream contributions to the environmental impact of each material assembly through greenhouse gas emissions and material utilization. The EPA's TRACI 2.o impact characterization factors were used. With respect to different sub-component investigations, some of the data used already had these characterization factors factored in. In other cases they were applied as part of the calculation process. As an example, the Structure sub-component's impact data was produced through the Athena Institute's EcoCalculator and has all of these factors embedded. Because the data for Photovoltaics was assembled via multiple scholarly papers, the TRACI factors became a multiplier within.

Traci 2.0 Characterization Factors for substances measured in US LCI database applicable to materials studied.

Substance Name	Climate Change (kg CO_2 eq/kg substance	Acidification (kg H+ moles eq/kg substance)	Eutrophication (kg N eq/kg substance)	Ozone Depletion (kg CFC-11 eq/kg substance)	Smog Formation (kg NO_x eg/kg substance)	Human Health CF (kg PM_{10} eg/kg substance)
Ammonia		95.49	.12			
Benzene					0.72	
Carbon dioxide	1.0					
Carbon monoxide					0.06	
Sulfuric acid		33.01				
Ethane				0.90		
Formaldehyde					9.46	
Hydrogen sulfide		95.49				
Isophorone					4.63	
Kerosene					1.62	
CFC-12	10900.00			1.0		
Methane	25.00				0.01	
Methacrylic acid					18.50	
Nitrous oxide	298.00	40.04	0.045		24.79	0.03
Phosphate			.37			
Phosphorus			1.12			
$PM_{2.5\ or\ 10}$						1.0
Phenol					2.76	
Styrene					1.73	
Sulfur oxides		50.79				0.17
VOC, volatile organic					3.60	
HCFC-140				0.12		
Acetone					0.36	
Nitrogen			0.99			
Nitrate			0.24			
Nitric acid		25.90	0.23			

Emissions to Air listed in RED; to Water listed in BLUE

LCA and Practice:

I. Implementations in practice

The prospect of incorporating LCA into practice is limited at present. Excuses can be made that the tools are not robust enough or too complex for the average designer, or perhaps that the underlying data is not yet good enough. But the reality is that this additional service is not yet understood well enough to have significant penetration. Though many firms have heard about LCA, few have considered that it could have a significant bearing upon their project. They are also reluctant to invest part of their fee into it either.[137] Possibly the best way for LCA to play a fruitful role in design practice in the next five years will be through EPDs in specifications. EPDs represent a packaged way for practitioners to view LCA data and make informed decisions based upon it. Using EPDs for environment performance in tandem with specifications for other criteria will prove to be another way for firms to demonstrate their aim for sustainability in practice and distinguish themselves. Additionally, practices that are heavily involved in certifying their projects through LEED and other third party sustainable programs are likely to come across newly inserted pilot sections of LCA.

J. Applicability in practice and its barriers

Performing a thorough lifecycle assessment is a complex, time-consuming practice that is often performed by LCA experts. Considering the stress and strains of architectural and engineering design paired with less-than-lavish design fees within the current US economic situation, an in depth, whole-building lifecycle assessment would be complex and costly for architects. That said, it is the position of this report that LCA is a practical and potentially vital part of the future of practice. Therefore, how can these two positions be reconciled?

The two most direct ways to integrate LCA into design practice is through the use of 'quick' tools that are designed specifically for use in the building industry and the use of EPDs to accompany specifications. EPDs would be used in tandem with tradition manufacturer's specifications as an extended parameter for potential issuance.[138] Using online calculators, though not always precise, can give designers an added amount of information into the environmental make up of a product. Considering that there are many available with reputable funding and oversight, one could see an opportunity for quick assessment at any point during early to mid design development phases.

Indirect ways that LCA, tools and their databases could become part of common practice could come in the forms of tools for communication with clients, official, media, etc., internal benchmarking for tracking and evaluation of improvements in building design and as a potential means of quantifying a building's environmental footprint. Even the dissemination of information that is related to lifecycle assessment within the architectural industry is a positive step forward. Long before official LCA documentation becomes procedural, there must be general awareness from practitioners as to the relevance of the assessment practice. Along with buzzing trends like transparency, LCA as its tools will find a voice in practice.

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[137] Survey Monkey Feedback

[138] Transparency Panel discussion, "Transparency to Specification," 2012. Accessible at http://www.youtube.com/watch?v=nyyON0MKWO0

Three general barriers to integrating LCA into practice are:

- High level of expertise required
- Uncertainty and variation in the method
- Incentives for engaging in its use

Not all LCA tools require deep understanding of its processes. As a general rule however, the tools that require more sophisticated input on the part of the user will generate more robust data.[139] That said, even with the use of the best tools available there is an immense amount of uncertainty through the LCA process that can skew the results. There is much effort within the professional LCA space to work through variation in measurement, recording, uncertainty and many others, but for now it remains that assumptions and allowances must be made for the completion of an LCA. Additionally there are few reasons to engage in the practice of LCA for architects. There is no financial incentives for owners to participate, there are no code official asking for documented compliance either. There are a few voluntary pilot credits related to LCA that may potentially be available in the next version of LEED and a small section in the Living Building Challenge, both of which will help in raising awareness on thinking in lifecycles. Until the foundation data of LCA is completely shored up there will be little incentive for building code to institute regulation and thus little reason for the practitioners of architecture to engage.

K. How EPDs can combine with LCA to produce sound decision-making?

Environmental Product Declarations (EPDs) are quantified environmental data for a product with pre-set categories of parameters (raw material, energy use, etc) based on the ISO 14040 series.[140] They are also known as Type III Eco Labels. An LCA is a method for gathering and interpreting the environmental impact of a product (material) and as such its results can be surmised into an EPD. What this means is an architect can avoid the messy task of creating the LCA by getting a product EPD.

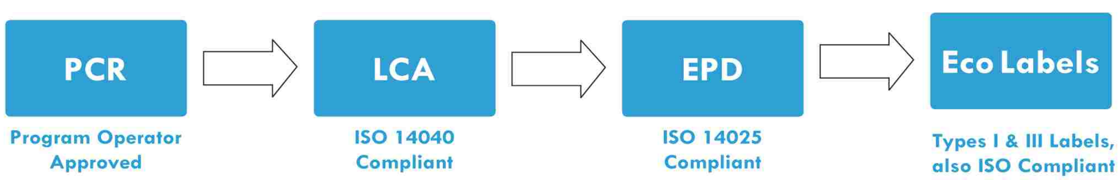

Image 11

As the diagram above indicates, EPDs are the results of an LCA, which is guided by Product Category Rules (PCRs). PCRs are a set of specific rules, requirements and guidelines for developing Type III environmental declarations for one or more product categories.[141] Examples of product categories include: concrete, windows, floor covering, roofing etc. PCRs are needed to establish uniformity for measuring and recording the inputs and outputs used within the process under investigation, i.e., establishing the scope of the study (cradle to gate or cradle to grave), and LCA assumptions such as how emissions are allocated between co-products. Consistently recorded data leads to more uniform LCA results and more valuable and credible LCA. EPDs are born from LCA and used by product manufacturers to declare their impacts.

[139] Simonen, K and Liv Haselbach (2012). "LCA for WA: Life Cycle Assessment (LCA) and Buildings Research for WA State." The Carbon Leadership Forum.
[140] http://www.ecolabelindex.com/glossary/
[141] ISO (2006) 14025:2006 Environmental labels and declarations — Type III environmental declarations — Principles and procedures. Geneva, CH: ISO

Image 12

With regard to future use of LCA in practice, EPDs pose the greatest chance of substantial near-term integration. Since 2004, the adaptation rate of EcoLabels has increased rapidly from a mere 510 in 2005 to 13,650 in 2008.[142] This market penetration is expected to continue with or without regulation mandates. As EcoLabeling continues to grow, architects will be at the forefront to begin using them to make more informed comparisons between products.[143] The confidence of this is built into the mandatory use of third party verification of the labels via ISO 14025. Conceptually, an architect could collect the EPDs of every product specified in the building, enter the data into a spreadsheet (or another organizational tool), and product a much more accurate environmental impact assessment of the whole building than ever before. This could be the form that LCA takes in long-term code compliance as well.

L. Thesis Framework Presentations: Feedback from firms, LCA, EPDs and Adaptability in Building Design

After spending nearly a year considering what LCA is and gaining a great appreciation for its practice, it became apparent that if it were to become a real part of architectural practice there needed to be a way of integrating it into practice. In order to gain a better insight, the framework of this thesis was presented to eleven separate architecture firms in Seattle and to the Bullitt Center's ownership group and developers. The presentation consisted of the background research including explanations of embodied energy and embodied carbon of materials and the process of construction. It outlined what lifecycle assessment is and how it could be integrated into practice and began a conversation of what building endurance is and how the creation of flexible, adaptable buildings can be a strategy for furthering sustainable design.

Each presentation consisted of an approximately 20 minute presentation by the author followed by a 30 to 45 minute discussion session. Each presentation opportunity was different and no specific agenda was followed. The discussion was always rich, filled with a few "ah HA!" moments, a few specific takeaways and always a general sense of "yes, this is important research that we need to think about more in our daily workflow." Each of the sections were able to catch attention and find conversation points. The general takeaway points were as follows:

- **Awareness** is the first key, most firms and architects do not know what LCA is, what EPDs are and would not consider embodied energy as a valuable part of sustainability.
- In order for this to be successful and integrated it (embodied energy, LCA, etc.) most be **connected to a financial mechanism** so ownership will take notice.
- Enduring design works well with ownership that has **long-term plans** to hold the building and be continuously responsible for it but developers or TI owners will not realize the importance in the same way. How can this be adjusted?

[142] Golden, Jay (2010). "An Overview of Ecolabels and Sustainability Certifications in the Global Marketplace."
[143] Remarks by Francesca Desmarais of Architecture 2030 on panel discussing Transparency to Specifications, May 2012

- EPDs sound great in theory but until they are **widespread** it will be hard to use them in a meaningful way.
- **Scenario Planning** could be a great tool that offers the client a greater range of reaching sustainability goals.
- How can **incentives** by tied to owner investment in both whole building LCA and designing for endurance? Some options, give variations in size requirements, setbacks, building heights, etc., and create or tie in these concepts to point systems like LEED.

After the presentations an informal online survey was conducted where one representative from each of the twelve firms was contacted and asked to participate. Though not meant to be a scientific survey, the response rate of just 50% was not great. However because the survey was meant to be a blend of questions about LCA, EPDs and enduring building design there were enough answers from which to draw a few conclusions.

- **All** of the respondents "would advocate for the use of EPDs and will begin requesting them for the products we specify" though most, **67%** were more likely to wait until they have more widespread availability.
- There was a mix of early adopters vs. the "wait and see" crowd at **50%** possibly reflecting that sentiment of widespread availability equals deeper market penetration equal more reliable data.
- **All** respondents saw EPDs as providing a greater level of transparency with some (**33%**) saying that EPDs can help steer them to *greener* products.
- When referring to providing LCA as an additional service, **80%** thought it would be a great service to add, however only **20%** thought clients would pay additionally for it. This gets back to incentives for motivating firms to engage in these deeper forms of sustainable building design.
- **All** of the respondents believe that their clients are or would be very interested in "the lifecycle management of their buildings," with **67%** citing maintenance issues as driver and **50%** citing performance monitoring as a driver

The net take away from these questions and feedback is that LCA and EPDs can become great tools in practice and it will take an awareness of them and their continued development to grow in relevancy. Most agree that thinking in terms of lifecycles of materials and buildings is a bold way of thinking about sustainability one that most in the field can get behind. It is that charge that this agenda must be featured more prominently in the landscape of green design principles alongside that of recycled content and energy efficiency.

M. Communication and Awareness for clients and colleagues

Awareness and communication is the key to any good relationship. Although there are many technical aspect of designing buildings for endurance it begins with a more practical side. These practical strategies include outreach and communication efforts on the part of architects to educate their clients to the importance of sustainable design and offering deeper solutions than energy efficiency. There is communication efforts need within the design community as well, every architect does not have the same knowledge set and open dialog among peers is very important to raising awareness. Reaching out to financial is a critical step toward raise the value level of sustainable design. Building value assessments do not currently take into account the added investment of high performance buildings. The structure for evaluation used is the same model from years ago with few updates.[144] In order to change this effort is needed on the part of the architect and ownership to work with banks and lenders to assess the merits of building design differently and to support them in updating their models of evaluation. Among others, one aspect needed is better data from which assessors will be able to pull from. This data comes in the form of energy monitoring reports, financial investment data and recorded lifecycle assessment data. More post commissioning data is needed to supply these assessor's databases hence the need for a more concerted effort on the part of the architectural and building engineering community.

The beginnings of change are being laid. A project is currently underway to create a new model for the assessment of high performance buildings. Called, *The Economics of Change*, it "provides effective alternatives to the current financial model and policy framework that drive investment decisions in real estate."[145]

Even within the walls of an architecture firm's office change can occur if the profession were to think in terms of:

- Greater focus on materiality, use optimization and selection
- Weather protection
- Connection types: Design connections to enable easy replacement of parts (e.g. bolts over welds, bracketed connections, etc.)
- Assembly methods
- Environmental Product Declarations (EPDs)
- Understand the value in existing materials
- Conserve first mentality

In 2008, Sadie Cline Martin proposed an interesting campaign with her thesis, *Constructing a Carbon Conscience*.[146] After demonstrating the volume and ill effects of greenhouse emissions (specifically carbon dioxide) in the construction industry, she indicated that a public awareness campaign may be the best way to fight against continuing construction in a *business as usual* fashion. Her public service announcements and advertisements were intended to be educational in nature and not combative to give a sense that with cooperation we can find great solutions to great problems. They were meant to find their way into print and online media as well as being used in specific events. See example advertisements below in Figures 30 and 31.

[144] Conversation with Theddi Wright-Chappell, July 2012

[145] Twill, J., Batker, D., Cowan, S., Wright Chappell, T. (2011). The Economics of Change: Catalyzing the Investment Shift Toward a Restorative Built Environment. Earth Economics, Tacoma WA.

[146] Martin, Sadie (2009) *Constructing a Carbon Conscience*, Master's of Architecture Thesis, WSU.

Image 30 and 31. Possible advertisements illustrating the need for direction change in design[147]

Based upon the author's experience meeting with architecture firms around Seattle, general public awareness is great but a targeted audience would perhaps reap greater benefits. Communicating directly with those that are engaged with the building industry and can affect change within it are more likely to take heed of what we need to change and why. These individuals would most certainly be clients and colleagues from developers to city officials to general contractors and consulting team members. As mentioned this is a necessary part of changing the ethos in design and construction and Ms. Martin has shown an attractive and effective strategy.

[147] Images 30 and 31 by Sadie Martin Cline, from her thesis Constructing and Carbon Conscience.