Future-Proof Building Materials: A Life Cycle Analysis

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Abstract

Future-proofing of existing and historic structures is dependent on the durability of the construction materials. Where several recent studies have explored the short term impacts of renovating existing buildings, this research compares the initial construction, periodic renovation, and regular maintenance impacts over a 200 year time span to determine which building systems have the least environmental impact. Maintenance of existing brick, stone, and concrete structures is shown to have similar impacts as multiple iterations of wood structures, metal structures are shown to have significantly larger impacts. The concept of "First Impacts," the environmental impacts of converting raw materials into installed building components, is introduced.

Introduction

It is widely acknowledged that Carl Elefante coined the phrase "the greenest building is the one that is already built".1 As a result, several recent studies on the environmental impacts of buildings and building construction have explored the short term impacts of renovating existing buildings. Examples include the 2012 study by the Preservation Green Lab titled "The Greenest Building: Quantifying the Environmental Value of Building Reuse"2, and studies by Larry Strain of Siegel and Strain3. These studies often focused on the immediate goal of carbon reduction and the resulting global warming impacts. However, because these studies have been limited to time scales of approximately 20 years, the true long term impacts of future-proofing our built environment are not well developed.

Future-proofing is the process of anticipating the future and developing methods of minimizing the negative effects while taking advantage of the positive effects of shocks and stresses due to future events. Future-Proofing Principle 8, Increase durability and redundancy, recommends that "interventions in existing buildings should use equally durable building materials. Don't mix short-term materials with long-term materials. Materials that deteriorate more quickly than the original building fabric require further interventions and decrease the service life of a building. Building designs should either include components with similarly long service lives or be designed for disassembly for replacement of the shorter life components. Redundant systems provide backup in the event that a primary system fails and allow a building to continue to function."[4]

This research intends to begin to quantify the impacts of initial construction, periodic renovation, and regular maintenance impacts for reuse of a building over a 200 year time span.

While this Life Cycle Analysis (LCA) has not been reviewed by a critical review panel, it is intended to comply with the requirements of ISO 14040, and would be ISO compliant pending the completion of critical review.

Goal and Scope

The goal of this research is to compare the long term impacts of resilient construction with low cost, short service life construction observed in contemporary educational facilities. This study is based on the Lakota Middle School Gymnasium in Federal Way, WA, built in 1960 and renovated in 2009. See Figure 1 of the renovated gym at Lakota. At the time of the project design, there was considerable discussion over the retention of the existing gym structure versus building a new gymnasium structure. The discussion was resolved based on the estimated cost of renovation versus new construction. However, there was the belief that retention of the existing building was a sustainable practice.

This research could have been used by the Owner and Design Team to assist in the decision of which option to choose. This Life Cycle Analysis is intended for the internal use of the project team and is not intended to be used in comparative assertions. There are several sub-goals for this research:

1. This author proposes the concept of "first impacts." Similar to the concept of first cost in construction, "first impacts" are the environmental impacts of

construction from extraction of raw materials to initial occupancy of the building. This research investigates “first impacts” versus long term environmental impacts of different building materials and techniques.

2. While wood materials have significantly less environmental impacts in the short term (20 to 40 years), how does this compare to more durable materials over the long term (200 to 1000 years)? And how does this compare to wood structures when biogenic carbon is not taken into account due to the long time period to be studied?

3. Depending on material quality, design and maintenance, wood and light gauge metal building materials are anticipated to have shorter service lives compared to brick, steel, and concrete due to the more rapid deterioration of the material. What are the environmental impacts of shorter life span materials (and thus anticipated higher frequency of replacement) compared to longer life span materials?

4. Do buildings that are typically considered to be more future-proof (or resilient), such as steel and concrete construction, have more or less environmental impact on the Earth than ones considered to be less resilient?

5. What might these conclusions suggest with regards to the existing built environment in general and historic buildings in particular?

Functional or Declared Unit

The declared unit in this LCA is one 12,150 square foot Middle School gymnasium including a main gym and an auxiliary gym. The gym building consists only of the athletic spaces (a main gym and an auxiliary gym) and excludes the locker rooms, offices, storage, lobby, and other related spaces. The study will also exclude mechanical, electrical, plumbing, fire sprinkler, alarm systems, and exterior site features. The above features are not included in the models to maximize similarity and simplicity of the models.

Scope of the Study

This study proposes to begin with new construction for each of the four gymnasiums and track the impacts of a 200 year period of time, though the buildings may last longer. Extrapolation of the results is possible, though circumstances around material extraction and fabrication would likely significantly change and render the data invalid. The study utilizes the Athena Impact Estimator for Buildings, version 4.5.0102 to model the buildings. The proposed wood gym is also analyzed using Athena Impact Estimator version 4.2 which did not include biogenic carbon in the calculations to understand the impacts of biogenic carbon sequestration in wood construction better. This gym is referred to as Gym A1. Athena Impact Estimator is a whole building, life cycle based environmental assessment tool that lets building designers, product specifiers and policy analysts compare the relative environmental effects or trade-offs across alternative building design solutions at the conceptual design stage. Athena evaluates whole buildings and assemblies based on internationally recognized life cycle assessment (LCA) methodology.

It includes maintenance and replacement cycles for each building appropriate to their planned service lives and material selections. Both minor and major renovations are anticipated by the Athena calculator and are planned to double the actual service life. Further, only the total impacts for the service lives calculated are considered in this analysis. Impacts of individual phases of the life cycle are not included in this analysis.

The literature describing the Athena Software indicates that the following life cycle phases are accounted for in this model: material manufacturing, including resource extraction and recycled content; related transportation; on-site construction; regional variation in energy use, transportation and other factors; building type and assumed lifespan; maintenance, repair and replacement effects; demolition and end-of-life disposition; and operating energy emissions and pre-combustion effects (requires input from another model).

In order to accurately model “first impacts” (as opposed to “first costs”), data is extracted from each model with a 1 (one) year service life, intended to represent initial construction. Since Athena includes maintenance, repair, and replacement impacts for the systems involved, the buildings are modeled again with their anticipated service life (20, 50, and 100 years), and a third time with double service life (40, 100, and 200 years). These service lives are then extrapolated to determine the impacts for 200 years.

It is not clear whether Athena incorporates major renovations at intervals within the service life of the buildings or whether buildings are simply demolished at the end of their service lives. For the purposes of this study, limited service lives are anticipated based on the authors experience as an architect. New buildings are anticipated to be built at the end of the 200% service life anticipated. Building impact data can be modeled at 50%, 100%, and 200% of anticipated service life and the data extrapolated to determine if the “maintenance, repair, and replacement effects” are linear. This data is then evaluated for the impacts of major renovations assumed to occur at the end of the anticipated service life.

LCA Phases, Outputs and Allocation

The use of Athena for the analysis is intended to include all phases of the life cycle from cradle to grave for raw material extraction, manufacturing, building construction, occupancy, and end of life. This LCA study uses the 7 summary environmental impacts as output from Athena as the basis of comparison. Raw impacts are not used in this analysis. The summary environmental impacts include: Fossil Fuel Consumption (MJ), Global Warming Potential (kg CO2 eq), Acidification Potential (kg SO2 eq), Human Health Particulate (kg PM2.5 eq), Eutrophication Potential (kg N eq), Ozone Depletion Potential (kg CFC-11 eq), and Smog Potential (kg O3 eq).

Default allocations for environmental impacts from Athena are accepted as baseline criteria for this LCA study and are not altered. Two default allocation techniques are worthy of note in this analysis. First, Athena does account for end of life recycling of steel building components (structural and reinforcing steel). Similar end of life allocations to recycling for other building materials are not applied despite potential recycling rates over 95% for some projects.

The second allocation technique worthy of note in this analysis is for biogenic carbon. Biogenic carbon is the carbon that is sequestered in a wood product as the natural material grows in the forest and a tree converts CO2 through the photosynthesis process. As noted elsewhere, a comparison of Gym A and Gym A1 endeavored to determine the effects of biogenic carbon sequestration in wood materials for the life of the wood. While this does not affect the data in most environmental impacts, Global Warming Potential (GWP) is higher when biogenic carbon is not taken into account. This result is noteworthy to this analysis because of the time span analyzed for the buildings. A 200 year service life is a sufficiently long time that the vast majority of wood products have completed their life cycle and released the carbon that was sequestered in the material.[5] Thus the beneficial effects of the carbon sequestration are negated.

Life Cycle Analysis - Inventory

The building inventory was developed by modeling the four gymnasiums in Athena Impact Estimator. The scope of the research is a comparison of the long term impacts of four gymnasiums of differing construction types and anticipated service lives. All three gymnasiums are the same configurations: 135’x90’x30’ high. The gym is divided into two parts by a bearing wall such that there is a 90’x90’ Main gym and a 90’x45’ Auxiliary gym. Foundations were kept identical between the three models due to limitations in the software. A summary table of the building systems follows at the end of this section. However, briefly, the design of the four gymnasiums may be described as follows:

Figure 1: The interior of the Main Gym at Lakota Middle School in Federal Way, WA. Credit: Brian Rich, 2013.

Gym A is intended to represent a low first cost gym with a 20 year service life. It is designed with wood structure and siding, vinyl windows and a 20 year asphalt roof. Gym A1 is modeled the same as Gym A, except that the data was run through Athena version 4.2, rather than version 4.5. The distinction is that Athena version 4.2 does not account for biogenic carbon. The gym at Lakota Middle School is an excellent example of the roof framing for Gym A and A1. See Figure 1 above.

Gym B is also anticipated to have a low first cost with a 20 year life span. It is designed with a structural steel columns and beams and open web joists, metal stud framing, light gauge metal siding, PVC windows, and an EPDM roof membrane. See Figure 2.

Figure 2: The gym at Skyline High School in Issaquah, WA, is an example of the metal framed roof structure in Gym B and C. Credit: Brian Rich, 2013.

Figure 3: The Gym at Shorewood High school in Shoreline, WA is an example of Gym C construction. The main volume of the gym has CMU exterior walls and metal roof structure. Credit: Brian Rich, 2013.

Gym C is typical of contemporary gym construction representing a mid-level first cost with a 50 year service life. It is designed with structural steel columns and beams, furred out CMU exterior walls, triple glazed aluminum windows and steel doors, and an EPDM roofing membrane. The gymnasiums at Shorewood High School in Shoreline, WA, and Skyline High School in Issaquah, WA are examples of this type of design. See Figure 2 and 3.

Gym D is intended to be a resilient/future-proof structure representing upper level first cost and a 100 year service life. This gym is constructed of a reinforced concrete frame, brick facing over furred 8" thick concrete walls, aluminum windows and steel doors, and a modified bitumen roofing system.

Maintenance and Replacement Cycles

Athena was also used to model the individual impacts of building components that would need to be replaced on a regular cycle so as to simulate the ongoing maintenance and renovations over the lifespan of the building. The results of this study subtracted first impacts from total 200 year impacts to discover the maintenance and replacement impacts over the 200 year service life that was assumed for the buildings.

Building components often included in regular maintenance cycles include roofing systems, insulation systems, interior and exterior paint finish systems, flooring materials, exterior wall cladding systems, windows, and interior wall materials.

Not surprisingly, the top replacement contributors are roofing, siding, and windows, as exemplified in Figure 10. This is a relatively consistent result regardless of the gym construction type or material quantity versus mass value, with the exception of Gym D. In Gym D, the brick facing is not considered required to be replaced over a 200 year life span. One might also conclude that the higher mass materials are also more durable and thus have a lower replacement frequency.

However, the maintenance regime in Athena is not transparent and thus it is unclear what materials are considered to require maintenance versus replacement at the end of the component's life cycle. Nor is it clear what impacts maintenance has on the overall life cycle of the structure. Further, it is not clear what impacts removal of a material that has reached the end of its service life has on the remainder of the building. For instance, does removal of wood siding have an impact upon the weather barrier that may wrap the building?

In addition, Athena assumes that building systems include certain components which are not clearly delineated in the system descriptions. For example, built-up roofing systems include ballast rock, as discovered in this analysis. The ballast rock was discovered when it rose to the top of the material replacement list during the maintenance analysis. The roofing system was revised to provide a more common modified bitumen roofing system.

This analysis also found that maintenance cycles included in Athena are for a specific use of a material. For example, since wood flooring was not available as a material for the interior gym floors, gyms C and D were modeled with tongue and groove wood siding as a flooring component. While this material was not an exact match to the sprung maple flooring systems typically used, this was believed to be an approximate match. However, no warnings were displayed that this was an inappropriate material or use of material in this application. Data extracted from the model was thus severely distorted and required recalculation.

The maintenance and replacement calculations revealed that interior finish materials rarely appeared in the maintenance cycle calculations. The most common materials found to be replaced were siding, roofing, and windows. These were closely followed by wood siding materials. The 200 year comparison of replacement materials in Gym A1 is typical of the results. It is clear that the wood siding of the gym was the dominant material replaced by material quantity. While the figure is not adjusted to accommodate different units for material quantities, it is indicative of the types of materials that commonly appeared on the material replacement lists.

Environmental Impacts

Environmental impacts may be studied under several different scenarios to develop appropriate responses to specific situation within the built environment. Four scenarios are envisioned in this analysis. Figure 4 diagrams the four different scenarios.

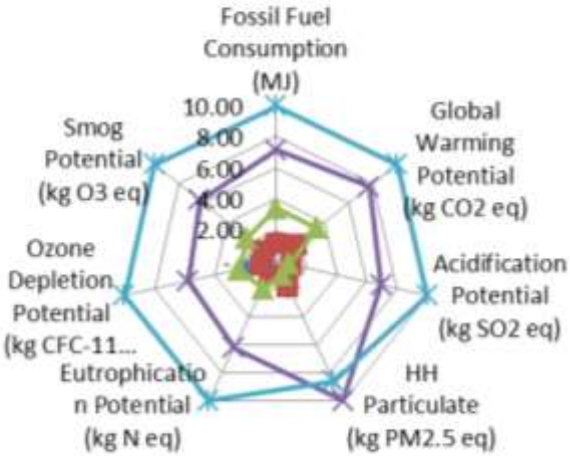

Figure 4: Life Cycle Analysis phases are diagrammed here for each of the four different scenarios analyzed in this LCA study. Credit: Brian Rich, 2014.

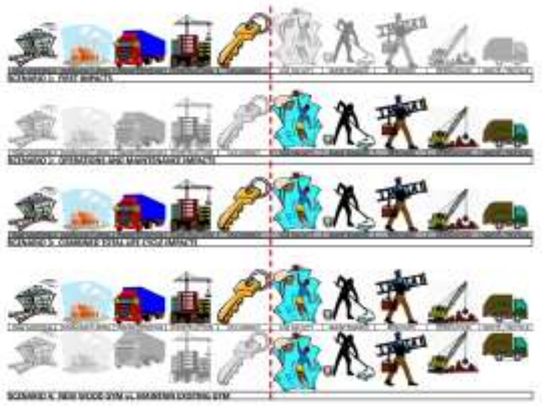

Figure 5: Scenario 1, a comparison of First Impacts, normalized on a scale of 10. Note that the buildings involving masonry and concrete (Gym C and D, blue and purple) have the most significant first impacts and wood (A and A1, red and dark blue) the least. Credit: Brian Rich, 2014.

Scenario 1: First Impacts of New Construction

The first scenario analyzes the environmental impacts of the construction of a new gym from raw materials to completion of construction. This analysis focuses on the first impacts of new construction and does not include any operation or maintenance impacts.

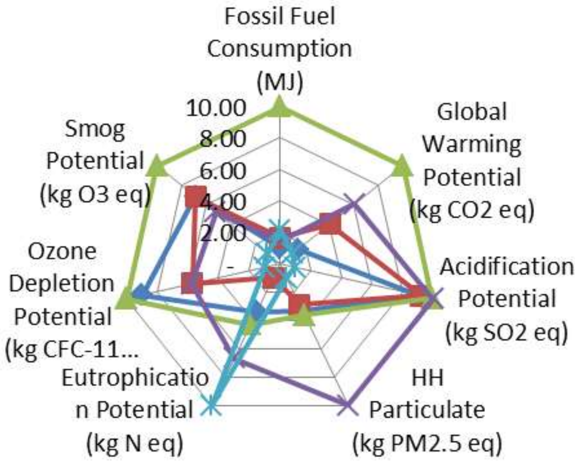

Figure 6: Scenario 2, a 200 year comparison of maintenance requirements, not including first impacts, normalized on a scale of 10. Gym D (light blue) has the least maintenance impact in most categories and Gym B (green) has the largest impacts in most categories. Credit: Brian Rich, 2014.

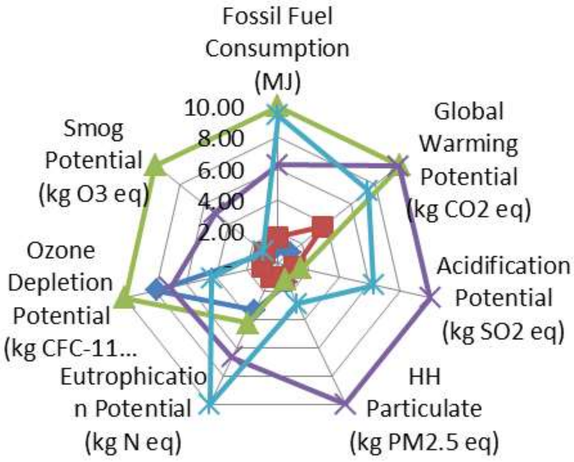

Figure 7: Scenario 3, a 200 year comparison of total environmental impacts, normalized on a scale of 10. Gym B and C (purple, green) typically have the largest impacts while Gym D (light blue) has mixed total impacts and Gym A and A1 (red and dark blue) the least total impacts. Credit: Brian Rich, 2014.

Scenario 2: Operations and Maintenance Impacts

The second scenario analyzes maintaining and operating an existing gym for 200 years. In this scenario, all five gym designs are to be maintained and operated. The first impacts are considered sunk impacts that cannot be recovered or avoided. The intent of this scenario is to compare the operating impacts of the different gyms and their respective environmental impacts. The graph below characterizes the impacts of the gym designs.

Scenario 3: Combined Total Impacts (First Impacts and Maintenance Impacts)

The third scenario analyzes the total environmental impacts of constructing a new middle school gymnasium on an undeveloped site, including all new materials and site work, and operating and maintaining it for 200 years. This analysis includes first impacts as well as maintenance and replacement impacts. Further, this scenario assumes that Gym A, A1 and B have a 40 year life, including regular maintenance and material replacement, and then is demolished and a new gymnasium is built. Similarly, this scenario assumes that Gym C has a 100 year life including regular maintenance and material replacement, and then is demolished and a new gymnasium is built. Last, this scenario assumes that Gym D has a 200 year life and is not replaced. The intent in scenario one is to compare the environmental impacts of shorter service life structures to those of more durable longer service life materials.

One hazard with this scenario is that the building is only as good as the weakest portion of the design. Often this weak link in modern construction is sealant or roofing systems. These elements can deteriorate and cause more rapid deterioration of even more durable building material products and systems.

Scenario 4: Total Impacts – New Wood vs. Maintenance of Metal, Masonry, or Concrete

The fourth scenario includes replacement of an existing gym versus ongoing operation of the existing facility. Further it supposes that Gym A or A1 are proposed for the replacement due the low first cost of construction and that they will be maintained and operated for 200 years rather than being replaced every 40 years. Gym B, C, and D are assumed to be maintained and operated for another 200 years. The first impacts are considered sunk impacts that cannot be recovered or avoided. Environmental impacts are then evaluated for a period of 200 years.

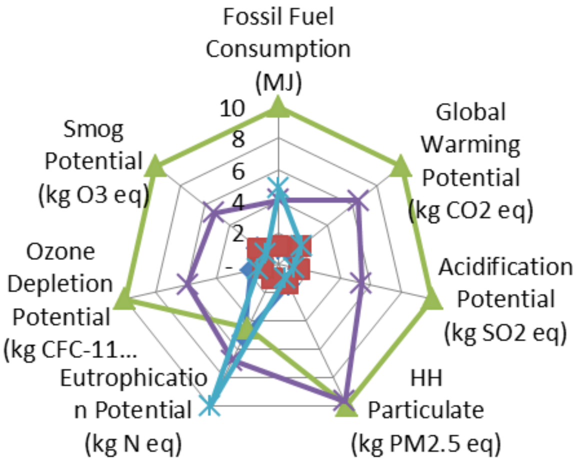

Figure 8: Scenario 4, a 200 year comparison of total environmental impacts, normalized on a scale of 10. This answers the question: If I am considering a new Gym, should I build a new wood gym or continue to maintain my existing concrete or masonry one? Note that there are many respects in which Gym A and A1 have lower impacts, Gym D has moderate impacts, and Gym B and C have the largest impacts. Credit: Brian Rich, 2014.

Interpretation

In this section, the results of the data provided by the Athena models are interpreted. However, there are a few appropriate notes about the data that was extracted that are important.

First, each of the three gyms was consistently modeled in terms of size and functions within the building, therefore the data should also be consistent. The one intentional exception to this is Gym A1 which was modeled in Athena 4.2 rather than Athena 4.5 in order to assess the impacts of biogenic carbon.

Second, the models varied in terms of the materials used. This is a deliberate variation in order to study the environmental impacts of different building systems.

Third, this study makes certain assumptions about the predicted service life for the entire building. Due to assumptions within Athena, this may lead to errors since the assumptions made in the spreadsheet calculations were based on author defined service lives for each building rather than the service lives included by Athena. The data produced by Athena should also be timely as the most recent update to the software was less than 1 year prior to the analysis.

Last, Athena is a good tool for use for projects in the Seattle area because of the location specific data available in its calculations. What could be better explained are the effects of data location on the model. For example, does location affect the energy mix used in the analysis?

The major contributors to the environmental impacts of the buildings modeled are readily split into two categories: first impacts versus maintenance and replacement impacts. As predicted prior to the study, building materials with higher levels of durability also have significantly higher first impacts. For example, the environmental impacts of making and installing concrete, steel, and CMU materials are higher than that of wood materials. See Figure 5. In Figure 5, the normalized data for First Impacts clearly indicates that Gym D has the highest environmental impacts in most categories. Gym A and A1, the wood structures, have the lowest first impacts.

Conversely, the maintenance and operations impacts of lower durability materials, such as metal siding and wood, are higher than the impacts of high durability materials, such as concrete, brick, and structural steel. See Figure 6. It is interesting to note that while Gym D, built of concrete and brick, has the least impact; the highest impact is actually that of Gym B with metal siding and an EPDM roof. Wood structures, with or without biogenic carbon, have varying impacts.

When the environmental impacts of maintenance and replacement are considered with first impacts for each gymnasium, a complete picture of the 200 year environmental impacts are formed. See Figure 7. This figure demonstrates the significant variability in the overall environmental impacts of each gym type. While gym A and A1 (wood) continue to demonstrate the lowest overall impacts, the other gym designs show mixed results.

The results of the LCA analysis are more favorable for buildings of higher durability materials, such as Gym D, when one is considering replacement of an existing gym with a new wood framed structure. Here, the impacts of the higher durability materials are shown to pay off. See Figure 8.

Conclusions

1. The concept of "First Impacts" is introduced in this research and reflects the environmental impacts of new construction from raw material extraction to occupancy of the building. As anticipated, "first impacts" are greater for steel, concrete, and masonry structures than for wood structures.

2. Prima facie evidence suggests that wood structures are a more sustainable building alternative when considering new construction. This is true in both the 20 year term and the 1000 year term when starting with new construction, regardless of how biogenic carbon is counted. The effects of a shift to a wood-based construction economy are unknown, though, and may outweigh the benefits of this building system.

3. When considering existing buildings, first impacts are "sunk costs" and may be disregarded. The evidence suggests that ongoing maintenance and operation of existing structures with higher durability and quality have comparable environmental impact to new wood construction. With the potential for durable construction to last up to several hundred years, the impacts may be lower than wood construction.

4. Biogenic Carbon affects only one environmental impact criteria: Global Warming Potential (GWP). When the benefits of the sequestration of carbon in wood materials are not included due to the relatively short life span of wood materials, wood materials still have less environmental impacts than steel and concrete materials (Gym A1).

5. Durability of all components of a building system should have equivalent service lives or allow for disassembly in order to maintain the shorter service life materials. This allows retention of materials that have longer service lives rather than disposing of them when removed to perform maintenance.

6. Though not clearly indicated in this study, proper maintenance of a building is critical to long term service life. Maintenance prevents deterioration of less durable materials and can significantly affect the service life of a building.[6]

7. Historic buildings have value above and beyond the environmental impacts of their materials and construction. The data in this analysis should be noted as a strictly numerical analysis. There are significant aspects of existing and historical buildings that have value beyond the environmental impacts, including the social, cultural, economic, and aesthetic value. Enduring buildings form the core identity of many places and provide stability and increased personal and community resilience because of the way people identify with their "homes."

8. Further research is needed into the design details, materials, and workmanship aspects which make buildings more future-proof. In addition, research is needed to validate the Principles of Future-Proofing and better understand the methods of calculating life cycle impacts in Athena.

Further information and the full research report, including the raw data, is available at www.principlesoffutureproofing.com.

Notes:

[1] Elefante, Carl. The Greenest Building Is...The One Already Built. Forum Journal: The Journal of the National Trust for Historic Preservation 21 (4) (2007): 26-38.

[2] Frey, Patrice, Liz Dunn, Ric Cochran, Katie Spataro, Jason F. McLennan, Ralph DiNola, Nina Tallering, Eric McDaniel, Dan Haas, Beth Heider, Steve Clem, Amanda Pike, Jon Dettling, and Sebastien Humbert. *The Greenest Building: Quantifying the Environmental Value of Building Reuse.* The National Trust for Historic Preservation, 2011.

[3] Strain, Larry. "The Clock is Ticking - Reducing Embodied Carbon". In BE14 Conference: Northeast Sustainable Energy Association (NESEA). Boston MA: Seigel & Strain Architects, 2014.

[4] Rich, Brian. "The Principles of Future-Proofing: A Broader Understanding of Resiliency in the Historic Built Environment." *Journal of Preservation Education and Research,* vol. 7 (2014): 31-49.

[5] Simonen, Kathrina. *Life Cycle Assessment*. New York: Routledge, 2014.

[6] Grant, Aneurin, Robert Ries, and Charles Kibert. Life Cycle Assessment and Service Life Prediction. Journal of Industrial Ecology 18 (2) (2014): 187-200.