United States Department of Agriculture

Life Cycle Assessment and Environmental Building Declaration for the Design Building at the University of Massachusetts

Hongmei Gu
Richard Bergman

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Abstract

With the world's increasing focus on sustainability in the construction sector through green building systems, the U.S. Department of Agriculture (USDA) has been actively engaged in green building advocacy in the United States through USDA Tall Wood Building competitions and follow-up research on use of mass timber for nonresidential buildings. The USDA Forest Service, Forest Product Laboratory (FPL) funded the study of environmental performance of the pioneer mass timber building (the John W. Olver Design Building) built at University of Massachusetts Amherst in 2016. The Athena Sustainable Materials Institute conducted the whole building life cycle assessment (LCA) using the Impact Estimator for Building software. Secondly, the reported LCA results led to development of an environmental building declaration (EBD) in conformance with European standard EN 15978. Environmental building declarations summarize the embodied and operational environmental impacts during the full building life cycle. An EBD is much like an environmental product declaration (EPD) which is intended for marketing and educational use, but instead of covering individual products like an EPD, an EBD covers the whole building. Lastly, the LCA results of the Design Building were then compared with a functionally equivalent steel and concrete building to acquire the whole building LCA credit in Leadership in Energy and Environmental Design (LEED) v.4 for green buildings. With the mass timber use in the Design Building, the building qualified for the whole building LCA credit in LEED v4. With this project, FPL is helping to standardize environmental performance reporting and advanced mass timber building sustainability.

Keywords: mass timber building, environmental building declaration (EBD), life cycle assessment, cross-laminated timber (CLT), LEED

Conversion table

English unit	Conversion factor	SI unit
square feet (ft^2)	0.092903	square meters (m^2)
cubic feet (ft^3)	0.028317	cubic meters (m^3)
pounds (lb), mass	0.45359	kilograms (kg)
tons	0.90718	tonnes (t) ($\times 10^3$ kg)

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February 2018 [Errata: Corrections to p. 63, May 2018]

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Life Cycle Assessment and Environmental Building Declaration for the Design Building at the University of Massachusetts

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Introduction

Sustainability in the construction sector is becoming increasingly important. The USDA Forest Service, Forest Products Laboratory (FPL) has long been providing valuable research to support the wood industry's sustainability profile in the marketplace (Ritter and others 2011). With growing awareness of the nature of our living environment, wood is replacing steel and concrete as the architectural material of the 21st century (Frearson 2016). Wood in general is recognized for its sustainability, overall low environmental impact, natural beauty, and speed of construction (Salazar and Meil 2009; Jakes and others 2016; Ramage and others 2017). These attributes have inspired architects and engineers interested in creating wood buildings with improved environmental performance (Asdrubali and others 2017). For instance, cross-laminated timber (CLT) — a new option for constructing mass timber buildings in the United States — offers advantages including renewability of the raw material, lower carbon footprint, long-term carbon storage within completed structures, and smaller mass requirements for foundations and footings (Pei and others 2012, 2016; Hammond and Jones 2011; FPInnovations 2013; Mallo and Espinoza 2014; Asdrubali and others 2017). In particular, Canadian CLT buildings have shown a lower carbon footprint relative to other materials (Grann 2013; Robertson and others 2012). Regardless of these benefits, research to support code approval and standardized design approaches is still needed for CLT in North America (Pei and others 2016).

USDA has been actively engaged in developing policies to support green buildings (Ritter and others 2011; USDA 2011), including mass timber structures through activities such as the USDA Tall Wood Building Prize Competition (USDA 2014, 2015). In conjunction with the advocacy efforts of USDA, FPL is actively engaged in research on mass timber including CLT. In November 2015, FPL hosted a premier mass timber workshop, which identified research needs in the United States (Williamson and Ross 2016). Research needs included fire resistance (Pei and Zelinka 2017), seismic performance (Amini and others 2016; Pei and others 2016), and CLT supply chain analysis, along with potential economic contributions and environmental implications of increased mass timber building construction (Kelley and Bergman 2017).

Background

This project assessed the environmental impacts for the John W. Olver Design Building recently completed at the University of Massachusetts Amherst (UMass) campus. It is the home of three departments with various educational spaces for classrooms, studios, labs, lounges, seminar and conference rooms, a wood shop, and office spaces. The Design Building is intended to exemplify the University's commitment to innovative design and use of sustainable materials and to demonstrate emerging wood construction technologies. It is a four-story 87,500-ft^2 structure. The building's structural system consists of CLT roof panels, composite CLT floor panels with reinforced concrete topping (second through fourth floors), reinforced concrete slabs (ground floor), reinforced slabs on grade, and a mix of glulam and structural steel framing. The building's lateral resistance is provided by the elevator and stair-core CLT wall panels and glulam cross-bracing. A zipper truss system consisting of glulam members and steel rods supports the low roof courtyard.

Detailed building elements and a bill of materials can be found in the tables in Appendix 1. The building features a three-story, folded, grand CLT staircase in the atrium. According to the designer (Leers Weinzapfel Associates, Boston, Massachusetts), this building was, at the time of its construction, the largest and most technologically advanced academic contemporary wood structure in the United States and was also the first in the United States to use a wood–concrete composite floor system. Figure 1 shows the architectural rendering of the building and a photograph of the completed structure.

Figure 1. The Design Building at University of Massachusetts Amherst as a demonstration project for mass timber in building structures.

Methods

The goal of this study was to conduct a whole building life cycle assessment (LCA) of the mass timber Design Building at UMass. This LCA would evaluate the environmental performance of the whole building and compare it to a steel-framed functionally equivalent alternative. The LCA outputs were also used to produce an environmental building declaration (EBD). An EBD is a transparent summary report of comprehensive environmental footprint data for a building. It declares the life cycle impacts according to a standardized format. This was the first EBD for a U.S. building performed by the Athena Sustainable Materials Institute. The Design Building EBD summarized the embodied and operational environmental impacts during the full building life and served marketing and educational purposes for UMass to present at the Design Building opening ceremony in April 2017.

Scope

The scope of this LCA was a cradle-to-grave assessment of the material effects of structure, envelope, and interior partition assemblies and operating energy and water use during a 60-year period modeled by the Athena Impact Estimator for Buildings (IE4B) version 5.1.0102 (ASMI 2016). The system boundary for the LCA assessment is demonstrated in Figure 2. The white blocks B1-Use and B5-Refurbishment were excluded from the comparative assessment because of the assumption of no difference between the two building types in the use stage and lack of empirical data for refurbishing CLT buildings. The assessment drew on three life cycle inventory (LCI) data sources, including the Athena LCI database v5.2.0104, the U.S. LCI database (NREL 2012), and the ecoinvent LCI database v3.3 (Ecoinvent 2016). The IE4B accounts for transportation of material

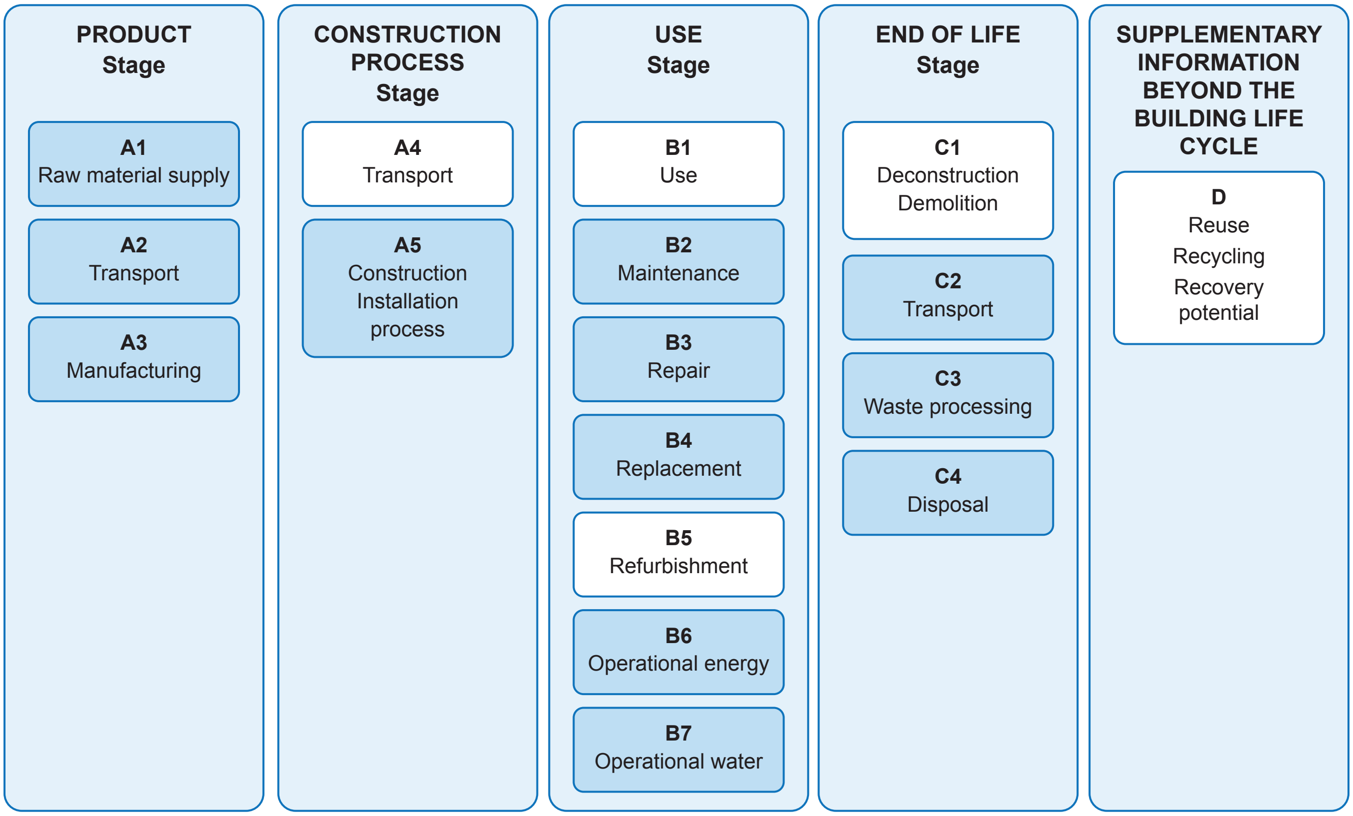

Figure 2. Assessment system boundary for University of Massachusetts Amherst Design Building.

to the sites, construction energy use, construction material waste, stage of material use, operational energy and water use, and demolition energy use. Material waste outcomes and waste transportation were included in the assessment with assumptions based on practical availability of the data.

Data Collection

The assessment started with data collection during the construction phase of the UMass Design Building. With help from the staff at UMass, the Athena team gathered detailed project information on the physical characteristics of the building to determine material types and quantities, as well as estimates for operating energy and operating water consumption. These are the key parameters for whole building LCA modeling (ASTM 2016).

Software Tool

The IE4B is a tool that provides a cradle-to-grave LCI profile to estimate a whole building's environmental footprint. The inventory results comprise the flows from and to nature: energy and raw material inputs plus emissions to air, water, and land. The material inputs for LCA came from the building's design blueprints and were included in the final report (Appendix 1). A 60-year time period was selected as a typical service life for a commercial structure (ASTM 2016). The cradle-to-grave LCA data found within the various LCI databases conform to ISO 14040/14044 standards (ISO 2006a, 2006b). The specific building LCA was conducted in accordance with EN 15978 (CEN 2011) and adjusted for a North American context, that is, the life cycle impacts were evaluated with the TRACI v2.1 (Bare 2011) category midpoint characterization method.

Environmental Building Declaration Development

UMass intended to promote the building's contemporary concepts and mass timber use benefits, which led to the development of an EBD in accordance with EN 15978 (CEN 2011) for building LCA assessment. The EBD contains detailed LCA results for the Design Building and provides information on the building, LCA method, data sources, and LCA assumptions (Appendix 1).

Comparative Assertion for Leadership in Energy and Environmental Design Credit

The LCA results for the Design Building were then compared with those for a functionally equivalent alternative design based on conventional construction. The alternate design was modeled with a floor and roof structure that came from an earlier light-steel-frame design iteration; all other building details are the same for the two design options. Detailed building materials for the two designs are listed in Appendix 2. The two sets of results were compared to determine the LCA credit in Leadership in Energy and

Table 1—Life cycle assessment environmental impact summary[a] for the 87,500-ft^2 Design Building at University of Massachusetts Amherst for 60 years

EN 15978[b] environmental impacts	Unit	Total
Global warming potential	kg CO_2 eq.	3.10E+07
Depletion of the stratospheric ozone layer	kg CFC[c]-11 eq.	8.05E–02
Acidification potential of land and water	kg SO_2 eq.	2.49E+05
Eutrophication potential	kg N eq.	5.96E+03
Formation potential of tropospheric ozone photochemical oxidants	kg O_3 eq.	1.12E+06
Abiotic resource depletion potential of fossil fuels	MJ surplus	6.96E+07

[a]Including operational energy and water consumption.
[b]CEN (2011).
[c]CFC, chlorofluorocarbons.

Environmental Design (LEED) v4. LEED is a building rating system devised by the U.S. Green Building Council (USGBC) to evaluate the environmental performance of a building and encourage market transformation toward sustainable design. The Athena IE4B has a LEED reporting feature that was used for this purpose.

Results

A whole building LCA was conducted for the Design Building on the UMass campus, a four-story 87,500-ft^2 building with mass timber components including CLT and glulam. The LCA results were also compared with a baseline steel alternative to evaluate for LEED credit. In addition, an EBD was developed from the whole building LCA results. Seventeen impact indicators were provided in the LCA results, including global warming, depletion of the stratospheric ozone layer, acidification potential of land and water, eutrophication, formation potential of tropospheric ozone photochemical oxidants, abiotic resource depletion potential of fossil fuels, renewable primary energy, nonrenewable primary energy, secondary material, secondary renewable and nonrenewable fuels, net use of fresh water, and hazardous and nonhazardous waste disposed, etc. The six most commonly presented LCA indicators were used to produce the EBD. Results of these six indicators are presented in Table 1. A complete report on the LCA results can be found in Appendix 1. These results are for the whole boundary system shown in Figure 2, from product stage to construction stage to use stage (including operational energy and water) to final end-of-life stage.

Contribution analysis based on the LCA results provided the resource-type contributions to the total LCA results, material-type contributions to the material use LCA results, and fuel-type contributions to the operational energy LCA results. The analysis showed that operational energy use caused the most impact on global warming (~83%), acidification (~85%), and fossil fuel depletion (~87%) potential in the total LCA results, which was more than the material use and operational water use contributions. The operational energy was mainly from natural gas and electricity for this whole building LCA study. For the material use LCA results, most impacts came from the concrete and steel use in the building for most of the LCA categories. For example, steel use in the building contributed 23% and concrete use contributed about 38% to the total global warming potential (GWP) in the material use LCA, whereas wood or CLT use only contributed about 10% to total GWP.

The EBD developed in accordance with EN 15978 (CEN 2011) was verified internally. The EBD contains detailed LCA results for the Design Building and provides information on the building, LCA method, data sources, and LCA assumptions. The Design Building EBD was summarized in one page to address embodied and operational environmental impacts during the full building life and to serve as a brochure or a poster for presentation at the Design Building opening ceremony for marketing and educational purposes (Appendix 3). This is the first EBD for a U.S. building done by the Athena Institute.

For evaluating the Design Building for LEED v4 whole building LCA credit, a comparative LCA was conducted on an alternative functionally equivalent building called the Baseline Building. The Baseline Building was designed with the same size, functions, and orientation as the Design Building. The Baseline Building reflects more conventional construction with steel-framed floor and roof structures and average concrete mixes. The operating energy for the two buildings was assumed to be essentially the same because the thermal resistance of the exterior walls was the same for the two buildings. Therefore, in this comparative analysis, the operational energy (B6) and operational water (B7) within the system boundary (Fig. 2) were not included in the LCA results. Table 2 lists the comparative LCA results for the six most common indicators and percentage differences. Global warming, ozone depletion, and nonrenewable energy depletion were all more than 10% lower for the

Table 2—Comparison of the life cycle assessment results[a] for the two functionally equivalent buildings with 87,500 ft^2, 60 years of service

Life cycle assessment impact measures[b]	Baseline Building	Design Building	Units	Percentage difference (%)
Global warming potential	4.61E+06	4.01E+06	kg CO_2 eq	–13.1
Stratospheric ozone depletion	8.53E–02	7.67E–02	kg CFC[c]-11 eq	–10.1
Acidification of land and water	2.38E+04	2.18E+04	kg SO_2 eq	–8.9
Eutrophication	1.38E+03	1.38E+03	kg N eq	0.0
Tropospheric ozone formation	3.82E+05	3.68E+05	kg O_3 eq	–3.6
Depletion of nonrenewable energy resources	5.65E+07	4.81E+07	MJ	–14.8

[a]Does not include operational energy and water consumption.
[b]Three measures had at least a 10% decrease (LEED v4 MR credit) (a decrease corresponds to a negative value percentage difference compared with steel baseline).
[c]CFC, chlorofluorocarbons.

Design Building with mass timber construction than for the Baseline Building. According to the LEED v4 (building life cycle impact reduction, option 4) credit for LCA impact, the whole building LCA would reflect at least a 10% decrease from a baseline building in at least three categories and allow up to a 5% increase in other categories. The comparative LCA results (Table 2) showed that the Design Building demonstrated a 10% decrease in three categories and a decrease or no change in all other categories. Therefore, the Design Building would qualify for the LEED LCA credit based on our study analysis.

Wood buildings can store carbon for long periods. For example, based on an estimation by UMass, a total of 70,000 ft^3 of wood was used in the Design Building. This quantity of wood removed (pulled) 2,000 tons of carbon dioxide from the atmosphere during forest growth and now is stored long-term in the building (https://bct.eco.umass.edu/about-us/the-design-building-at-umass-amherst/) (70,000 ft^3 wood * 31.2 oven-dried (OD) lb/ft^3 * 0.5 lb carbon/1.0 lb OD wood * 44 kg CO_2/12 kg carbon * 1 ton/2,000 lb = 2,000 tons CO_2).

Summary

As a mechanism for transparent reporting of measured environmental performance data, an EBD from the whole building LCA is similar to an environmental product declaration (EPD). An EPD is a verified and registered document that communicates transparent and comparable information about the life cycle environmental impact of products according to ISO 14025 (ISO 2006c). Although product manufacturers are increasingly publishing EPDs and demonstrating their willingness to report environmental impacts, this is not happening yet at the level of the whole building. The Design Building EBD is only the fourth building in North American and first in the United States to have an EBD published. With this project, the Forest Products Laboratory is helping to standardize environmental performance reporting and build accountability in the sustainable building design community.

Acknowledgments

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Appendix 1—Environmental Building Declaration

Athena Sustainable Materials Institute

www.athenasmi.org

Design Building
University of Massachusetts, Amherst

An Environmental Building Declaration According to EN 15978 Standard

January 2017

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1.0 General Information on the Assessment

This document presents a whole-building environmental life cycle assessment (LCA) of the University of Massachusetts (UMass) **Design Building**, an educational building in Amherst, Massachusetts. The LCA was commissioned to publicly declare the environmental performance of the building.

The assessment has been conducted in conformance with the Committee for European Standardization (CEN) standard **EN 15978**[1], which stipulates an LCA-based calculation method and reporting requirements for whole-buildings or building parts. While European in scope, EN 15978 provisions are quickly becoming the standard for whole-building LCA worldwide. We therefore applied our North American interpretation of EN 15978 as a suitable methodological choice to meet the purpose of the assessment.

Table 1: Assessment Information Summary

Client for assessment	US Department of Agriculture - Forest Service
Assessor	Matt Bowick (M.A.Sc.), Senior Research Associate, Athena Sustainable Materials Institute
Internal verifier	Jamie Meil (M.Sc.), Research Principal, Athena Sustainable Materials Institute
Date of assessment	December 2016
Assessment timing	Construction completed (December 2016)
Period of validity	5 years

The scope of LCA is a cradle-to-grave analysis of the material effects of structure, envelope, and interior partition assemblies, and operating energy and water use, over a 60-year period. The LCA primarily draws on data from the Athena Sustainable Materials Institute's ISO 14040/44 conforming *Impact Estimator for Buildings* software database, and augmented with the Institute's secondary databases. Life cycle impacts were evaluated according to TRACI v2.1 category mid-point characterization methodology[2] and the LCA modeling was performed with a customized Excel-based tool.

Seventeen indicators covering environmental impacts, resource use, waste, and output flows leaving the system are reported – see Table 2 for summary results of the six environmental impacts most commonly reported. Various contribution and sensitivity analyses are provided, along with additional information, including avoided impacts and burdens occurring beyond the life cycle and carbon sequestration of wood and concrete products.

[1] EN 15978:2011 *Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method.*

[2] http://www.epa.gov/nrmrl/std/traci/traci.html

Table 2: 60-year Design Building Life Cycle Environmental Impact Summary

EN 15978 Environmental Impact Indicator	Unit	Total
Global warming potential	kg CO_2 eq.	3.10E+07
Depletion of the stratospheric ozone layer	kg CFC-11 eq.	8.05E-02
Acidification potential of land and water	kg SO_2 eq.	2.49E+05
Eutrophication potential	kg N eq.	5.96E+03
Formation potential of tropospheric ozone photochemical oxidants	kg O_3 eq.	1.12E+06
Abiotic resource depletion potential of fossil fuels	MJ surplus	6.96E+07

Table 2 note: eq.=equivalence

1.1 Purpose of the Assessment

As per EN 15978, the goal of the assessment is to quantify the environmental performance of the object of assessment by means of compiling environmental information.

This assessment was commissioned for the following purpose:

To publicly declare the environmental performance of the Design Building.
This document presents a model derived estimate of the environmental performance of the Design Building according to a standardized format in order to publicly communicate results in a transparent and comparable manner. The intended use of this assessment is for educating/informing building and wood-industry stakeholders about the environmental implications of the Design Building design, and wood-based low-rise construction in general.

1.2 Identification of the Building

The building of study is the University of Massachusetts Amherst Design Building, a four-storey, 8,147 m^2 (87,573 ft^2), structure located at 551 North Pleasant Street, Amherst, Massachusetts – see Table 3 for the project directory and Figure 1 through Figure 5 for building photos.

The Design Building will be home to the University's Architecture + Design, Building and Construction Technology, Landscape Architecture, and Regional Planning departments, and includes various educational spaces (classrooms, studios, labs, lounges, seminar and conference rooms, wood shop) for students, and office space.

1.3 Assessment Verification

While studies compliant with EN 15978 do not specifically require verification, the standard stipulates a set of requirements when it is to be performed. This LCA has been internally verified for compliance with the standard.

Statement regarding verification of this assessment: *The internal verifier has determined that this LCA-based study meets the requirements for methodology, data, and reporting in EN 15978, and is consistent with its principles.*	Jamie Meil, Research Principal, Athena Sustainable Material Institute

Table 3: Project Directory

Owner	University of Massachusetts
Architect & Design Lead	Leers Weinzapfel Associates Architects Inc.
Structural Design Engineer	Equilibrium Consulting Inc.
Structural Engineer Of-Record	Simpson Gumpetz & Heger
MEP & Fire Protection	BVH Integrated Service, P.C.
Site Utilities	BVH Integrated Service, P.C.
Code Consultant	Howe Engineers
Civil Consultant	Nitsch Engineering
Landscape Architect	Stephen Stimson Associates
Site/Hazmat	Weston and Sampson
Sustainable Design & Lighting	Atelier Ten
Acoustics & Audiovisual	Acentech
Geotechnical Consultant	GZA Geoenvironmental Inc.
Accessibility	Kessler McGuiness & Associates
Cost Estimating	Faithful & Gould
Hardware	Campbell - McCabe
Specifications	Steven McHugh
Wood Shop/Digital Fabrication Consulting	Radlab

Figure 1: Building section

Figure 2: North exterior, along campus path

Figure 3: Commons (rendering)

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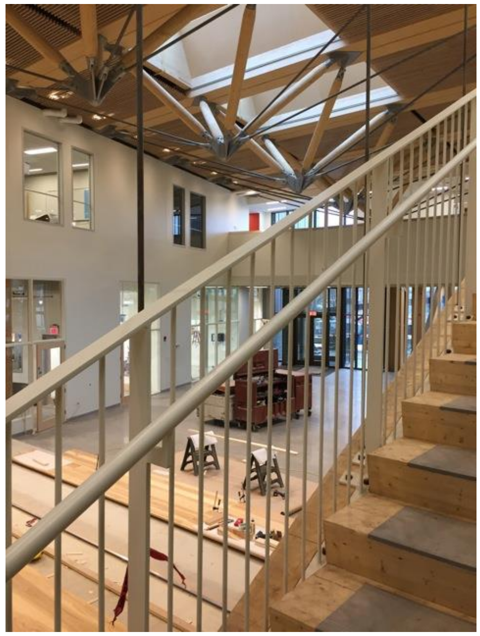

Figure 4: Commons under construction

Figure 5: The building under construction

Graphics courtesy of Leers Weinzapfel Associates Architects Inc.

2.0 General Information on the Object of Assessment

2.1 Functional Equivalent

EN 15978 requires identification of a functional equivalent for the building to enable a valid basis for future comparisons to other buildings. According to EN 15978, a **functional equivalent** is "the quantified functional requirements and/or technical requirements for a building or an assembled system (part of works) for use as a basis for comparison." In other words, the functional equivalent is a set of design criteria that both buildings must have in common to ensure an apples-to-apples comparison.

Table 4 defines the functional equivalent of the Design Building.

Table 4: Functional Equivalent

Building type	Educational
Technical[3] and functional[4] requirements	Massachusetts Base Code (8th edition); LEED Gold certified (pending)
Pattern of use	Typical for the functions provided, 82 full-time equivalent (FTE) building occupants (74 full-time, 8 part-time); 1,000 daily average transients, 384 peak transients
Required service life[5]	60 years[6]

2.2 Reference Study Period

While the functional equivalent requires a statement of a building's required service life, it doesn't necessarily have to be the same as the **reference study period**, which is defined in EN 15978 as "the period over which the time dependent characteristics of the object of assessment are analyzed." For this declaration, the reference study period of the assessment is the same as the assumed required service life of the building, 60 years.

[3] Defined in EN 15978 as the "type and level of functionality of a building or assembled system which is required by the client and/or by users and/or by regulations."
[4] Defined in EN 15978 as "type and level of technical characteristics of a construction works or an assembled system (part of works), which are required or are a consequence of the requirements made either by the client, and/or by the users and/or by regulations."
[5] Defined in EN 15978 as the "service life required by the client or through regulations."
[6] The building has no required service and therefore a service life of 60 years was assumed assessment purposes.

2.3 Object of Assessment Scope

The **object of assessment** is a definition of what is to be analyzed; EN 15978 stipulates that "the object of assessment is the building, including its foundations and external works within the curtilage of the building's site, over the life cycle." However, when conducting whole-building LCA, not all aspects of a building can typically be assessed given finite project resources and data limitations.

The object of assessment of this study is the Design Building and includes materials from the construction elements noted in Table 5, along with the operating energy and water end-uses noted.

The construction elements assessed broadly include structure, envelope, and interior partition materials, which corresponds to the current modeling capacity of the Athena Impact Estimator for Buildings (IE4B). The assessment considers the paint on interior gypsum board to be a finish and therefore paint is not included in analysis.

Other notable material omissions from the included elements are:

- Some lateral load resisting connections and steel zipper truss connections (main members included);
- Non-structural connections;
- Surface treatments (e.g. fire retarding coatings);
- Adhesives and sealants;
- Soffit, drain covers, vents, roof hatches, etc.;
- Temporary works used during construction and demolition/de-construction phases (e.g. shoring, formwork).

Table 5: Object of Assessment Summary

Material Use (UniFormat)	**Operating Energy Use** (end-uses)	**Operating Water Use** (end-uses)
• A1010 Standard Foundations • A1020 Special Foundations • A1030 Slab on Grade • A2020 Basement Walls • B1010 Floor Construction • B1020 Roof Construction • B2010 Exterior Walls • B2020 Exterior Windows • B2030 Exterior Doors • B3010 Roof Coverings • B3020 Roof Openings • C1010 Partitions • C1020 Interior Doors • C2010 Stair Construction	• Space Heating • Space Cooling • Ventilation (fans) • Domestic Hot Water • Lighting • Auxiliary Energy (pumps) • Plug Loads • Exterior Lighting	• Water Closets • Urinals • Showers • Lavatory Taps • Kitchen Taps

2.4 Building Design Description

The Design Building is intended to exemplify the University's commitment to sustainable and innovative design via its LEED Gold certification (pending) and demonstration of emerging wood construction technologies.

The building's structural system consists of cross laminated timber (CLT) roof panels, composite CLT floor panels with reinforced concrete topping (second through fourth floors), reinforced concrete slabs (ground floor), and reinforced slabs on grade, and a mix of glulam and structural steel framing. The building's lateral resistance is provided by the elevator and stair core CLT wall panels, and glulam X-bracing. A zipper truss system consisting of glulam members and steel rods supports the low roof courtyard.

The building's perimeter is supported by concrete basement walls on strip footings; columns along the perimeter are supported by piers integrated into the basement walls (i.e. wall thickenings) and pad footings, whereas interior columns are supported by concrete columns/piers at the basement level and pad footings.

Double-glazed, low-E insulating glass curtain wall with 1.65 W/m2 °C U-value (0.29 Btu/hr-ft2-°F) and solar heat gain coefficients (SHGC) of 0.27-0.38 make up approximately 58% of the building's perimeter walls. The building is otherwise clad in bluestone veneer (between grade and the ground floor), and aluminum panel rainscreen (above the ground floor) with steel stud wall back up – these walls generally have a 4.30 RSI value (R-value of 24.4). The roof envelope generally consists of a TPO membrane assembly with 8.38 RSI value (R-value of 47.6).

Partitions are for the most part light gauge steel stud walls with fibreglass batt sound attenuation insulation and 16 mm gypsum board.

Table 14 (Appendix B) presents a more detailed summary of the construction element assemblies – see Table 15 (Appendix C) for the resulting whole-building bill of materials. We calculated material quantities based on "Conformance Set" drawings, which include architectural drawings produced by Leers Weinzapfel Associates Architects Inc., and structural drawings produced by Equilibrium Consulting Inc. (dated September 25, 2015).

The building draws on *UMass Amherst Campus Central Utility Plant*[7] for hot water, chilled water and some of the electricity consumed. Other building integrated technologies have been employed to reduce energy demand, including[8]:

- Lighting Power Densities reduced below ASHRAE 90.1-2007 with occupancy sensors in select perimeter office spaces;
- Automatic daylight dimming controls in perimeter spaces;
- Air-side supply air reset temperature;
- Dual Enthalpy economizers on air handling units; and
- Energy Recovery Ventilators on the Dedicated Outdoor Air System (DOAS).

3.0 Statement of System Boundary Used in the Assessment

The assessment **system boundary** defines which life cycle activities (undergone by the object of assessment) are to be included in the analysis. As illustrated in Figure 6, the system boundary according to EN 15978 is characterized by the temporal flow of the building life cycle – i.e. Product, Construction Process, Use, and End of Life stages. The various processes that occur at each stage are classified and grouped in **information modules** (or simply "modules"), labeled with alpha-numeric designations "A1" through "C4". This modular structure provides a consistent and transparent reporting format for building assessments as well as environmental product declarations (EPDs) in conformance with the standard EN 15804[9].

Accounting for the life cycle of a building is complete when all its constituent materials reach a state where they are no longer considered waste – an allocation methodology known as the *polluter pays*. The potential environmental benefit or burden arising from subsequent use of secondary materials and energy recovered from the system of study is optionally accounted for as additional information in module "D" – e.g. the net benefit of a reused wood beam substituting a new manufactured wood beam.

The system boundary of this assessment is cradle-to-grave and includes the information modules shown as green boxes in Figure 6, and Table 6 provides further details about the various life cycle activities accounted for by each module.

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[7] The Central Utility Plant *"Provides steam heat and electrical power to campus by means of a combine cycle plant. The Central Heating Plant has three boilers, capable of firing natural gas and ultra-low number two fuel oil at 125,000 pounds per hour each and one heat recovery steam generator for an additional 100,000 pounds per hour. Total annual steam generated approaches 1.2 billion pounds. Electrical power is supplied by two generators that can produce a total of 14 megawatts. One generator is driven by a combustion turbine; the other is driven by a steam turbine."* Source: https://www.umass.edu/physicalplant/utilities-0

[8] Source: CA Phase Energy Analysis Report (atelier ten).

[9] EN 15804:2012 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products

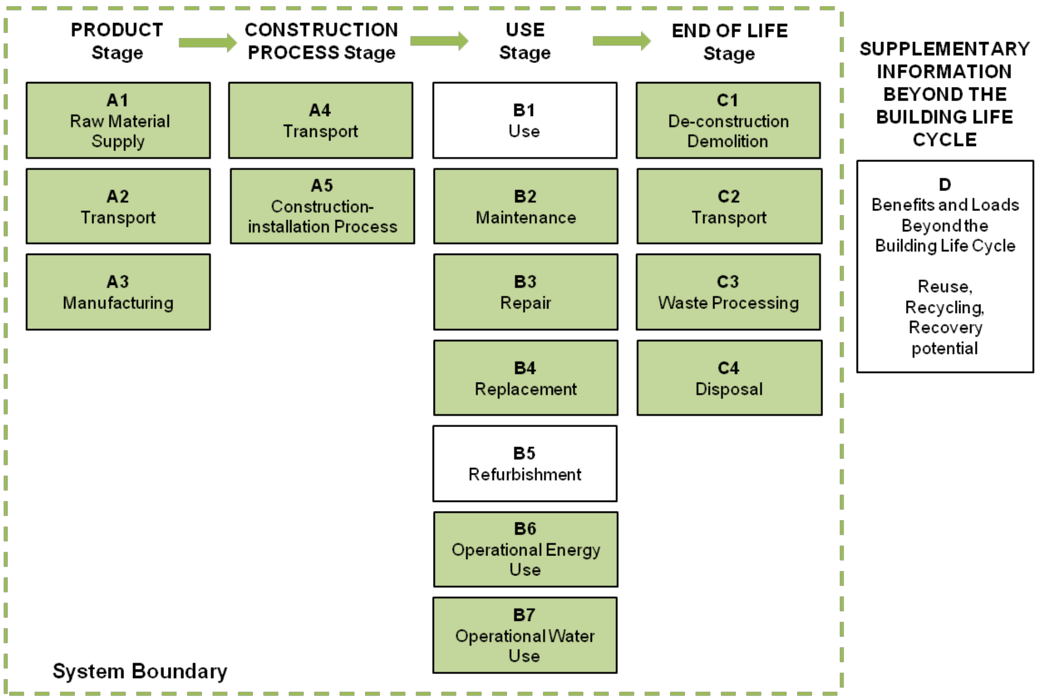

Figure 6: Assessment System Boundary

Two modules were not included for the following reasons:

- **B1:** there is currently insufficient consensus in terms of methodology and data to practically quantify these effects for all products used in the building.
- **B5:** at this time, there is no known planned refurbishment for the building and no available scenario information on typical refurbishment activities for this type of building.

Table 6: Assessment System Boundary and Scope Summary

Information Module	Name	Included?	Processes Included
A1	Raw material supply	Y	primary resource harvesting and mining
A2	Transport	Y	transport up to manufacturing plant gate
A3	Manufacturing	Y	manufacture of raw materials into products
A4	Transport	Y	transport of materials to site
A5	Construction-installation process	Y	construction equipment energy use, and production, transport and waste management of materials lost during construction
B1	Installed product in use	N	not applicable
B2	Maintenance	Y	production, transport, construction and waste management of materials used for maintaining building components during use
B3	Repair	Y	production, transport, construction and waste management of materials used for repairing building components during use
B4	Replacement	Y	production, transport, construction and waste management of replaced materials during use
B5	Refurbishment	N	not applicable
B6	Operational energy use	Y	energy production, transportation and use
B7	Operational water use	Y	water supply and wastewater treatment facilities
C1	De-construction demolition	Y	demolition equipment energy use
C2	Transport	Y	transport of waste materials from site to disposal facilities; transport of steel to preprocessing and recycling facilities
C3	Waste Processing	Y	sorting/preprocessing facility equipment energy use
C4	Disposal	Y	landfill and incinerator energy use and site effects

This assessment assumes that once the material is either [1] separated for recycling, reuse, or energy recovery purposes or [2] disposed of (i.e. either via landfill or incineration), it has reached its end-of-waste state[10]. For example, a wood beam left on-site for the purpose of reuse has reached its end-of-waste state provided it does not require further sorting from other waste. In this case, no further environmental burdens (e.g. from transport to storage facility) associated with the beam are allocated to the building.

The one exception to this approach is recycled steel products, since the production stage of the steel LCI data used does not include preprocessing of secondary steel (scrap processing and transport). Therefore, steel preprocessing effects are allocated to the appropriate modules in which steel is recycled.

[10] This is the same approach as that taken by the IE4B software.

4.0 Statement of Scenarios Used in the Assessment

Because not all information is practically available to the assessor and because buildings have long and uncertain services lives, **scenarios** (i.e. assumptions) are required to provide a complete description of the building beyond the Product stage.

For this assessment, a scenario is defined as information generally required to calculate inputs for the process-based environmental data used. For example, the distance a material is transported to site is required to calculate the tonne*km input of the modal transportation life cycle inventory data (LCI) used in the assessment.

This section describes the scenarios assumed that are relevant to the object of assessment and its system boundary, and are based on current practice. ***All scenario tables can be found in Appendix D.***

4.1 Transport of Materials to Site

The assumed plant-to-site material transportation scenarios are presented in Table 16. The modes and distances for the following products were estimated based on the location of the project's actual product suppliers, and comprise the majority (an estimated 81%) of the building's mass:

- Curtain wall aluminum extrusions
- Cast-in-place concrete
- Cross laminated timber; glulam
- Galvanized studs
- Hollow structural sections; hot rolled sheet; screws, nuts & bolts; steel plate; wide flange sections; wire rod.

Estimates for all other products are taken from the *Athena Transportation Database* for New York – the closest available location to Amherst, MA.

4.2 Construction Energy Use

Construction phase equipment energy use (module A5) was provided by Suffolk Construction and allocated to the various construction elements and materials types on a mass basis. In order to estimate fuel usage for maintenance, repair and replacement activities (modules B2, B3, and B4), the energy consumption provided for module A5 was scaled to these other modules based on the mass of materials used.

Construction fuel usage is presented in Table 17.

4.3 Construction Material Wastage

On-site construction waste due to cut-offs, or unused, lost, or damaged materials require greater quantities of materials to be purchased than what is specifically required in the constructed building. The assessment accounts for these additional quantities by multiplying materials required by the building by *Construction Waste Factors*. The assumed scenarios presented in Table 18 are estimates from the *Athena Construction Waste Factor Database*.

4.4 Use Stage Material Use

Maintenance, repair and replacement activities (information modules B2, B3, B4, respectively) typically involve periodic tasks (i.e. material replacements) to ensure the continued functional performance of the building. This assessment calculates the number of times a task occurs over the lifetime of the building according to Equation (1), which is the methodology used by the IE4B software.

$$N_x = (S - F_x) / F_x \qquad (1)$$

where,

N_x	is the number of times task x occurs
S	is the building reference study period (years)
F_x	is the task frequency for task x (years)

This methodology typically results in only a percentage of the final task being allotted to the building. For example, if the service life of a building is 65 years and the replacement frequency of a window unit is 15 years, only 33% of the window replacement occurring at year 60 (5 years/15 years) is allotted to the building.

Equation (2) deviates from the methodology outlined in EN 15978. The standard requires that [1] only whole replacements are to be considered, and [2] if the remaining service life of the building is short in proportion to the estimated service of a product, the actual likelihood of the task shall take into account the required technical and functional performance for the product. In other words, the assessor may have to make value judgments as to whether the final task occurs. It is our opinion that this causes inconsistency between assessments.

Equation (2) was used to calculate the total material quantities replaced over the building lifetime:

$$Q_{x,y} = N_x M_y P_{x,y} \qquad (2)$$

where,

$Q_{x,y}$	is the total quantity of material y replaced due to task x
N_x	is the number of times task x occurs
M_y	is the total quantity of material y in the assembly
$P_{x,y}$	is the percent of M_y replaced due to task x

Task frequency (F_x) and percent of material replaced ($P_{x,y}$) estimates assumed are presented in Table 19, Table 20, and Table 21, along with the various sources used.

The reporting format and calculation methodology of the sourced task frequencies (F_x) and material use percentages ($P_{x,y}$) are not compliant with ISO standards 15686-1[11] and 15686-8[12], as required by EN 15978. However, it is our opinion that until service life planning is a more established practice in North America, the sources from which the estimates were developed are both consistent and of sufficient quality for this building assessment.

4.5 Operational Energy Use

The annual operational energy use scenario presented in Table 22 reflects estimates from simulations performed by Atelier Ten as part of the building's LEED certification. The natural gas and electricity use reported are the net consumption at the District Plant that has been allocated to the building. It is assumed that this energy consumption represents a typical annual demand over the 60-year building service life. In other words, it is assumed that the building's energy systems, thermal performance, and local climate do not change over the 60-year reference study period. Similarly, it is assumed that purchased energy sources do not change over the building's required service life, e.g. purchased electricity is assumed to be generated using the same energy source mix.

4.6 Operational Water Use

The annual operational water use scenario presented in Table 23 reflects estimates calculated by Atelier Ten as part of the building's LEED certification. Wastewater flows are assumed to be equal to the demand since [1] there is no water reported for irrigation, and [2] water consumed by occupants is assumed to make up a small portion of total usage. Water system technologies and their rate of use are assumed not to change over the 60-year required service life.

4.7 Demolition Energy Use

This assessment assumes that diesel-fuelled equipment is used to demolish construction assemblies. The fuel use estimates for each building case found in Table 24 were calculated based on information from the *Athena Demolition Energy Database.*

[11] ISO 15686-1:2011 Buildings and constructed assets - Service life planning - General principles and framework
[12] ISO 15686-8:2008 Buildings and constructed assets - Service life planning - Reference service life and service-life estimation

4.8 Material Waste Outcomes

After a building assembly has been demolished and/or deconstructed, there are several possible outcomes for the resulting waste materials. The waste may be disposed of via landfill or incineration, or reused, recycled or converted to usable energy, and may undergo processing (e.g. sorting).

All materials are assumed to be first sent to the *Western Processing Facility* located in Wilbraham, MA. The assumed waste outcomes post-sorting presented in Table 25 are taken from the *Athena End of Life Database*. Landfilled waste is assumed to be disposed of at the neighboring *Chicopee Landfill*.

4.9 Waste Transport

The relevant assumptions for waste transport presented in Table 26 include the distance from building site to the *Western Processing Facility*, the distance from the *Western Processing Facility* to the *Chicopee Landfill*, and steel scrap transportation distance estimates for New York City from *the Athena End of Life Transportation Database.* New York City is the closest available location to Amherst, MA.

5.0 Additional Information

This section presents the methods and assumptions used to quantify the additional environmental information reported in Section 8.4. This information has been treated separately from the core assessment because the topics addressed either are not part of the life cycle study or the methodologies used to calculate the information are not currently standardized within the EN 15978 calculation framework. ***All additional information scenario (i.e. assumption) tables can be found in Appendix D.***

5.1 Module D

Module D quantifies the future potential net benefit or load of materials and energy sources recovered from the building and exiting the system boundary. These output flows are assumed to substitute for materials or energy production from existing technologies and/or current practice.

This assessment estimates the potential benefits and/or loads from the fraction of concrete, steel, and aluminum products that are recovered for recycling.

Substitution effects were calculated according to Equation (3):

$$LCI_D = NF * PY * (lci_1 - lci_2) \qquad (3)$$

where,
LCI_D is the module D substitution effects LCI of the secondary material/fuel
NF is the net output flow of the secondary material/fuel

PY is the process yield of the recycling, reuse, or energy recovery process (e.g. >1kg scrap is required to produce 1kg steel)

lci_1 is the unit process LCI (e.g. per-kg-product) for producing the material/ energy that is substituted

lci_2 is the unit process LCI for producing the materials/energy from secondary sources which substitutes primary production

The net output flow (NF) is the difference between the recovered secondary material/fuel leaving the product system and the secondary material/fuel that was used by the system, for all relevant information modules included in the life cycle of the object of assessment. It represents the net amount of secondary material/fuel added-to, or removed-from, the technosphere. The assumed net output flows presented in Table 27 were calculated with information from Athena databases.

PY (lci1 - lci2) is the net value of producing materials/energy via secondary vs. primary production, per unit net output flow.

This assessment assumes the following:

- **Recycled steel** materials substitute for primary metal production. PY (lci1 - lci2) is therefore the difference between primary and secondary metals production (i.e. the “scrap value”).
- **Recycled aluminum** materials substitute for primary metal production. PY (lci1 - lci2) is therefore the difference between primary and secondary metals production (i.e. the “scrap value”).
- **Recycled concrete** materials are crushed on-site and substitute for aggregate. PY (lci1 - lci2) is therefore the difference between the effects primary aggregate production (i.e. quarrying, crushing, transporting) and crushing of concrete. Relative transportation effects are assumed to be the same and ignored.

Substitution benefits and burdens for other materials are not considered in the assessment.

5.2 Carbon Sequestration

5.2.1 Biogenic Carbon Sequestration of Wood Products

This assessment accounts for the net biogenic carbon sequestration from landfilling of wood products. The global warming potential benefits of sequestration have been estimated using FPInnovation's *Carbon Tool B2C v2.18*[13] – see Table 25 for the assumed percentages of wood products landfilled, incinerated, and recycled at end of life and Table 28 other assumptions.

[13] For more information on the tool used and its methodology, see: https://fpinnovations.ca/ResearchProgram/environment-sustainability/epd-program/Pages/default.aspx

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5.2.2 Concrete Carbonation

Carbon dioxide is a product of the chemical reactions that take place during cement production, a process known as calcination. Carbonation is the reverse chemical process, whereby CO_2 reacts with hydration products such as calcium hydroxides (CH) and calcium silicate hydrates (C-S-H) in the presence of water to produce calcium carbonate ($CaCO_3$).

The chemical reactions that occur are well-understood, but the speed at which the reactions occur in concrete products is still under study. Lagerblad[14] gives the depth of carbonated concrete as a function of time according to Equation (4), which is based on Fick's 1st Law of Diffusion:

$$x(t) = s * b * k * t^{0.5} \quad (4)$$

where,

$x(t)$	is the depth of carbonated concrete (mm) at time t
s	is a correction factor based on surface treatment and cover, which ranges between 0.7 and 1
b	is a correction factor based on the type and quantity of binder additive used, which ranges between 1.0 and 1.3
k	is the carbonation rate coefficient (mm/year$^{0.5}$), which ranges between 0.5 and 15 based on the concrete compressive strength and type of exposure
t	is the time elapsed (years)

The mass of CO_2 sequestered via carbonation is given by Equation (5) (Collins[15]):

$$m_{CO2}(t) = x(t) / 1000 * A * c * CaO * r * M \quad (5)$$

where,

$m_{CO2}(t)$	is the mass of CO_2 sequestered via carbonation at time t (kg)
$x(t)$	is the depth of carbonated concrete (mm) at time t
A	is the exposed surface area (m^2)
c	is the quantity of ordinary Portland cement in the concrete (kg/m^3)
CaO	is the calcium oxide (CaO) content of ordinary Portland cement, assumed by Collins to be 0.65
r	is the proportion of CaO in fully carbonated ordinary Portland cement converted to calcium carbonate, assumed by Lagerblad (2005) to be 0.75
M	is the molar fraction of CO_2/CaO, which is 0.79

Carbon sequestration from carbonation of concrete products has been quantified in accordance with the Equations (4) and (5) – see Table 29 for relevant assumptions.

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[14] Lagerblad, B. (2005). *Carbon dioxide uptake during concrete life cycle : State of the art*. Oslo: Nordic Innovation Centre.

[15] Collins, F. (2010). Inclusion of carbonation during the life cycle of built and recycled concrete: influence on their carbon footprint. *The International Journal of Life Cycle Assessment*, *15*(6), 549–556.

Two carbonation values are reported:

1. Module A-C sequestration results include carbonation that occurs during the 60-year building use phase and 100 years of carbonation of the waste fraction that is landfilled. It is assumed that landfilled concrete waste is composed of 100mmx100mmx100mm rubble.
2. Module D sequestration results are the substitution credits that the recycled concrete waste fraction receives. The crushing of concrete is assumed to produce aggregate with a range of particle sizes as per
   Table 30. Over the course of the recycled aggregate's assumed 60-year service life, it becomes completely carbonated.

6.0 Environmental Data

6.1 Data Sources

Whole-building LCA typically draws on **environmental product declaration** (EPD)[16] and/or **life cycle inventory** (LCI)[17] environmental data sources. This assessment does not use EPDs as a source of data since there is a general lack of consistency between EPDs of different product categories and a lack of EPDs which include all EN 15978 indicators.

The assessment draws on the following three LCI data sources:

- The Athena LCI Database, v5.2.0104[18]
- The US LCI Database[19]
- The ecoinvent LCI Database, v3[20]

Table 31 presents a summary of LCI data sources used for the various information modules considered in the assessment. In general, the Athena LCI Database is the primary source for process data; this database in turn draws on the US LCI Database for energy combustion and pre-combustion processes, including those related to electricity generation and transportation. The ecoinvent LCI Database was used for processes not available in either Athena or US LCI databases, in particular waste processing and landfill effects. Since ecoinvent data is European in context, the datasets used were adjusted to better reflect an American or Massachusetts system boundary context, as outlined in Section 6.2.

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[16] An EPD is a third-party verified document that reports *environmental* data based on LCA and other relevant information.
[17] An LCI is a list of primary resource input flows and emissions (air, water, land) output flows attributed to an industrial process or group of processes (e.g. a building life cycle)
[18] http://www.athenasmi.org/our-software-data/lca-databases/
[19] http://www.nrel.gov/lci/
[20] http://www.ecoinvent.ch/

6.2 Data Adjustments and Substitutions

In order to improve geographic representativeness and data consistency, the following adjustments were made to ecoinvent LCI Database processes used in the assessment:

- European energy use profiles were substituted with data from the US LCI.
- Material processes were substituted with data from the US LCI, if available.
- Infrastructure effects were removed from the processes to retain consistency with current North American LCA practice.

LCI data for some of the building's materials were unavailable. In order to include these materials in the scope of assessment, materials from the Athena LCI Database deemed to most closely approximate their environmental profile were substituted. In some cases, the resulting estimates required a combination of more than one LCI profile. Some of the substitutions also required scaling the material takeoff to adjust for differences between the products. See Table 32 for a summary of LCI data substitutions.

6.3 Data Quality

Precision: all LCI data sources used were compiled in accordance with ISO 14040/14044 procedures and requirements. The data adjustments and substitutions noted in Section 6.2 introduce inaccuracies.

Completeness: all relevant, specific processes, including inputs (raw materials, energy, water) and outputs (emissions and production volume) are considered and modeled to represent the object of assessment (the building).

Consistency: the assessment draws primarily on a single LCI database (Athena LCI) with consistent system boundary and scope. Ecoinvent processes were adjusted to align with Athena/US LCI Database system boundaries.

Reproducibility: the data used is available in the LCI databases noted; the document specifies the adjustments and substitutions made to data such that they are generally reproducible.

Representativeness:

- Time related coverage-while the most recent validation of some LCI data sets used are beyond the EN 15978 limit of ten years, these processes are of limited significance to the total environmental effects of the whole-building assessment
- Geographical coverage - at minimum North America and representative of the region (USA, Massachusetts) where the building is located.
- Technological coverage - average, reflecting the physical reality of the products found in the building.

7.0 List of Indicators Used for Assessment and Expression of Results

A summary of the environmental indicator results required by EN 15978 is presented in Table 7. Indicators excluded from the assessment were not evaluated because the underlying LCI datasets used do not sufficiently support them.

Table 7: Reported Environmental Indicators

EN 15978 Environmental Indicator	Methodology	Unit
Environmental Impacts		
Global warming potential	TRACI v2.1	kg CO_2 eq.
Depletion of the stratospheric ozone layer	TRACI v2.1	kg CFC-11 eq.
Acidification potential of land and water	TRACI v2.1	kg SO_2 eq.
Eutrophication potential	TRACI v2.1	kg N eq.
Formation potential of tropospheric ozone photochemical oxidants	TRACI v2.1	kg O_3 eq.
Abiotic resource depletion potential for elements	*not in scope*	
Abiotic resource depletion potential of fossil fuels	TRACI v2.1	MJ surplus
Resource Use		
Renewable primary energy excluding energy resources used as raw material	CED	MJ
Renewable primary energy resources used as raw material	CED	MJ
Non-renewable primary energy excluding resources used as raw material	CED	MJ
Non-renewable primary energy resources used as raw material	CED	MJ
Secondary material	Sum of LCI flows	kg
Renewable secondary fuels	*not in scope*	
Non-renewable secondary fuels	*not in scope*	
Net use of fresh water	Sum of LCI flows	m^3
Waste Categories		
Non-hazardous waste disposed	Sum of LCI flows	kg
Hazardous waste disposed[21]	*not in scope*	
Radioactive waste disposed	*not in scope*	
Output Flows Leaving the System		
Components for re-use	Sum of LCI flows	kg
Materials for recycling	Sum of LCI flows	kg
Materials for energy recovery (not being waste incineration)	Sum of LCI flows	kg
Exported energy	Sum of LCI flows	MJ

CED= Cumulative Energy Demand (v1.08)

[21] North American LCI datasets generally do not track waste flows by type; a limitation of this study is that some hazardous and radioactive wastes have likely been characterized as non-hazardous.

The environmental impacts considered were evaluated according to the EPA's *Tool for the Reduction and Assessment of Chemical and other environmental Impacts* (TRACI) v2.1 life cycle impact assessment (LCIA)[22] methodology. TRACI provides a North American context for the supported measures, with a result that some of the indicator units are different than those required by EN 15978. This has been deemed acceptable for this assessment since North American adoption of a standard like EN 15978 would presumably be structured on the use of TRACI as LCIA methodology.

Energy resource use was evaluated according to *Cumulative Energy Demand* (CED) methodology. All other indicators considered were evaluated by summing elementary LCI flows (e.g. net use of fresh water) or intermediate LCI flows (e.g. non-hazardous waste disposed) over the building life cycle.

Please note the following:

- *Net use of fresh water is* a summation of primary fresh water withdrawals, including water consumed and water discharged after withdrawal.
- *Use of secondary material* is a summation of the use of recycled and reused materials in products that make up the building.
- *Non-hazardous waste disposed* is a summation of the final waste flows landfilled and incinerated.
- *Output Flows Leaving the System* indicators include only flows that are downstream from the building, i.e. they do not include flows leaving the system from the Product Stage (one exception to this is steel waste from fabrication).

8.0 Communication of Assessment Results

This section presents LCA results tables for the Design Building; please note the following:

- Table entries marked "xx" refer to information modules or environmental indictors that are not included in the study scope.
- EN 15978 stipulates that results for non-building-related operational energy (e.g. plug loads), should be disaggregated from building-integrated technical system operational energy results (e.g. space heating), however this type of breakdown was unavailable and therefore module B6 is presented as a single set of results including plug loads in this report.
- As a declaration of environmental performance, results synthesis and conclusions regarding the building's level of performance are left to the reader.

[22] **Life cycle impact assessment** (LCIA) is the process of evaluating the environmental effects of an LCI – e.g. evaluating global warming potential from various greenhouse gas emissions

8.1 Life Cycle Results

Table 8 presents 60-year total life cycle results for the Design Building, along with results normalized per-m^2 (gross floor area), per-occupant, per-year, per-m^2-year, and per-occupant-year.

8.2 Contribution Analysis

As required by EN 15978, total life cycle results are presented by information module in Table 9 through Table 11.

Figure 7 through Figure 12 in Appendix A graphically present the following contribution analyses:

- Information Module Contributions to Total LCA Results
- Resource Type Contributions to Total LCA Results
- Construction Element Contributions to Material Use LCA Results
- Material Type Contributions to Material Use LCA Results
- Fuel Type Contributions to Operational Energy LCA Results
- Municipal Service Contributions to Operational Water LCA Results

8.3 Sensitivity Analysis

EN 15978 requires that "the significance of the influence of the data chosen for the building assessment shall be determined (e.g. through a sensitivity analysis) and reported." For the most part, the assessment draws on data from a single source (Athena LCI Database), which has a high degree of methodological consistency.

The following five sensitivity analyses were conducted; each aims to explore the sensitivity of aspects whose assumed scenarios, LCI datasets, and/or material quantity calculations could measurably change life cycle results:

- **Scenario 1:** operational energy use estimates are increased by 10%
- **Scenario 2:** operational water use estimates are increased by 10%
- **Scenario 3:** cross laminated timber and glulam quantities are increased by 10%.
- **Scenario 4:** concrete and rebar quantities are increased by 10%
- **Scenario 5:** Wide flange and hollow structural steel section quantities are increased by 10%

Table 12 presents the ratios of the total life cycle results of these sensitivity cases to the baseline case.

8.4 Additional Results

Table 13 presents indicator results for the following additional information outlined in Section 5.0:

- Modules A-C, wood carbon sequestration
- Modules A-C, concrete carbon sequestration
- Module D, steel recycling
- Module D, aluminum recycling
- Module D, concrete recycling
- Module D, concrete recycling carbon sequestration

Table 8: UMass Design Building LCA Results

EN 15978 Environmental Indicator	Unit	Total	Per-m2	Per-occupant	Per-year	Per-m2-year	Per-occupant-year
Environmental Impacts							
Global warming potential	kg CO_2 eq.	3.10E+07	3.81E+03	3.78E+05	5.17E+05	6.34E+01	6.30E+03
Depletion of the stratospheric ozone layer	kg CFC-11 eq.	8.05E-02	9.89E-06	9.82E-04	1.34E-03	1.65E-07	1.64E-05
Acidification potential of land and water	kg SO_2 eq.	2.49E+05	3.06E+01	3.04E+03	4.15E+03	5.10E-01	5.06E+01
Eutrophication potential	kg N eq.	5.96E+03	7.31E-01	7.26E+01	9.93E+01	1.22E-02	1.21E+00
Formation potential of tropospheric ozone photochemical oxidants	kg O_3 eq.	1.12E+06	1.37E+02	1.36E+04	1.86E+04	2.28E+00	2.27E+02
Abiotic resource depletion potential for elements	kg Sb eq.	xx	xx	xx	xx	xx	xx
Abiotic resource depletion potential of fossil fuels	MJ surplus	6.96E+07	8.55E+03	8.49E+05	1.16E+06	1.42E+02	1.42E+04
Resource Use							
Renewable primary energy excluding energy resources used as raw material	MJ	1.23E+07	1.51E+03	1.50E+05	2.05E+05	2.52E+01	2.50E+03
Renewable primary energy resources used as raw material	MJ	2.03E+07	2.50E+03	2.48E+05	3.39E+05	4.16E+01	4.13E+03
Non-renewable primary energy excluding resources used as raw material	MJ	5.31E+08	6.52E+04	6.48E+06	8.85E+06	1.09E+03	1.08E+05
Non-renewable primary energy resources used as raw material	MJ	1.80E+06	2.21E+02	2.19E+04	2.99E+04	3.68E+00	3.65E+02
Secondary material	kg	6.89E+05	8.46E+01	8.41E+03	1.15E+04	1.41E+00	1.40E+02
Renewable secondary fuels	MJ	xx	xx	xx	xx	xx	xx
Non-renewable secondary fuels	MJ	xx	xx	xx	xx	xx	xx
Net use of fresh water	m^3	9.01E+04	1.11E+01	1.10E+03	1.50E+03	1.84E-01	1.83E+01
Waste Categories							
Non-hazardous waste disposed	kg	5.42E+06	6.66E+02	6.61E+04	9.04E+04	1.11E+01	1.10E+03
Hazardous waste disposed	kg	xx	xx	xx	xx	xx	xx
Radioactive waste disposed	kg	xx	xx	xx	xx	xx	xx
Output Flows Leaving the System							
Components for re-use	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Materials for recycling	kg	4.64E+06	5.70E+02	5.66E+04	7.73E+04	9.49E+00	9.43E+02
Materials for energy recovery (not being waste incineration)	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Exported energy	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

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Table 9: Information Module Contributions to Environmental Impact Indicator Results

EN 15978 Environmental Indicator	Environmental Impacts						
	Global warming potential	Depletion potential of the stratospheric ozone layer	Acidification potential of land and water	Eutrophication potential	Formation potential of troposheric ozone photochemical oxidants	Abiotic resource depletion potential for elements	Abiotic resource depletion potential of fossil fuels
	kg CO2 eq.	kg CFC-11 eq.	moles of H+ eq.	kg N eq.	kg O3 eq.	kg Sb eq.	MJ surplus
A1 Raw Material Supply, A2 Transport, A3 Manufacturing	2.59E+06	6.44E-02	1.27E+04	8.22E+02	1.61E+05	xx	2.31E+06
A4 Transport	1.52E+05	6.12E-06	1.63E+03	1.09E+02	5.64E+04	xx	2.91E+05
A5 Construction Installation Process	4.41E+05	1.73E-03	2.41E+03	1.16E+02	4.43E+04	xx	7.60E+05
B1 Use of Products	xx	xx	xx	xx	xx	xx	xx
B2 Maintenance	1.35E+03	6.81E-06	8.29E+00	2.71E-01	1.25E+02	xx	7.16E+03
B3 Repair	3.64E+05	2.09E-03	2.26E+03	1.20E+02	4.27E+04	xx	3.63E+05
B4 Replacement	3.75E+05	2.96E-03	2.27E+03	1.21E+02	3.47E+04	xx	5.09E+05
B5 Refurbishment	xx	xx	xx	xx	xx	xx	xx
B6 Operational Energy Use	2.68E+07	9.90E-05	2.26E+05	2.38E+03	7.28E+05	xx	6.49E+07
B7 Operational Water Use	3.93E+04	1.48E-03	4.83E+02	2.13E+03	2.96E+03	xx	5.50E+04
C1 De-construction and Demolition	9.49E+04	3.94E-06	1.14E+02	9.35E+00	2.76E+03	xx	1.88E+05
C2 Transport	8.71E+04	3.33E-06	8.74E+02	5.70E+01	2.92E+04	xx	1.59E+05
C3 Waste Processing	5.27E+04	3.37E-03	4.99E+02	2.18E+01	8.58E+03	xx	9.61E+04
C4 Disposal	2.65E+04	4.39E-03	2.22E+02	6.79E+01	5.82E+03	xx	4.37E+04
Total	**3.10E+07**	**8.05E-02**	**2.49E+05**	**5.96E+03**	**1.12E+06**	**xx**	**6.96E+07**

Table 10: Information Module Contributions to Resource Use Indicator Results

EN 15978 Environmental Indicator	Resource Use							
	Use of renewable primary energy excluding energy used as raw material	Use of renewable primary energy resources used as raw material	Use of non-renewable primary energy excluding energy used as raw material	Use of non-renewable primary energy resources used as raw material	Use of secondary material	Use of renewable secondary fuels	Use of non-renewable secondary fuels	Use of net fresh water
	MJ, net calorific value	MJ, net calorific value	MJ, net calorific value	MJ, net calorific value	kg	MJ	MJ	m3
A1 Raw Material Supply, A2 Transport, A3 Manufacturing	6.36E+06	2.00E+07	2.88E+07	1.15E+06	6.66E+05	xx	xx	1.61E+04
A4 Transport	9.93E+02	0.00E+00	2.04E+06	0.00E+00	0.00E+00	xx	xx	0.00E+00
A5 Construction Installation Process	1.62E+05	2.20E+05	6.62E+06	3.55E+04	1.61E+04	xx	xx	4.64E+02
B1 Use of Products	xx	xx	xx	xx	xx	xx	xx	xx
B2 Maintenance	2.43E+02	0.00E+00	1.43E+04	3.89E+04	0.00E+00	xx	xx	5.03E-01
B3 Repair	8.17E+04	5.57E+02	3.27E+06	2.23E+05	6.38E+03	xx	xx	2.65E+02
B4 Replacement	1.11E+05	1.65E+05	4.39E+06	3.53E+05	7.43E+02	xx	xx	6.34E+02
B5 Refurbishment	xx	xx	xx	xx	xx	xx	xx	xx
B6 Operational Energy Use	5.53E+06	0.00E+00	4.82E+08	0.00E+00	0.00E+00	xx	xx	1.80E-03
B7 Operational Water Use	2.61E+04	0.00E+00	6.76E+05	0.00E+00	0.00E+00	xx	xx	7.26E+04
C1 De-construction and Demolition	5.73E+02	0.00E+00	1.31E+06	0.00E+00	0.00E+00	xx	xx	0.00E+00
C2 Transport	5.12E+02	0.00E+00	1.12E+06	0.00E+00	0.00E+00	xx	xx	0.00E+00
C3 Waste Processing	4.18E+04	0.00E+00	9.39E+05	0.00E+00	0.00E+00	xx	xx	3.47E+00
C4 Disposal	3.34E+03	0.00E+00	3.62E+05	0.00E+00	0.00E+00	xx	xx	4.51E+00
Total	**1.23E+07**	**2.03E+07**	**5.31E+08**	**1.80E+06**	**6.89E+05**	**xx**	**xx**	**9.01E+04**

Table 11: Information Module Contributions to Waste Category and Output Flow Indicator Results

EN 15978 Environmental Indicator	Waste Categories			Output Flows			
	Non hazardous waste to disposal	Hazardous waste to disposal	Radioactive waste	Components for reuse	Material for recycling	Material for energy recovery	Exported energy
	kg	kg	kg	kg	kg	kg	MJ
A1 Raw Material Supply, A2 Transport, A3 Manufacturing	1.50E+05	xx	xx	0.00E+00	5.12E+03	0.00E+00	0.00E+00
A4 Transport	1.60E+03	xx	xx	0.00E+00	0.00E+00	0.00E+00	0.00E+00
A5 Construction Installation Process	1.74E+05	xx	xx	0.00E+00	1.95E+05	0.00E+00	0.00E+00
B1 Use of Products	xx	xx	xx	xx	xx	xx	xx
B2 Maintenance	2.17E+03	xx	xx	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B3 Repair	2.12E+05	xx	xx	0.00E+00	3.52E+04	0.00E+00	0.00E+00
B4 Replacement	2.25E+05	xx	xx	0.00E+00	1.75E+04	0.00E+00	0.00E+00
B5 Refurbishment	xx	xx	xx	xx	xx	xx	xx
B6 Operational Energy Use	3.66E+05	xx	xx	0.00E+00	0.00E+00	0.00E+00	0.00E+00
B7 Operational Water Use	6.57E+02	xx	xx	0.00E+00	0.00E+00	0.00E+00	0.00E+00
C1 De-construction and Demolition	1.03E+03	xx	xx	0.00E+00	0.00E+00	0.00E+00	0.00E+00
C2 Transport	8.27E+02	xx	xx	0.00E+00	0.00E+00	0.00E+00	0.00E+00
C3 Waste Processing	5.93E+02	xx	xx	0.00E+00	4.39E+06	0.00E+00	0.00E+00
C4 Disposal	4.29E+06	xx	xx	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Total	**5.42E+06**	**xx**	**xx**	**0.00E+00**	**4.64E+06**	**0.00E+00**	**0.00E+00**

Table 12: Sensitivity Analysis Results

EN 15978 Environmental Indicator	Unit	Scenario 1: 10% increase in operating energy use	Scenario 2: 10% increase in operating water use	Scenario 3: +10% CLT & Glulam	Scenario 4: +10% Concrete & Rebar	Scenario 5: +10% W Sections & HSS
Environmental Impacts						
Global warming potential	kg CO_2 eq.	1.086	1.000	1.001	1.005	1.001
Depletion of the stratospheric ozone layer	kg CFC-11 eq.	1.000	1.002	1.026	1.039	1.009
Acidification potential of land and water	kg SO_2 eq.	1.091	1.000	1.001	1.002	1.000
Eutrophication potential	kg N eq.	1.040	1.036	1.005	1.009	1.001
Formation potential of tropospheric ozone photochemical oxidants	kg O_3 eq.	1.065	1.000	1.007	1.007	1.002
Abiotic resource depletion potential for elements	kg Sb eq.	xx	xx	xx	xx	xx
Abiotic resource depletion potential of fossil fuels	MJ surplus	1.093	1.000	1.001	1.001	1.000
Resource Use						
Renewable primary energy excluding energy resources used as raw material	MJ	1.045	1.000	1.048	1.003	1.000
Renewable primary energy resources used as raw material	MJ	1.000	1.000	1.097	1.000	1.000
Non-renewable primary energy excluding resources used as raw material	MJ	1.091	1.000	1.001	1.002	1.001
Non-renewable primary energy resources used as raw material	MJ	1.000	1.000	1.021	1.000	1.000
Secondary material	kg	1.000	1.000	1.000	1.034	1.024
Renewable secondary fuels	MJ	xx	xx	xx	xx	xx
Non-renewable secondary fuels	MJ	xx	xx	xx	xx	xx
Net use of fresh water	m^3	1.000	1.081	1.001	1.005	1.002
Waste Categories						
Non-hazardous waste disposed	kg	1.007	1.000	1.017	1.050	1.000
Hazardous waste disposed	kg	xx	xx	xx	xx	xx
Radioactive waste disposed	kg	xx	xx	xx	xx	xx
Output Flows Leaving the System						
Components for re-use	kg	n/a	n/a	n/a	n/a	n/a
Materials for recycling	kg	1.000	1.000	1.002	1.088	1.003
Materials for energy recovery (not being waste incineration)	kg	n/a	n/a	n/a	n/a	n/a

Note: values presented in this table are the total life cycle sensitivity scenario results divided by the baseline results

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Table 13: Additional Information Results

EN 15978 Environmental Indicator	Unit	Modules A-C, wood carbon sequest.	Modules A-C, concrete carbon sequest.	Module D, steel recycling	Module D, aluminum recycling	Module D, concrete recycling	Module D, recycled concrete carbon sequest.
Environmental Impacts							
Global warming potential	kg CO_2 eq.	-9.61E+05	-1.47E+05	7.57E+04	-1.61E+05	-1.22E+04	-1.69E+05
Depletion of the stratospheric ozone layer	kg CFC-11 eq.	0.00E+00	0.00E+00	-2.63E+00	-7.70E-06	-3.24E-07	0.00E+00
Acidification potential of land and water	kg SO_2 eq.	0.00E+00	0.00E+00	1.73E+02	-1.14E+03	-1.37E+02	0.00E+00
Eutrophication potential	kg N eq.	0.00E+00	0.00E+00	3.01E+00	-1.75E+01	-6.01E+00	0.00E+00
Formation potential of tropospheric ozone photochemical oxidants	kg O_3 eq.	0.00E+00	0.00E+00	1.69E+03	-8.76E+03	-3.10E+03	0.00E+00
Abiotic resource depletion potential for elements	kg Sb eq.	xx	xx	xx	xx	xx	xx
Abiotic resource depletion potential of fossil fuels	MJ surplus	0.00E+00	0.00E+00	6.20E+02	-1.05E+05	-2.31E+04	0.00E+00
Resource Use							
Renewable primary energy excluding energy resources used as raw material	MJ	0.00E+00	0.00E+00	0.00E+00	-1.02E+06	-1.50E+04	0.00E+00
Renewable primary energy resources used as raw material	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Non-renewable primary energy excluding resources used as raw material	MJ	0.00E+00	0.00E+00	4.29E+05	-1.63E+06	-2.05E+05	0.00E+00
Non-renewable primary energy resources used as raw material	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Secondary material	kg	0.00E+00	0.00E+00	-4.99E+04	0.00E+00	3.98E+06	0.00E+00
Renewable secondary fuels	MJ	xx	xx	xx	xx	xx	xx
Non-renewable secondary fuels	MJ	xx	xx	xx	xx	xx	xx
Net use of fresh water	m^3	0.00E+00	0.00E+00	0.00E+00	-1.16E+03	0.00E+00	0.00E+00
Waste Categories							
Non-hazardous waste disposed	kg	0.00E+00	0.00E+00	-1.88E+03	-6.66E+04	-6.18E+01	0.00E+00
Hazardous waste disposed	kg	xx	xx	xx	xx	xx	xx
Radioactive waste disposed	kg	xx	xx	xx	xx	xx	xx
Output Flows Leaving the System							
Components for re-use	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Materials for recycling	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Materials for energy recovery (not being waste incineration)	kg	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Exported energy	MJ	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Note: a negative value means a sequestration or avoided impact

Appendix A: Contribution Analysis Charts

Please note that some of the indicator names in this Appendix have been modified for conciseness.

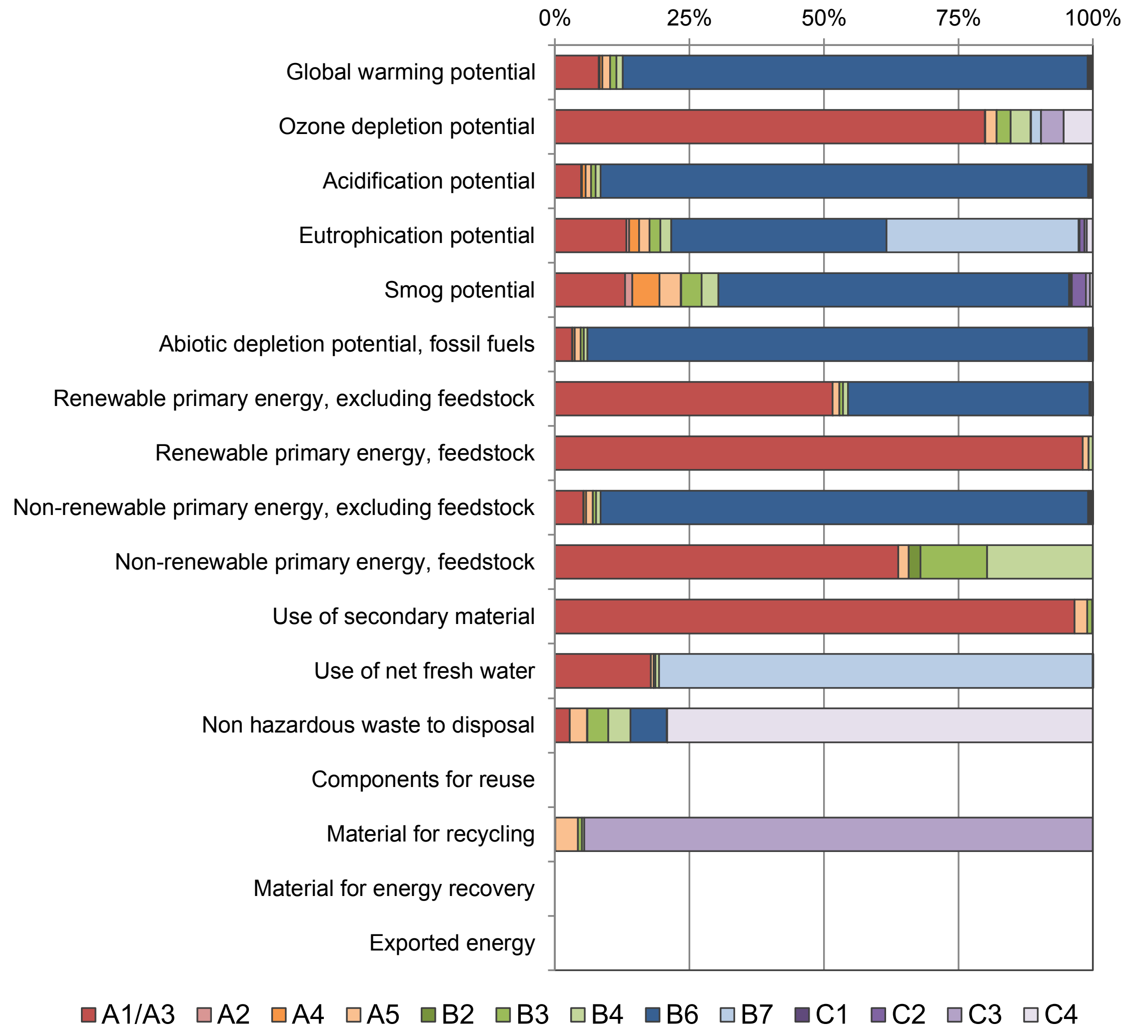

Figure 7: Information Module Contributions to Total LCA Results

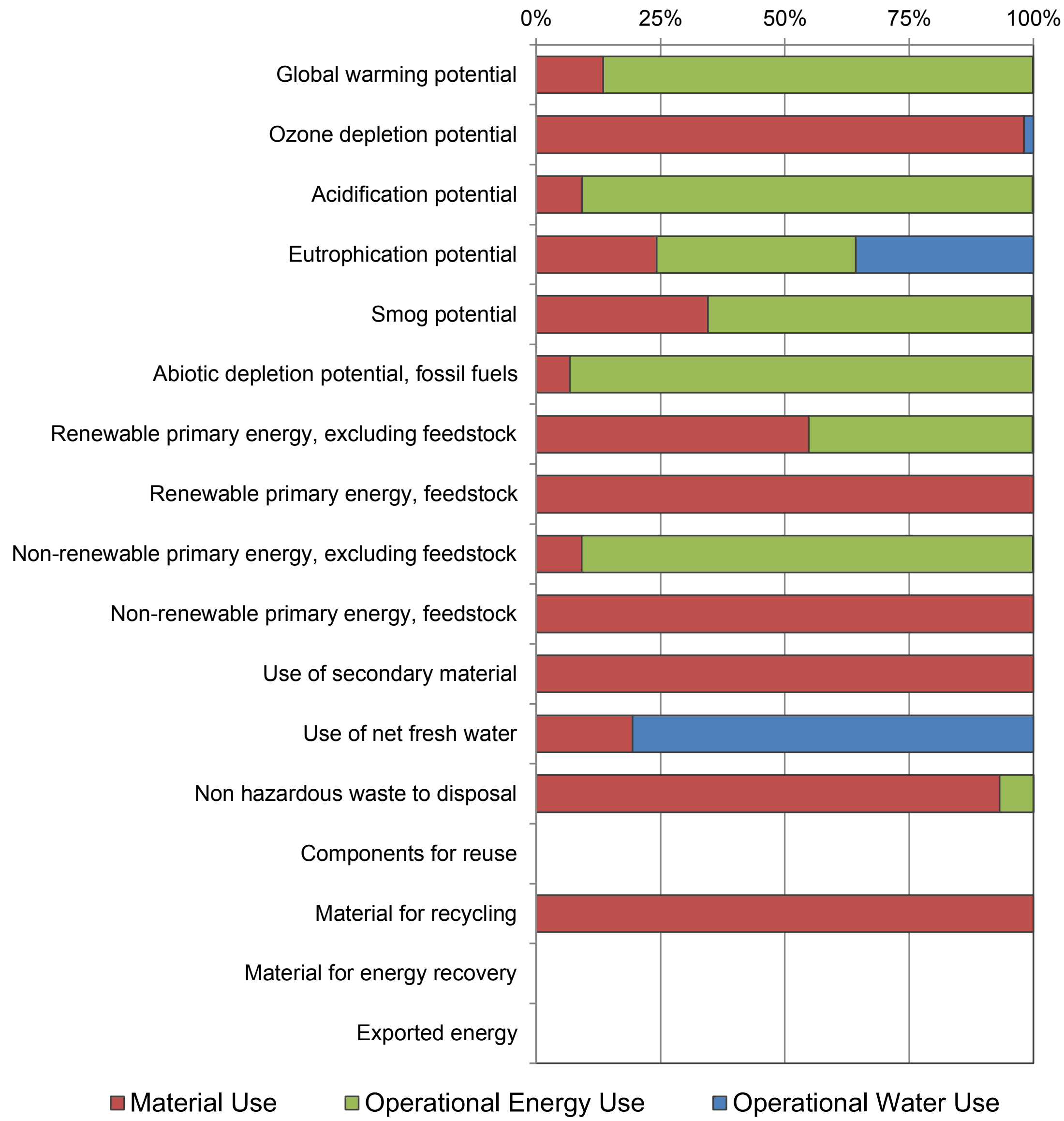

Figure 8: Resource Type Contributions to Total LCA Results

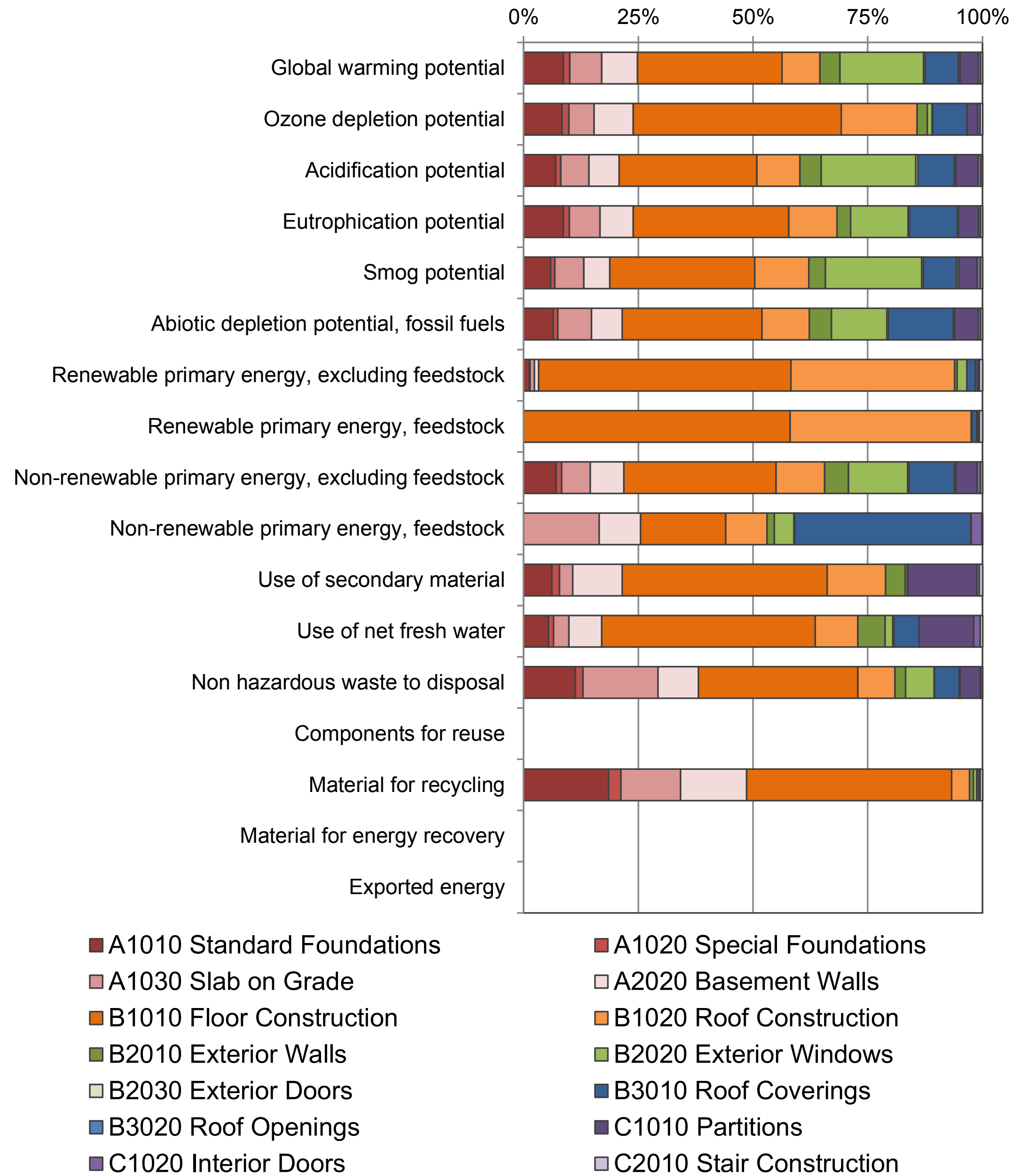

Figure 9: Construction Element Contributions to Material Use LCA Results

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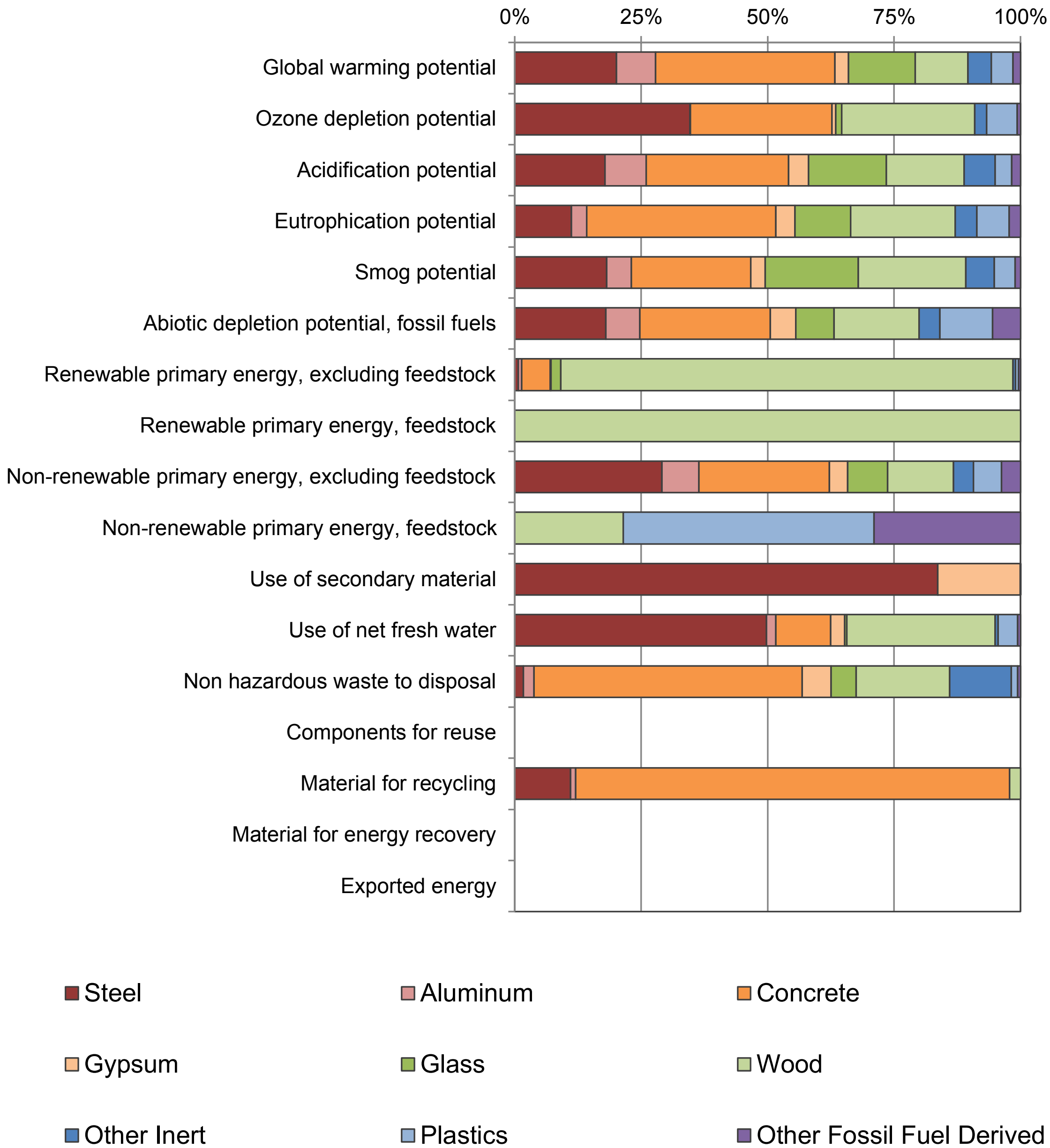

Figure 10: Material Type Contributions to Material Use LCA Results

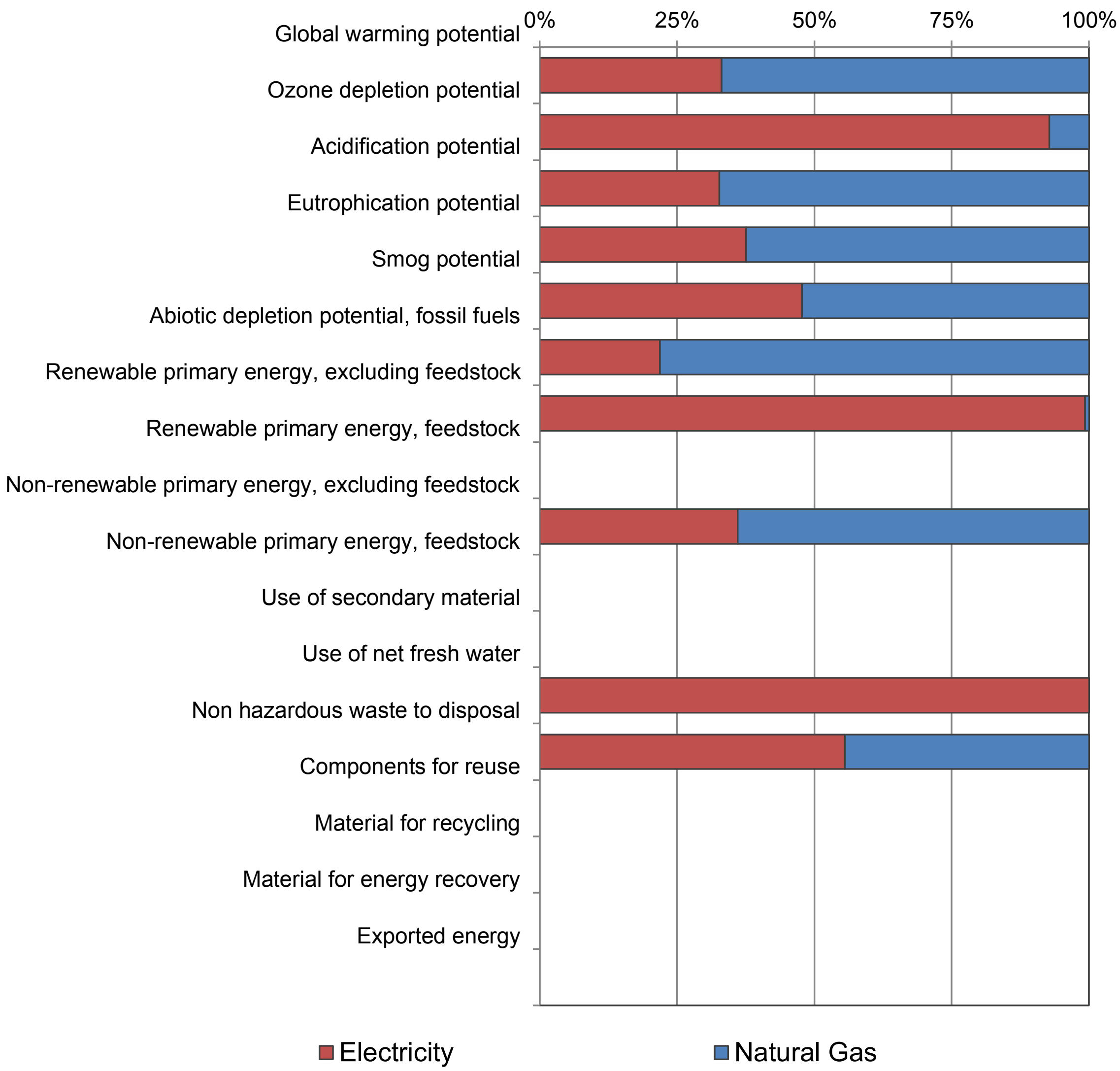

Figure 11: Fuel Type Contributions to Operational Energy LCA Results

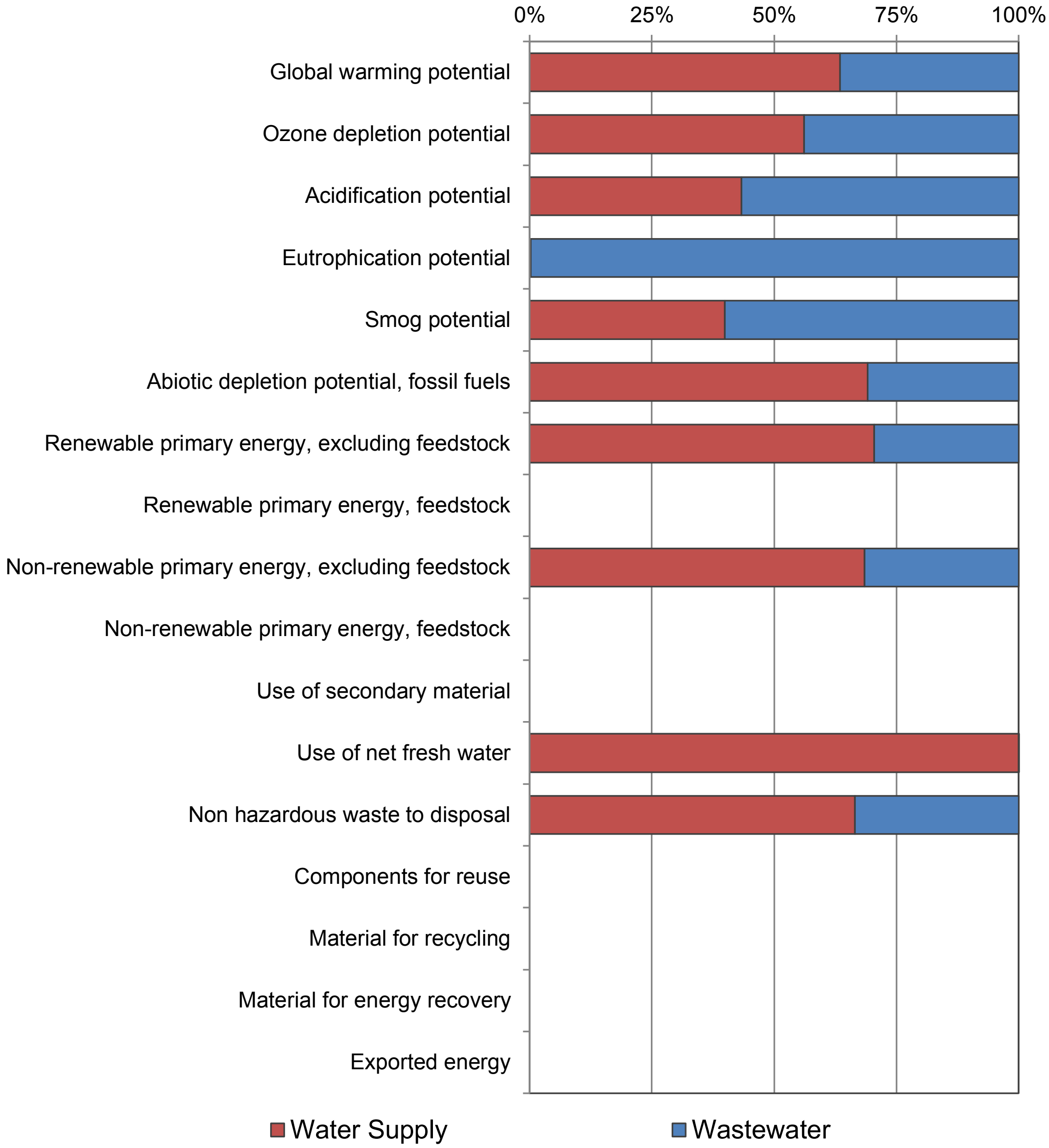

Figure 12: Municipal Service Contributions to Operational Water LCA Results

Appendix B: Building Element Design Summary

Table 14: Building Element Design Summary

Element	Design Summary
A1010 Standard Foundations	• 350-900 deep reinforced concrete pad footings • 300-600 deep reinforced concrete strip footings
A1020 Special Foundations	• 600-1625 deep reinforced concrete grade beams
A1030 Slab on Grade	• 150 reinforced concrete slab (+ 75 topping at first floor) with 15 mil polyethylene, 50 XPS insulation • 100 housekeeping pads
A2010 Basement Excavation	*not included in scope*
A2020 Basement Walls	• 300-500 thick reinforced concrete walls
B1010 Floor Construction	• Columns: 400x400, 450x450, 600x600, 550x750 reinforced concrete (basement); 356x563, 356x638, 356x788 glulam, 100-250 diameter hollow structural steel • Beams: 300-1825 deep reinforced concrete (basement); 356x375, 356x413 glulam; 125-825 deep W sections; misc. hollow structural steel • Floor: 250-600 reinforced concrete slab (first floor); 175 CLT with 100 reinforced concrete topping, 25 rigid insulation • Walls: 245 CLT • Braces: 356x356 glulam
B1020 Roof Construction	• Columns: 356x563, 356x638 glulam; 200 deep hollow structural steel • Beams: 150-525 deep glulam; 125-200 deep W sections • Truss: 225-450 deep hollow structural sections • Braces: 356x356 glulam • Roof: 175 CLT with 100 reinforced concrete topping, 25 rigid insulation; 245 CLT; 38 deep metal deck • Walls: 245 CLT
B2010 Exterior Walls	• Aluminum plate rain screen, 100 mineral wool insulation, membrane air/vapor barrier, 150-200 deep light gauge steel stud wall, 38 spray foam insulation, 16 gypsum board • 100 bluestone, 38 drainage panel, 65 polyisocyanurate insulation, membrane air/vapor barrier, 65-200 deep light gauge steel stud wall, 38 spray foam insulation, 16 gypsum board
B2020 Exterior Windows	• Low-e double glazed, aluminum framed curtain wall
B2030 Exterior Doors	• Aluminum rail and stile glass, glass bifold, hollow metal doors
B3010 Roof Coverings	• 60 mil TPO membrane, tapered polyisocynurate insulation (R-35 min), roof vapor retarder, roof board underlayment • Mix of vegetative roof and wood decking with 150 XPS insulation, drainage mat, protection layer/root barrier, 215 mil reinforced hot rubberized asphalt
B3020 Roof Openings	• Low roof skylights
C1010 Partitions	• Light gauge steel stud walls @400 (65, 90, 100, 150 deep), fibreglass insulation, 16 gypsum board
C1020 Interior Doors	• Hollow metal, solid wood doors

Element	Design Summary
C1030 Fittings	*not included in scope*
C2010 Stair Construction	• 175 CLT with glulam treads • 6 thick plate with concrete topping, structural steel channel stringers
C2020 Stair Finishes	*not included in scope*
C3010 Wall Finishes	*not included in scope*
C3020 Floor Finishes	*not included in scope*
C3030 Ceiling Finishes	*not included in scope*

Table Notes:
1) all dimensions given in mm;
2) for conciseness, not all assembly/assembly components are listed;

Appendix C: Whole-building Bill of Materials

Table 15: Whole-building Bill of Materials

Material	Quantity	Unit
1/2" Moisture Resistant Gypsum Board	1093.700	m2
5/8" Fire-Rated Type X Gypsum Board	2015.627	m2
5/8" Regular Gypsum Board	16764.278	m2
6 mil Polyethylene	5095.480	m2
Aluminum Cold Rolled Sheet	9.758	Tonnes
Aluminum Extrusion	22.096	Tonnes
Bolts, Fasteners, Clips	0.843	Tonnes
Coarse Aggregate Crushed Stone	836.474	Tonnes
Coarse Aggregate Natural	12.563	Tonnes
Cold Rolled Sheet	0.073	Tonnes
Concrete 4000 psi, 25% fly ash	633.583	m3
Concrete 5000 psi, 25% fly ash	1955.111	m3
Cross Laminated Timber	1586.124	m3
EPDM membrane (black, 60 mil)	269.912	kg
Expanded Polystyrene	4238.921	m2 (25mm)
Extruded Polystyrene	8600.967	m2 (25mm)
FG Batt R11-15	8069.284	m2 (25mm)
FG Batt R20	4492.182	m2 (25mm)
FG Batt R30	629.036	m2 (25mm)
Fiber Cement	2795.199	m2
GAF Everguard© white TPO membrane 60 mil	2187.400	m2
Galvanized Decking	0.819	Tonnes
Galvanized Sheet	8.991	Tonnes
Galvanized Studs	38.610	Tonnes
Glazing Panel	63.203	Tonnes
GluLam Sections	556.740	m3
Hollow Structural Steel	46.905	Tonnes

Material	Quantity	Unit
Hot Rolled Sheet	8.942	Tonnes
Joint Compound	12.040	Tonnes
Laminated Veneer Lumber	3.526	m3
Large Dimension Softwood Lumber, kiln-dried	14.161	m3
Modified Bitumen membrane	1992.178	kg
Mortar	8.849	m3
MW Batt R11-15	7256.932	m2 (25mm)
Nails	0.896	Tonnes
Natural Stone	368.960	m2
Paper Tape	0.145	Tonnes
Polyester felt	0.012	Tonnes
Polyiso Foam Board (unfaced)	16140.355	m2 (25mm)
Rebar, Rod, Light Sections	211.514	Tonnes
Roofing Asphalt	1325.248	kg
Screws Nuts & Bolts	7.100	Tonnes
Small Dimension Softwood Lumber, kiln-dried	13.261	m3
Softwood Plywood	1812.567	m2 (9mm)
Solvent Based Alkyd Paint	31.219	L
Spruce Wood tongue and groove siding	70.550	m2
Steel Plate	126.135	Tonnes
VR 1/2" Drainage Mat	1525.193	m2
VR 20 mil Root Barrier	295.800	m2
Water Based Latex Paint	85.459	L
Welded Wire Mesh / Ladder Wire	21.054	Tonnes
Wide Flange Sections	102.752	Tonnes
Wire Rod	6.907	Tonnes

Please note that the reported quantities are those required by the building at initial construction and do not include wastage.

Appendix D: Scenario Tables

Please note that the table captions include references to the relevant information modules.

Table 16: Scenarios – Transport of Materials to Site (modules A4, B2, B3, B4)

Material	Road Short Haul, diesel (km)	Road Long Haul, diesel (km)	Rail, diesel (km)	Barge, residual fuel oil (km)	Ocean, residual fuel oil (km)
1/2" Moisture Resistant Gypsum Board		346	496	0	0
5/8" Fire-Rated Type X Gypsum Board		346	496	0	0
5/8" Regular Gypsum Board		346	496	0	0
6 mil Polyethylene		826	261	0	0
Aluminum Cold Rolled Sheet		997	292	0	0
Aluminum Extrusion		1,868	547	0	0
Bolts, Fasteners, Clips		305	735	0	0
Coarse Aggregate Crushed Stone	45		0	0	0
Coarse Aggregate Natural	45		0	0	0
Cold Rolled Sheet	13	411	0	0	0
Concrete 4000 psi, 25% fly ash	13		0	0	0
Concrete 5000 psi, 25% fly ash	13		0	0	0
Cross Laminated Timber		850			
EPDM membrane (black, 60 mil)		498	388	0	0
Expanded Polystyrene		798	558	0	0
Extruded Polystyrene		405	0	0	0
FG Batt R11-15		468	0	0	0
FG Batt R20		468	0	0	0
FG Batt R30		468	0	0	0
Fiber Cement	185	468	0	0	0
GAF Everguard© white TPO membrane 60 mil		1,398			
Galvanized Decking		401	342	0	0
Galvanized Sheet		365	571	0	0
Galvanized Studs	169				
Glazing Panel		966	797	0	0
GluLam Sections		850			
Hollow Structural Steel	60	456	405	0	0
Hot Rolled Sheet		321	486	0	0
Joint Compound		558	0	0	0
Laminated Veneer Lumber		1,497	1,083	279	0
Large Dimension Softwood Lumber, kiln-dried	45	910	0	0	0
Modified Bitumen membrane		740	347	0	0
Mortar		330	0	0	0
MW Batt R11-15		522	522	0	0
Nails		298	0	0	0
Natural Stone		500	0	0	0

Material	Road Short Haul, diesel (km)	Road Long Haul, diesel (km)	Rail, diesel (km)	Barge, residual fuel oil (km)	Ocean, residual fuel oil (km)
Paper Tape		888	0	0	0
Polyester felt		736	694	0	0
Polyiso Foam Board (unfaced)	188		40	0	0
Rebar, Rod, Light Sections		293	175	0	0
Roofing Asphalt	33	642	590	0	0
Screws Nuts & Bolts	60	456			
Small Dimension Softwood Lumber, kiln-dried		797	1,200	0	0
Softwood Plywood		900	2,225	0	0
Solvent Based Alkyd Paint		530	0	0	0
Spruce Wood tongue and groove siding		1,842	956	0	0
Steel Plate	60	456	310	0	0
VR 1/2" Drainage Mat		300	0	0	0
VR 20 mil Root Barrier		300	0	0	0
Water Based Latex Paint		530	0	0	0
Welded Wire Mesh / Ladder Wire		830	25	0	0
Wide Flange Sections	60	456	405	0	0
Wire Rod	60	456	310	0	0

Table 17: Scenarios – Construction Energy Use (modules A5, B2, B3, B4)

Module	Gasoline (L)	Electricity (kWh)
A5	94,635	205,765
B2	13	28
B3	2,134	4,639
B4	1,670	3,630

Table 18: Scenarios – Construction Material Wastage (modules A5, B2, B3, B4)

Material	Construction Waste Factor
1/2" Moisture Resistant Gypsum Board	1.1
5/8" Fire-Rated Type X Gypsum Board	1.1
5/8" Regular Gypsum Board	1.1
6 mil Polyethylene	1.02
Aluminum Cold Rolled Sheet	1
Aluminum Extrusion	1.01

Material	Construction Waste Factor
Bolts, Fasteners, Clips	1.03
Coarse Aggregate Crushed Stone	1
Coarse Aggregate Natural	1
Cold Rolled Sheet	1.01
Concrete 4000 psi, 25% fly ash	1.05
Concrete 5000 psi, 25% fly ash	1.05
Cross Laminated Timber	1.01
EPDM membrane (black, 60 mil)	1.03
Expanded Polystyrene	1.05
Extruded Polystyrene	1.05
FG Batt R11-15	1.05
FG Batt R20	1.05
FG Batt R30	1.05
Fiber Cement	1.1
GAF Everguard© white TPO membrane 60 mil	1.03
Galvanized Decking	1.01
Galvanized Sheet	1.01
Galvanized Studs	1.01
Glazing Panel	1
GluLam Sections	1.01
Hollow Structural Steel	1.01
Hot Rolled Sheet	1.01
Joint Compound	1.07
Laminated Veneer Lumber	1.01
Large Dimension Softwood Lumber, kiln-dried	1.05
Modified Bitumen membrane	1.03
Mortar	1.15
MW Batt R11-15	1.05
Nails	1.03
Natural Stone	1.05
Paper Tape	1.05
Polyester felt	1.01
Polyiso Foam Board (unfaced)	1.05
Rebar, Rod, Light Sections	1.01
Roofing Asphalt	1
Screws Nuts & Bolts	1.03
Small Dimension Softwood Lumber, kiln-dried	1.08
Softwood Plywood	1.05
Solvent Based Alkyd Paint	1.02
Spruce Wood tongue and groove siding	1.1
Steel Plate	1.01
VR 1/2" Drainage Mat	1.02
VR 20 mil Root Barrier	1.02
Water Based Latex Paint	1.02

Material	Construction Waste Factor
Welded Wire Mesh / Ladder Wire	1.02
Wide Flange Sections	1.01
Wire Rod	1.01

Table 19: Scenarios – Maintenance (module B2)

Assembly/Building Element	Replaced Materials	Task Frequency (F_x)	Material Use % ($P_{x,y}$)	Source[a]
Exterior hollow metal doors	Solvent Based Alkyd Paint	10	100	1
Interior hollow metal doors	Solvent Based Alkyd Paint	4	100	1
Interior hollow wood doors	Water Based Latex Paint	4	100	1
Interior solid wood doors	Water Based Latex Paint	4	100	1

[a] 1 = Whitestone Maintenance and Repair Cost Reference

Table 20: Scenarios – Repair (module B3)

Assembly/Building Element	Replaced Materials	Task Frequency (F_x)	Material Use % ($P_{x,y}$)	Source[a]
Slab on grade	Concrete 4000 psi, 25% fly ash	15	2	1
	Rebar, Rod, Light Sections	15	2	1
	6 mil Polyethylene	15	2	1
	Extruded Polystyrene	15	2	1
Gypsum Board	5/8" Regular Gypsum Board	20	2	1
	Joint Compound	20	2	1
	Paper Tape	20	2	1
	Nails	20	2	1
Wood soffit	Spruce Wood tongue and groove siding	20	2	1
Aluminum cladding	Aluminum Cold Rolled Sheet	20	2	1
Curtain Wall	EPDM membrane	1	3.0	1
	Glazing Panel	1	3.0	1
	Screws Nuts & Bolts	1	3.0	1
Roof covering	GAF Everguard© white TPO membrane 60 mil	1	1.5	3
	Fiber Cement	1	1.5	3
	Polyiso Foam Board (unfaced)	1	1.5	3
	Modified Bitumen membrane	1	1.5	3
	1/2" Moisture Resistant Gypsum Board	1	1.5	3
	Extruded Polystyrene	1	1.5	3
	VR 1/2" Drainage Mat	1	1.5	3
	VR 20 mil Root Barrier	1	1.5	3
	Roofing Asphalt	1	1.5	3
	Coarse Aggregate Natural	1	1.5	3
	Polyester felt	1	1.5	3
Exterior aluminum	Aluminum Extrusion	12	12	1

Assembly/Building Element	Replaced Materials	Task Frequency (F_x)	Material Use % $(P_{x,y})$	Source[a]
and glass doors	Glazing Panel	12	12	1
	Nails	12	12	1
Exterior steel doors	Galvanized Sheet	17	15	1
	Solvent Based Alkyd Paint	17	15	1
	Expanded Polystyrene	17	15	1
	Nails	17	15	1

Table 21: Scenarios – Replacement (module B4)

Assembly/Building Element	Replaced Materials	Task Frequency (F_x)[a]	Material Use % $(P_{x,y})$	Source[b]
Slab on grade	Concrete 4000 psi, 25% fly ash	75	100	1
	Rebar, Rod, Light Sections	75	100	1
	6 mil Polyethylene	75	100	1
	Extruded Polystyrene	75	100	1
Gypsum Board	5/8" Regular Gypsum Board	75	100	1
	Joint Compound	75	100	1
	Paper Tape	75	100	1
	Nails	75	100	1
Cedar soffit	Spruce Wood tongue and groove siding	25	100	2
Aluminum cladding	Aluminum Cold Rolled Sheet	50	100	2
Curtain wall	Glazing panel	35	100	3
	EPDM membrane	35	100	3
	Glazing Panel	35	100	3
	Screws Nuts & Bolts	35	100	3
Roof covering	GAF Everguard© white TPO membrane 60 mil	20	100	3
	Fiber Cement	20	100	3
	Polyiso Foam Board (unfaced)	20	80	3
	Modified Bitumen membrane	20	100	3
	1/2" Moisture Resistant Gypsum Board	20	100	3
	Extruded Polystyrene	20	80	3
	VR 1/2" Drainage Mat	20	100	3
	VR 20 mil Root Barrier	20	100	3
	Roofing Asphalt	20	100	3
	Coarse Aggregate Natural	20	100	3
	Polyester felt	20	100	3
Ext. sliding glass door	Triple Glazed No Coating Air	50	100	1
	Aluminum Window Frame	50	100	1
Ext. steel doors	Galvanized Sheet	75	100	1
	Solvent Based Alkyd Paint	75	100	1
	Expanded Polystyrene	75	100	1
	Nails	75	100	1
Ext. overhead metal door	Galvanized Sheet	35	100	1
	Solvent Based Alkyd Paint	35	100	1
	Expanded Polystyrene	35	100	1

Assembly/Building Element	Replaced Materials	Task Frequency (F_x)[a]	Material Use % ($P_{x,y}$)	Source[b]
	Nails	35	100	1
Int. hollow metal doors	Galvanized Sheet (Tonnes)	75	100	1
	Solvent Based Alkyd Paint (L)	75	100	1
	Nails (Tonnes)	75	100	1
Int. hollow wood doors	Small Dimension Softwood Lumber, kiln-dried (m3)	30	100	1
	Nails (Tonnes)	30	100	1
	Water Based Latex Paint (L)	30	100	1
Int. solid wood doors	Small Dimension Softwood Lumber, kiln-dried (m3)	50	100	1
	Nails (Tonnes)	50	100	1
	Water Based Latex Paint (L)	50	100	1

[a] Please note that materials with task frequencies in excess of the reference study period are not replaced

[b] 1 = Whitestone Maintenance and Repair Cost Reference 2013-2014, 2 = Athena IE4B Database, 3 = Athena report *Maintenance, Repair and Replacement Effects for Building Envelope Materials* (2002)

Table 22: Scenarios – Annual Operational Energy Use (B6)

Energy[a] Type	Quantity	Unit
Natural Gas	122,514	m^3
Electricity	240,171	kWh

[a] The energy use presented is the net grid-supplied consumption, i.e. natural gas consumed by the district plant and grid electricity consumption.

Table 23: Scenarios – Annual Operational Water Use and Wastewater Discharge (B7)

End-use	From Municipal Water Supply (m^3)	To Municipal Wastewater (m^3)
Water Closets	903	903
Urinals	39	39
Showers	34	34
Lavatory Taps	100	100
Kitchen Taps	134	134
Total	**1,211**	**1,211**

Table 24: Scenarios – Demolition Energy Use (modules B2, B3, B4, C1)

Module	Diesel (L)
B2	0
B3	158
B4	74
C1	31,163

Table 25: Scenarios – Waste Outcomes (modules A5, B2, B3, B4, C3, C4)

Waste Type	To Reuse	To Recycling	To Energy Recovery	To Landfill	To Inciner-ation
Steel - rebar & fasteners		70.0%		30.0%	
Steel - all other steel products		98.0%		2.0%	
Aluminum		95.0%		5.0%	
Concrete		60.0%		40.0%	
Wood[a]		10%		80%	10%
Aggregate[b]	50.0%				
All other materials				100.0%	

[a] These assumptions are likely very conservative estimates for CLT and glulam members

[b] 50% of aggregate assumed to be left on site

Table 26: Scenarios – Waste Transport (modules A5, B2, B3, B4, C2)

Transportation Type	Rail, diesel (km)	Barge, residual fuel oil (km)	Road Short Haul, diesel (km)	Road Long Haul, diesel (km)
Secondary steel: site to waste processing	99	534	0	753
All materials: site to sorting plant	0	0	32	0
All materials: sorting plant to landfill/incineration	0	0	8.5	0

Table 27: Scenarios – Module D Assumptions

Material	Secondary Material (kg/kg product used)	Recovery Rate (kg/kg product used)	Net Output Flow[a] (kg/kg product used)
Steel Products			
Bolts, Fasteners, Clips	1.020	0.70	-0.320
Cold Rolled Sheet	0.177	0.98	0.803
Galvanized Sheet	0.439	0.98	0.541
Galvanized Sheet	0.439	0.98	0.541
Galvanized Studs	0.439	0.98	0.541
Hollow Structural Steel	0.838	0.98	0.142
Nails	1.020	0.70	-0.320
Rebar, Rod, Light Sections	1.020	0.70	-0.320
Screws Nuts & Bolts	1.020	0.70	-0.320
Steel Plate	1.020	0.98	-0.040
Wide Flange Sections	1.020	0.98	-0.040
Wire Rod	1.020	0.70	-0.320
Aluminum Products	0.000	0.60	0.600
Extrusions	0.426	0.95	0.524
Cold Rolled Sheet	0.649	0.95	0.301
Concrete	0.000	0.60	0.600

[a] negative value indicates that the system is a net consumer of secondary material

Table 28: Scenarios – Wood Product Biogenic Carbon Assumptions

Wood Product	Oven dry mass (kg/m^3)[a]	Wood species	Carbon content of wood (%)[b]
Cross Laminated Timber	378	Spruce	50.39%
Glulam Sections	470	D. Fir	50.50%
Laminated Veneer Lumber	446	?	50.00%
Large Dimension Softwood Lumber, kiln-dried	378	S-P-F	50.00%
Small Dimension Softwood Lumber, kiln-dried	378	S-P-F	50.00%
Softwood Plywood	404	D. Fir	50.50%

[a] source: WoodWorks Carbon Calculator

[b] source: FPInnovation Carbon Tool B2C v2.18

Table 29: Scenarios – Concrete Carbonation Assumptions

Carbonation Parameter	Value
s factor	1
b factor	1.05
k factor	
Wet/submerged	0.75
Buried	1
Exposed	1.5
Sheltered	4
Indoors	6
$c_{4000\ PSI}$ (kg/m3)	313.7
$c_{5000\ PSI}$ (kg/m3)	395.6

Table 30: Scenarios – Particle Size Distribution of Crushed Concrete

Particle size (mm)	Proportion	Average radius (mm)
19-26.5	1%	11.375
13.2-19.0	11%	8.05
9.5-13.2	13%	5.675
4.75-9.5	22%	3.5625
2.36-4.75	12%	1.7775
0.425-2.36	22%	0.69625
0.075-0.425	12%	0.125
<0.075	6%	0.0375

Source: Collins

Appendix E: LCI Data Source Tables

Table 31: Data Sources Summary

LCI Data	Time Frame[a]	Geographical Represent-ativeness	Information Modules	Database Source
Common fossil fuels	2004-2008	North America	All	US LCI
Electricity generation and delivery	2004-2012	North America, Massachusetts	All	US LCI
Transportation	2004-2010	North America	All	US LCI
Softwood lumber, LVL, plywood	2012	USA	A1, A3, B2, B3, B4	Athena LCI
Cross laminated timber	2013	USA	A1, A3, B2, B3, B4	Athena LCI
Glulam	2012	USA	A1, A3, B2, B3, B4	Athena LCI
Spruce siding	2004	USA	A1, A3, B2, B3, B4	Athena LCI
Aluminum products	2014	North America	A1, A3, B2, B3, B4	Athena LCI
Steel products	2011, 2013	North America, USA	A1, A3, B2, B3, B4	Athena LCI
Ready-mix concrete	2014	USA	A1, A3, B2, B3, B4	Athena LCI
Mortar	2004	USA	A1, A3, B2, B3, B4	Athena LCI
Gypsum board products	2012	USA	A1, A3, B2, B3, B4	Athena LCI
Joint compound and paper tape	1997	USA	A1, A3, B2, B3, B4	Athena LCI
Fibreglass and mineral wool batt insulation	2012	USA	A1, A3, B2, B3, B4	Athena LCI
Polyisocyanurate insulation	2011	USA	A1, A3, B2, B3, B4	Athena LCI
Extruded and expanded polystyrene insulation	2007	USA	A1, A3, B2, B3, B4	Athena LCI
Glazing	2013	USA	A1, A3, B2, B3, B4	Athena LCI
Polyethylene vapor retarder	2010	USA	A1, A3, B2, B3, B4	Athena LCI
Modified bitumen membrane	2013	USA	A1, A3, B2, B3, B4	Athena LCI
TPO membrane	2013	USA	A1, A3, B2, B3, B4	Athena LCI
Roofing asphalt	2001	USA	A1, A3, B2, B3, B4	Athena LCI
Drainage Mat, root barrier	2013	USA	A1, A3, B2, B3, B4	Athena LCI
Fiber Cement	2009	USA	A1, A3, B2, B3, B4	Athena LCI
Water based latex, solvent based alkyd paint	1999	USA	A1, A3, B2, B3, B4	Athena LCI
Coarse aggregate	2004	USA	A1, A3, B2, B3, B4	Athena LCI
Water supply and waste water plants	2005, 2009	World (excluding Europe), adjusted to Massachusetts	B7	Ecoinvent LCI
Steel scrap preprocessing	2013	North America	C3	Athena LCI
Landfilling and incineration	2012-2014	Quebec, adjusted to Massachusetts	C4	Ecoinvent LCI

LCI Data	Time Frame[a]	Geographical Represent-ativeness	Information Modules	Database Source
Steel scrap value	2011	North America	D	Athena LCI
Aluminum scrap value	2014		D	
Concrete crushing	2005		D	

[a]"Time Frame" is the period between the known initiation of data and its final update and/or validation

Table 32: LCI Data Substitutions

Material	Athena LCI Database Substitution(s)
Foundation waterproof membrane	Modified Bitumen membrane
Weldable rebar	Rebar, Rod, Light Sections
HSK connectors	Hot Rolled Sheet
Laminated strand lumber	Laminated Veneer Lumber
Aluminum plate rainscreen	Aluminum Cold Rolled Sheet
Spray foam insulation	Polyiso Foam Board (unfaced)
Wall membrane air/vapor barrier	Modified Bitumen membrane
Fire treated plywood	Softwood Plywood
Tongue and groove soffit	Spruce Wood tongue and groove siding
Breather membrane (soffit)	Modified Bitumen membrane
Reinforced hot rubberized asphalt roof membrane	Roofing Asphalt
	Coarse Aggregate Natural
	Polyester felt
Roof vapor retarder	Modified Bitumen membrane
Roof board underlayment	1/2" Moisture Resistant Gypsum Board
1" shaft liner	5/8" Fire-Rated Type X Gypsum Board
Curtain wall, skylights	Aluminum Extrusion
	EPDM membrane (black, 60 mil)
	Glazing Panel
	Screws Nuts & Bolts
Exterior glazed aluminum doors	Aluminum Extrusion
	Glazing Panel
	Nails
Exterior glazed metal doors	Expanded Polystyrene
	Galvanized Sheet
	Glazing Panel
	Nails
	Solvent Based Alkyd Paint

Material	Athena LCI Database Substitution(s)
Exterior hollow metal doors	Galvanized Sheet
	Solvent Based Alkyd Paint
	Expanded Polystyrene
	Nails
Exterior overhead metal door	Galvanized Sheet
	Solvent Based Alkyd Paint
	Expanded Polystyrene
	Nails
Interior Glazing	Glazing Panel
	Aluminum Extrusion
	Nails
Interior hollow metal doors	Galvanized Sheet
	Solvent Based Alkyd Paint
	Nails
Interior hollow wood doors	Small Dimension Softwood Lumber, kiln-dried
	Water Based Latex Paint
	Nails
Interior solid wood doors	Small Dimension Softwood Lumber, kiln-dried
	Water Based Latex Paint
	Nails

Appendix 2—LEED Whole Building LCA Credit Submittal

General Assessment Information

The purpose of this report is to provide information required for on-line submittal for **LEED v4 Materials and Resources credit "Building life cycle impact reduction" Option 4**. Whole-building life-cycle assessment.

The results of this assessment have been generated by *the Impact Estimator for Buildings* software. Please refer to the *Athena Guide to Whole-building LCA in Green Building Programs* for useful guidance on how to complete the credit.

*Provide the following **general information** on the assessment*	
Project Name	UMass Amherst Design Building
Assessor	Matt Bowick, Senior Research Associate, Athena Sustainable Materials Institute
Verifier (optional)	Jamie Meil, Research Principal, Athena Sustainable Materials Institute ☑ Internal ☐ External
Date of assessment	December 2016
Assessment timing	☐ Schematic Design ☑ Construction ☐ Design Development ☐ Operations & Maintenance ☐ Construction Documents ☐ End of Life

Whole-building LCA Results

Life Cycle Assessment Impact Measures	Baseline Building	Proposed Building	Units	Percent Difference (%)
Global warming potential	4,612,572	4,009,240	kg CO2 eq	-13.1%
Stratospheric ozone depletion	8.53E-02	7.67E-02	kg CFC-11 eq	-10.1%
Acidification of land and water	23,883	21,755	kg SO2 eq	-8.9%
Eutrophication	1,378	1,378	kg N eq	0.0%
Tropospheric ozone formation	382,026	368,320	kg O3 eq	-3.6%
Depletion of non-renewable energy resources	56,492,129	48,143,200	MJ	-14.8%
Number of measures with at least 10% reduction *(a reduction corresponds to a negative value percent difference)*				3

Values in "Percent Difference" column corrected May 2018.

LEED Whole-building LCA Credit Submittal 2

Assessment Scope

*Describe the **functional equivalent** of the buildings assessed*	
Building type (optional)	Educational
Technical and functional requirements (optional)	Massachusetts Base Code (8th edition); LEED Gold certified (pending)
Pattern of use (optional)	Typical for the functions provided, 82 full-time equivalent (FTE) building occupants (74 full-time, 8 part-time); 1,000 daily average transients, 384 peak transients
Required service life (optional)	60 years assumed (no defined required service life)
Other information (optional)	

*Select which construction elements are included in the **object of assessment**.*

☑ A1010 Standard Foundations	☑ B2010 Exterior Walls	☐ C1020 Interior Doors
☑ A1020 Special Foundations	☑ B2020 Exterior Windows	☑ C2010 Stair Construction
☑ A1030 Slab on Grade	☑ B2030 Exterior Doors	☐ C2020 Stair Finishes
☑ A2020 Basement Walls	☑ B3010 Roof Coverings	☐ C3010 Wall Finishes
☑ B1010 Floor Construction	☑ B3020 Roof Openings	☐ C3020 Floor Finishes
☑ B1020 Roof Construction	☐ C1010 Partitions	☐ C3030 Ceiling Finishes

*Select which information modules are included in the assessment **system boundary***

☑ A1 Raw material supply	☑ B2 Maintenance	☑ C1 De-construction demolition
☑ A2 Transport	☑ B3 Repair	☑ C2 Transport
☑ A3 Manufacturing	☑ B4 Replacement	☑ C3 Waste Processing
☑ A4 Transport	☐ B5 Refurbishment	☑ C4 Disposal
☑ A5 Construction-installation process	☐ B6 Operational Energy	
☐ B1 Use	☐ B7 Operational Water	

LEED Whole-building LCA Credit Submittal 3

Building Descriptions

*Provide a summary description of the **proposed building**. Describe the size, function, orientation and operating energy performance.*

The building of study is the University of Massachusetts Amherst Design Building, a four-storey, 8,147 m^2 (87,573 ft^2), structure located at 551 North Pleasant Street, Amherst, Massachusetts. The building footprint is approximately square and oriented along Stockbridge Way (A road ±15º counter clockwise of North-South).

The Design Building will be home for the University's Architecture + Design, Building and Construction Technology, Landscape Architecture, and Regional Planning departments, and includes various educational spaces (classrooms, studios, labs, lounges, seminar and conference rooms, wood shop) for students, and office space.

The Design Building is intended exemplify the University's commitment to sustainable and innovative design via its LEED Gold certified design (pending) and demonstration of emerging wood construction technologies.

The building's structural system consists of cross laminated timber (CLT) roof panels, composite CLT floor panels with reinforced concrete topping (second through fourth floors), reinforced concrete slabs (ground floor), and reinforced slab on grades, and a mix of glulam and structural steel framing. The building's lateral resistance is provided by the elevator and stair core CLT wall panels, and glulam X-bracing. A zipper truss system consisting of glulam members and steel rods supports the low roof courtyard.

The building's perimeter is supported by concrete basement walls on strip footings; columns along the perimeter are supported by piers integrated into the basement walls (i.e. wall thickenings) and pad footings, whereas interior columns are supported by concrete columns/piers at the basement level and pad footings.

Double-glazed, low-E insulating glass curtain wall with 1.65 W/m2 °C U-value (0.29 Btu/hr-ft2-°F) and solar heat gain coefficients (SHGC) of 0.27-0.38 make up approximately 58% of the building's perimeter walls. The building is otherwise clad in bluestone veneer (between grade and the ground floor), and aluminum panel rainscreen (above the ground floor) with steel stud wall back up – these walls generally have a 4.30 RSI value (R-value of 24.4). The roof envelope generally consists of a TPO membrane assembly with 8.38 RSI value (R-value of 47.6).

Partitions are for the most part light gauge steel stud walls with fibreglass batt sound attenuation insulation and 16 mm gypsum board (not included in this assessment).

The building draws on *UMass Amherst Campus Central Utility Plant* for hot water, chilled water and some of the electricity consumed. Other building integrated technologies have been employed to reduce energy demand, including:

- Lighting Power Densities reduced below ASHRAE 90.1-2007 with occupancy sensors

in select perimeter office spaces;
- Automatic daylight dimming controls in perimeter spaces;
- Air-side supply air reset temperature;
- Dual Enthalpy economizers on air handling units; and
- Energy Recovery Ventilators on the Dedicated Outdoor Air System (DOAS).

The material quantities of the Proposed Building were calculated by the LCA assessor, October 2016.

*Provide a summary description of the **baseline building**.* Describe how the baseline building is of comparable size, function, orientation, and operating energy performance to the proposed building

The Baseline Building has the same size, functions, and orientation as the Proposed Building.

The Baseline Building design reflects more conventional construction, and differs from the Proposed Building in the following ways:
- The building's foundation (A1010), and floor (B1010) and roof structure (1020) (including floor plates, columns & beams, stair and elevator walls, and lateral load resisting system), and stair construction (C2010) come from the Design Development phase of the project, prior to the decision to switch to a more wood products based structural design. This design includes the use of metal deck with concrete topping floors supported by steel framing, and concrete elevator and stair walls. The foundation employs the same scheme, but was designed for this structure's dead loads. Material quantities were taken from the cost report produced by VJ Associates, dated September 4, 2014.
- Average concrete "benchmark" mixes were assumed
- The building is assumed to be clad in brick veneer, and a thermally comparable amount of polyisocyanurate board insulation (2 1/2" of polyisocyanurate insulation vs. 4" mineral wool insulation) was substituted in the exterior walls.

The operating energy performance of the Baseline Building is assumed to be essentially the same as the Proposed Building since [1] the thermal resistance of the exterior walls was maintained relative to the Proposed building, [2] all other envelope assemblies are the same as the Proposed Building, and [3] the Baseline Building has the same size, functions, orientation, and assumed mechanical systems as the Proposed Building.

Special Circumstances

Describe the circumstances limiting the project team's ability to provide the submittals required. Be sure to reference what additional documentation has been provided, if any. Non-standard documentation will be considered upon its merits. (optional)

No special circumstances to report.

LCA Software Summary

General Information	
Report template generated by	Athena Impact Estimator for Buildings
Software version	5.1.0102
Date this report was created	December 7, 2016

The Athena Sustainable Materials Institute certifies that the *Impact Estimator for Buildings* LCA software tool is fully compliant with the requirements of the LEED v4 whole-building life cycle assessment credit.

Software Data Sources	
Life Cycle Scenarios	Scenarios used in this assessment come from databases maintained by the Athena Sustainable Materials Institute.
Life Cycle Inventory (LCI)	LCI data used in this assessment is from the Athena LCI database and is compliant with ISO 14040 and ISO 14044.
Life Cycle Impact Assessment (LCIA) method	TRACI v2.1

See the software's *User Manual and Transparency Document* for further information on data sources.

LCA Software Inputs

Project Information	**Baseline Building**	**Proposed Building**
Project Location	USA	USA
Units	SI	SI
Building Type	Institutional	Institutional
Building Life Expectancy	60	60
Building Height (ft or m)	16.6	16.6
Gross floor area (ft^2 or m^2)	8,146	8,146

LEED Whole-building LCA Credit Submittal 6

Building Bill of Materials	Unit	Baseline Building	Proposed Building
1/2" Moisture Resistant Gypsum Board	m2	4673.928	4673.928
5/8" Regular Gypsum Board	m2	3658.339	3658.339
6 mil Polyethylene	m2	5509.233	5509.233
Aluminum Cold Rolled Sheet	Tonnes	0.000	12.099
Aluminum Extrusion	Tonnes	36.923	36.923
Bolts, Fasteners, Clips	Tonnes	0.001	0.868
Coarse Aggregate Crushed Stone	Tonnes	836.474	836.474
Coarse Aggregate Natural	Tonnes	15.112	15.112
Cold Rolled Sheet	Tonnes	0.429	0.074
Concrete 4000 psi, 25% fly ash	m3	0.000	684.780
Concrete 5000 psi, 25% fly ash	m3	0.000	2055.660
Concrete Benchmark 4000 psi	m3	744.466	0.000
Concrete Benchmark 5000 psi	m3	2360.956	0.000
Cross Laminated Timber	m3	0.000	1601.986
EPDM membrane (black, 60 mil)	kg	968.663	968.663
Expanded Polystyrene	m2 (25mm)	85.634	4474.421
Extruded Polystyrene	m2 (25mm)	13036.494	13929.339
Fiber Cement	m2	9347.856	9347.856
GAF Everguard© white TPO membrane 60 mil	m2	8752.992	8752.992
Galvanized Decking	Tonnes	162.365	0.828
Galvanized Sheet	Tonnes	1.712	1.712
Galvanized Studs	Tonnes	20.545	20.545
Glazing Panel	Tonnes	199.526	199.526
GluLam Sections	m3	7.121	562.308
Hollow Structural Steel	Tonnes	68.655	47.374
Hot Rolled Sheet	Tonnes	0.000	9.031
Joint Compound	Tonnes	1.813	1.813
Laminated Veneer Lumber	m3	0.000	3.561
Large Dimension Softwood Lumber, kiln-dried	m3	0.000	14.869
Metric Modular (Modular) Brick	m2	2254.836	0.000

LEED Whole-building LCA Credit Submittal 7

Building Bill of Materials	Unit	Baseline Building	Proposed Building
Modified Bitumen membrane	kg	4012.645	4153.383
Mortar	m3	59.227	10.176
MW Batt R11-15	m2 (25mm)	0.000	7619.779
Nails	Tonnes	0.131	0.531
Natural Stone	m2	0.000	387.408
Paper Tape	Tonnes	0.021	0.021
Polyester felt	Tonnes	0.046	0.046
Polyiso Foam Board (unfaced)	m2 (25mm)	55003.337	50240.975
Rebar, Rod, Light Sections	Tonnes	200.577	214.573
Roofing Asphalt	kg	5148.587	5148.587
Screws Nuts & Bolts	Tonnes	2.894	7.821
Small Dimension Softwood Lumber, kiln-dried	m3	24.031	24.031
Softwood Plywood	m2 (9mm)	156.386	1369.943
Solvent Based Alkyd Paint	L	35.886	35.886
Spruce Wood tongue and groove siding	m2	189.356	189.356
Steel Plate	Tonnes	59.615	127.396
VR 1/2" Drainage Mat	m2	2431.300	2426.147
VR 20 mil Root Barrier	m2	1172.167	1172.167
Welded Wire Mesh / Ladder Wire	Tonnes	35.108	21.475
Wide Flange Sections	Tonnes	492.233	103.780
Wire Rod	Tonnes	5.449	6.976

Instructions and Notes

Complete this document and use it for all the upload requirements in LEED on-line. We suggest the entire document be used for each upload request.

Whole-building LCA results
This table rounds all values to two decimal places because the LEED on-line form has that limit. This will typically impact stratospheric ozone depletion results, as those values are often extremely small and will turn to zero when truncated to two decimal places.

The values shown in this table are in units that are consistent with the TRACI LCA methodology. The LEED on-line form may use different units. Note that units are not a factor for the percent difference calculation and hence they are meaningless for the LEED on-line form. If there is a mismatch, we suggest ignoring the units and simply entering the values. However, if necessary, convert tropospheric ozone depletion from O_3 to C_2H_4 with this formula: kg O_3 eq / 0.28065 = kg C_2H_4.

Object of Assessment
This table defaults with a checkmark for all the elements required for compliance with the credit. Unchecked elements are optional. Check those boxes if those elements were included.

System Boundary
This table defaults with a checkmark for all the modules required for compliance with the credit. Note that module B1 is currently not applicable, as there is inadequate data to support it at the moment in the Impact Estimator. Note that module B3 is also not currently well-supported with data. Note that module B5 is only addressed if there is a definitive future plan for refurbishment; typically, there is none and therefore this module typically has zero impacts. If there are known impacts in these modules, they should be added to the Impact Estimator results.

For further detail on methods and data in the Impact Estimator, see the User Manual and Transparency Document.

Have feedback for how we can improve this report? Tell us! mailto:info@athenasmi.org

Appendix 3—EBD Summary Print-Ready Poster and Brochure

Environmental Building Declaration Summary
Design Building, University of Massachusetts, Amherst

Athena Sustainable Materials Institute

About this Summary

The data shown here reports the lifetime environmental footprint of this building. Results were calculated using an analytical technique known as life cycle assessment (LCA), a scientific method for assessing all the interactions between a building and nature and estimating the resultant burdens on air, land and water. Additional results for this building are transparently reported in a detailed and publically-available Environmental Building Declaration. The Athena Institute performs LCA in accordance with the international standards ISO 14040 and 14044. The Environmental Building Declaration conforms to Athena's North American interpretation of the EN 15978 standard, which specifies how LCA is to be performed and reported for buildings.

Life Cycle Results

Environmental Indicator	*Unit*	*Per m²-year*
TRACI v2.1 Environmental Impacts		
Global warming potential	kg CO_2 eq.	6.34E+01
Depletion potential of the stratospheric ozone layer	kg CFC-11 eq.	1.65E-07
Acidification potential of land and water	kg SO_2 eq.	5.10E-01
Eutrophication potential	kg N eq.	1.22E-02
Formation potential of tropospheric ozone photochemical oxidants	kg O_3 eq.	2.28E+00
Abiotic resource depletion potential for elements	kg Sb eq.	xx
Abiotic resource depletion potential of fossil fuels	MJ surplus	1.42E+02
Resource Use		
Renewable primary energy excluding energy resources used as raw material	MJ	2.52E+01
Renewable primary energy resources used as raw material	MJ	4.16E+01
Non-renewable primary energy excluding resources used as raw material	MJ	1.09E+03
Non-renewable primary energy resources used as raw material	MJ	3.68E+00
Secondary material	kg	1.41E+00
Renewable secondary fuels	MJ	xx
Non-renewable secondary fuels	MJ	xx
Net use of fresh water	m^3	1.84E-01
Waste Categories		
Non-hazardous waste disposed	kg	1.11E+01
Hazardous waste disposed	kg	xx
Radioactive waste disposed	kg	xx
Output Flows		
Components for re-use	kg	0.00E+00
Materials for recycling	kg	9.49E+00
Materials for energy recovery	kg	0.00E+00
Exported energy	MJ	0.00E+00

xx = inadequate data for assessment

Date of Assessment
December 2016

Assessor
Matt Bowick, Athena Institute

Verifier
Jamie Meil, Athena Institute

Life Cycle Impact Assessment Method
TRACI v2.1, Cumulative Energy Demand (CED)

Scope of Assessment
- Cradle-to-grave assessment with a 60-year study period
- All major building materials for core, shell and interior partitions are included
- Finishes, landscaping materials, furnishings and mechanical/electrical equipment are excluded
- Operating energy and water are included
- System boundary includes EN 15978 modules A1-C4 with the exception of B1 and B5, due to inadequate scenario data for those modules at the time of the study

Data Sources
- Athena Institute life cycle inventory database
- US life cycle inventory database
- ecoinvent life cycle inventory database
- Project-specific data provided by the design team

References

EN 15978:2011 Sustainability of construction works — Assessment of environmental performance of buildings — Calculation method.

ISO 14040: 2006 Environmental management — Life cycle assessment — Principles and framework.

ISO 14044: 2006 Environmental management — Life cycle assessment —– Requirements and guidelines.

Full Report
"Design Building, University of Massachusetts, Amherst: An Environmental Building Declaration According to the EN 15978 Standard." Athena Sustainable Materials Institute, January 2017. Available on the Athena Institute web site.

www.AthenaSMI.org