Teaching Building Life Cycle Assessment: LCA in Architecture & Engineering Education

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ABSTRACT
Architects are under increasing pressure to deliver high quality, high performance buildings and to be able to quantify, assess and reduce the environmental impact of their designs. The data and methods of Life Cycle Assessment (LCA) can provide information and structure to architects and engineers looking to achieve these goals. While building industry specific tools exist, challenges remain in integrating LCA into building design and construction practice. LCA provides a framework to develop both quantitative and qualitative understanding of the impacts of building materials, components and construction over the full life cycle and thus is a valuable for use in architectural education. Four courses offered from departments of architecture are presented to demonstrate a range of analysis types and design integration appropriate for advanced professional architecture students. Three courses within engineering curriculum provide a broader context of LCA education representing courses appropriate for architecture students and/or that directly address buildings. The opportunities and challenges of both current LCA practice and integrating LCA into design education are presented and strategies to implement and address these issues are outlined. Additionally, these class projects can be seen as research exploring the most effective methods to integrate LCA into design and construction practice. Given the scale of the economic, social, and environmental challenges we currently face, an active integration between teaching and research is appropriate if we are to help advance significant and timely improvements to our industry.

KEYWORDS

Pedagogy, sustainability, design, research, life cycle assessment, construction, materials

INTRODUCTION

Architects are under increasing pressure to deliver high quality, high performance buildings and to be able to quantify, assess and reduce the environmental impact of their designs. Architectural educators must adapt teaching methods to reflect the changing needs and conditions of contemporary practice and ensure the emerging generation of architects are prepared and empowered to lead under increasingly challenging economic, social, and environmental conditions.

Significant innovations are needed to advance a more sustainable built environment. Architectural students must understand the complexity of global environmental challenges, evaluate and integrate technical criteria and work effectively with diverse teams. As educators, a key challenge is to find the appropriate balance between technical specificity and design context to engage and empower the broadest spectrum of architecture students possible. Teaching must be intuitive enough to enable effective design integration as well as rigorous enough to be a basis for advanced study and practice.

This paper explores how the use of Life Cycle Assessment (LCA) methodology can provide both the context and technical details needed to engage students in the challenge of assessing and designing for a lower environmental impact built environment. The method and history of LCA is introduced, case studies in both engineering and architectural education are presented, and opportunities and challenges of integrating LCA into curriculum are identified and discussed.

LIFE CYCLE ASSESSMENT

Life Cycle Assessment (LCA) is a method of tracking environmental (and also economic and social) impacts, over the full life cycle from 'cradle' to 'grave' (and ideally back to cradle again) of a product or process. ISO standards have been developed to define the requirements of 'compliant' LCAs[2]. The basic steps included in a LCA include:

1. Goal and scope definition: Establishing the amount and timeframe of production and the industrial processes to be included in the studied system and ignored is a critical first step and understanding this is essential to be able to understand and interpret results of an LCA.

A core principle of life cycle assessment is the 'functional unit' which defines a process or product based on function and must include measures of quality and time. Thus if analyzing siding, the functional unit could be 1 square meter of finished material that met appropriate ASTM performance standards for a 50 year building life. The impacts of maintenance and replacement would thus need to be included in the LCA.

2. Inventory analysis: Quantifying the material and energy flows of the studied system over the full life cycle, extending from materials acquisition (e.g., mining and agriculture) through construction, use, and demolition. These inventories can be created from primary data (actual quantities and measured energy use), predicted by analysis or estimated by industry experts or LCA practitioners.

3. Impact assessment: Characterizing the environmental, economic, and social impacts associated with the materials and energy use and waste identified in the inventory analysis such as the contributions to resource depletion (e.g., energy, water, land, employment opportunities), climate change, acidification, and changes in human and ecosystem health.

4. Interpretation: Evaluating the results of the LCA, providing context to the data. This includes identifying the processes that were the primary contributors to the major identified impacts, an assessment of data quality and impacts of uncertain data on the uncertainty of the final conclusions and/or comparing the results either between alternates or in relationship to established data points (e.g. 10% of total U.S. emissions).

The rigorous methods and data behind a LCA provide a clear framework to understand and communicate the impacts of a process or product and therefore is useful in teaching both the conceptual underpinnings of sustainability in life cycle design and the technical conditions and criteria that must be understood to effectively evaluate and integrate LCA data into design. LCA provides a framework for incorporating a broad spectrum of environmental impacts from all phases of a buildings life into the evaluation of buildings, systems and materials.

History

LCA methodology was developed from efforts to evaluate and improve manufacturing processes of products. In the 1960's Coca-Cola commissioned research to investigate different packaging options[1]. In the 1970's, energy assessments in light of the energy crisis brought forward the importance of inter-sector/ supply chain relationships in conservation and national efficiency. These efforts became the technical foundation for the development of International Standards Organization LCA standards in the 1990's (ISO 14000 series[2]), which is the current baseline standard for most LCAs. Originally designed to support process and system innovation, the standards have been expanded to provide guidance on creating Environmental Product Declarations (EPDs)[3] enabling comparison between two products[4].

Building LCAs

Buildings can be seen as a complex product and thus LCA has been used to analyze and assess the environmental impacts of all phases of a building life from material extraction, manufacturing[5], construction[6], operation, maintenance and end of life[7]. Building industry specific tools and databases[8] (e.g., BEES[9], ATHENA[10] and GaBi BuildIt[11]) have been created and research has been done regarding the comparison between different building systems such as comparing steel, wood and concrete construction[12]. Additionally, global LCA databases and tools can be utilized to analyze building materials, components and full buildings.

Nearly half of the energy consumption and greenhouse gas emissions in the U.S. have been attributed to the building sector.[13] While the majority of this is results from the operating (heating, lighting etc) of buildings, the energy and environmental impacts embodied in the materials, transportation and effort of construction are significant- 5% to 8% of total annual U.S. energy consumption.[14]

Designers, owners and policy makers are increasingly looking to use LCA methods and data to assess, report and reduce the impacts of the built environment, currently with a focus on climate change above all other impacts. Architecture 2030's original 2030 Challenge calling to reduce the operational impact of buildings has just been supplemented with the 2030 Challenge for Products[15] calling for manufactures to provide LCA data and for designers to specify products that meet increasingly stringent carbon footprint standards. The Washington State legislature is currently considering a bill to require LCA to be completed during the design process of all major public buildings[16]. The USGBC has initiated a LCA into LEED pilot credit looking to 'connect the real-world application of the LEED rating systems to the evolving field of life-cycle assessment'[17]. Expanding the pool of architects and engineers who understand the philosophy, strengths and weaknesses of LCA is critical in order to ensure that proposals such as these can be implemented efficiently and effectively.

CASE STUDIES

Presented here are case studies of courses using LCA methods taught in Departments of Architecture, Civil and Mechanical Engineering at the Universities of Washington, Oregon and British Columbia. The first four courses presented are offered within departments of Architecture and thus are designed to address the specific needs of architecture students. The other courses are offered through engineering departments and either specifically focus on the built environment or are interdisciplinary and have included architecture students. In each case the course description, objectives, and integration of LCA are provided here. A summary of data, method and tools used in each course is summarized in a table at the end of this section.

Integrated Practice Studio

K. Simonen, C. Dossick & R. Pena
University of Washington

The Integrated Practice Studio (ARCH/CM 404) is an upper level undergraduate design studio that includes architecture and construction management (and sometimes engineering) students at the University of Washington. The primary objective of the course is to model Integrated Project Delivery (IPD) methods with students expected to bring disciplinary knowledge in design, energy modeling, cost estimating and construction and scheduling to develop an integrated design and construction proposal in collaborative teams.

Offered for three consecutive years, the course has historically included the integration of energy use and passive design strategies. In the winter of 2011, LCA methodology was introduced to the class and students were expected to evaluate design options using life cycle thinking and create a LCA report of their final proposal following an outline of ISO standards. Construction management students had prior exposure to life cycle costing and were encouraged to explore opportunities to integrate cost and environmental impact. Architecture students brought understanding of operational energy use and an ability to develop simplified project specific energy use models

Early in the design process students evaluated the embodied and operational impacts of their proposed designs (using the Athena EcoCalculator and the Energy Star Target Finder). In tandem with the development of the designs, the students created building specific energy performance models and tested environmental, cost and aesthetic impacts of design options. This exercise helped the students understand the dominant impacts of operational energy and provided an additional metric by which to compare and select materials and systems. Student teams were expected to document their exploration of design alternatives and include a consideration of cost, schedule, design and environmental impact. The LCA results were most interesting in the alternate assessment as students were required to act upon data that indicated contradictory results. The imprecision of both the embodied and operational energy analysis efforts made comparisons between final results within the studio more difficult to assess.

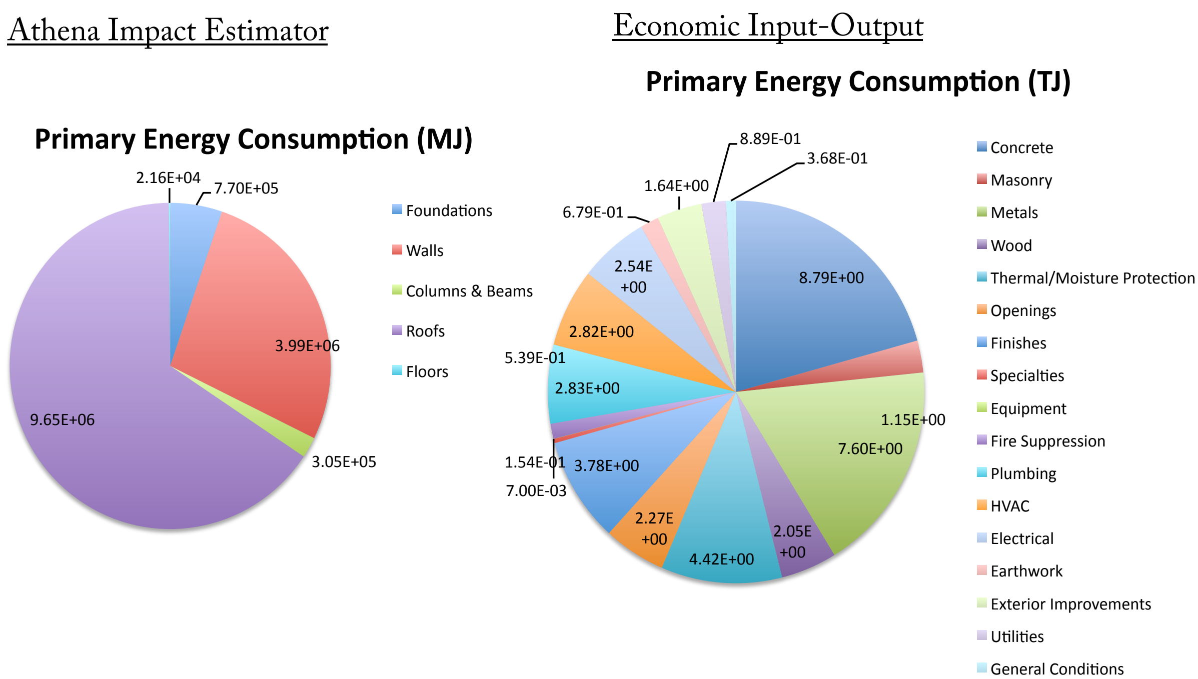

Figure 1: Comparison between process based and economic input-ouput methods of analyzing embodied primary energy consumption of fire station. By J. North in 2011 Structuring Efficiency seminar.

Structuring Efficiency
K. Simonen at University of Washington

Structuring Efficiency (ARCH 498V) an upper division/graduate seminar that includes architecture, structural engineering and construction management students. The course is designed to integrate a whole building life cycle approach with a focus on understanding and reducing the environmental the impacts of structural materials and systems. Students are introduced to the technical underpinnings of LCA data and methods and use established LCA tools to evaluate and assess building design options. Students in the first iteration of the class (2010) developed individually directed projects exploring the relationship between structural performance and environmental impact. The 2011 course will use existing buildings as case studies. Documentation (including construction drawings, cost estimates and energy use/modeled data) has been assembled for notable projects and students will work in teams to evaluate the project as designed, propose and explore the opportunity to reduce overall environmental impact using alternate structural systems or materials.

Students will be expected to produce LCA of their building that follows ISO standards and be able to evaluate and critique the data used in generating their LCA. Student teams will use multiple methods and tools to develop a comparative set of inventory and impact assessment data. These results will enable teams to compare the relative effort and precision of these methods and is expected to provide interesting opportunities for discussion surrounding the uncertainty included in a typical LCA. Reports will be prepared to share with the firms who have provided the data. The research effort of the students will be used as a pilot project to advance more focused research evaluating LCA tools and methods and developing recommendations for integration into practice.

Ecology of Building Materials
E. Moore at University of Oregon

The research seminar Ecology of Building Materials (ARCH 4/507) is an advanced technology elective seminar in the Architecture Department at the University of Oregon developed and taught by Assistant Professor Erin Moore. The course is meant to introduce students to the environmental context of the extraction, manufacture, use, and disposal of construction materials.

The seminar begins at the end of the life of buildings with a visit from a construction waste management expert at the Oregon Department of Environmental Quality and with a (somewhat overwhelming) visit to a local Material Recovery Facility (MRF) where construction waste roll offs are sorted. During these first weeks, students are also introduced to basic principles of LCA with an emphasis on impact indicators, and on particular topics in lifecycle thinking in buildings such as design for disassembly.

Wohnsidlung in Chantepie (Residential development in Chantepie, France)
Architect: Eric Lenoir, Charleville-Mezieres

Key	Material in Wall Section	Volume Calculations: thickness (mm)	thickness (m)	length (m)	height (m)	volume (m3)	total kg	Environmental Impact Categories and Calculations: Embodied Energy (MJ)	Water Resources (litres)	GWP (g CO2-equ./kg)	AP (g SO2-equ)
1	Corrugated steel sheet, galvanized	39	0.039	4.278	1.000	0.1668	1251.3	31282.9	4254471.0	2752893.0	12513.
3	Thermal insulation, rock wool	110	0.11	3.5	1.000	0.3850	28.9	577.5	39270.0	50242.5	288.
4	Steel sheet, galvanized	3	0.003	3.5	1.000	0.0105	78.8	1968.8	267750.0	173250.0	787.
5	Thermal insulation, glass wool	100	0.1	3.5	1.000	0.3500	7.9	275.6	10710.0	13387.5	70.
6	Gypsum board	13	0.013	3.5	1.000	0.0455	41.0	204.8	9828.0	10237.5	81.
7	Steel I-beam: top flange		0.01	0.1	1.000	0.0010	8.0	72.0	0.0	8000.0	24.
	Steel I-beam: bottom flange		0.01	0.1	1.000	0.0010	8.0	72.0	0.0	8000.0	24.
	Steel I-beam: webbing		0.01	0.06	1.000	0.0006	4.8	43.2	0.0	4800.0	14.
							bay total	34496.7	4582029.0	3020810.5	13804.
							per m2	**10004.0**	**1328788.4**	**876035.0**	**4003.3**

Note: Number "2." is not used

Material Environmental Impacts	Weight (kg/m3)	Embodied Energy (MJ/kg)	Water Resources (litres/kg)	GWP (g CO2-equ./kg)	AP (g SO2-equ/kg)
Corrugated steel sheet, galvanized	7500	25	3400	2200	10
Thermal insulation, rock wool	75	20	1360	1740	10
Steel sheet, galvanized	7500	25	3400	2200	10
Thermal insulation, glass wool	22.5	35	1360	1700	9
Gypsum board	900	5	240	250	2
Steel I-beam column					
top flange	8000	9	0	1000	3
bottom flange	8000	9	0	1000	3
webbing	8000	9	0	1000	3

Notes:
Information on black enamel paint was unable to be found, therefore, the final calculations do not account for the paint used on the exterior siding. The steel beam included in the wall is taken into account though calculating the bay length of the wall (3.5m) by one meter high, and finding volumes based on this bay. The total environmental impacts for the bay length (3.5m) by bay height (1m) are divided by 28% (1meter/3.5meters) to determine the impacts for one square meter.

Notes and Extra Calculations

Corregated steel sheet	length cm	/on center cm	equals unit	(actual length cm)	equals actual cm	convert to m
	350	18	19.4	22	427.8	4.278

average of given values
Material Values from The Ecology of Building Materials Second Edition by Bjorn Berge
Project Resource: Detail Magazine 2010, Volume 11

Works Cited

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Berge, Bjørn, and Filip Henley. The Ecology of Building Materials. Oxford: Architectural Press, 2000. Print.

Emily McGloh
Ecology of Building Materia
Case Study- Page
May 27, 201

Figure 2: Inventory analysis of 1m2 of exterior wall in Ecology of Building Materials Course. By E.McGhlon, 2011.

For each of four primary material categories—concrete, steel, timber, and plastic—the students hear from a guest speaker who shares their research on the materials' environmental contexts (drawing from the Civil Engineer/Green Materials and Forestry Departments at nearby Oregon State University and from our own Green Chemistry Program here at the UO). In the same week, the class takes a field trip to a building material manufacturing plant (truss joist manufacturer, steel roller, concrete plant, etc.). These field trips have turned out to be very effective in bringing a level of reality to the quantitative LCA characteristics that the students have read. It's one thing for students to read about the embodied energy of steel. It's another to stand directly in front of the furnace at smelting.

The final project returns to quantitative analysis of embodied lifecycle environmental impacts. The students choose a case study building for which a detailed wall section is available, mark off a square meter of wall assembly and use the wall section to compile a list of the quantity and type of material in that portion of wall. Using database factors in the course textbook, *Ecology of Building Materials*,[18] for embodied energy, embodied global warming potential (GWP), and embodied water, the students generate a rough per square meter analysis of the building envelope.

Introduction to LCA for Building Design
E. Moore at University of Oregon

Moore has received funding to offer a short, intensive graduate student seminar, LCA for Building Design (ARCH 607), in the spring term 2011. The course will offer architecture graduate students a crash course in the principles of LCA, exposure to industry standard LCA software options (SimaPro, GaBi, Athena, SolidWorks Sustainability), and guest lectures (some telecast) from industry professionals. The guest lectures will be opened up to students enrolled in related courses in the journalism and business schools and to members of the UO Green Product Design Network LCA Working Group.

The seminar is intended to give architecture graduate students advanced knowledge of current topics in LCA such as LCA in current and future green building certification, the LCA industry and practitioners, and LCA modeling

Life Cycle Assessment
J. Cooper at University of Washington

Life Cycle Assessment (ME 515) is a graduate project-based course that has run since 2003[19] teaching the computational structure and data sources for environmental LCA. Interdisciplinary students develop unique ISO compliant LCAs for projects appropriate to their discipline and current research, at times becoming a part of their MS or PhD research.

Students are expected to assemble the project inventory and impact data from primary and secondary data sources and are faced with the challenge of integrating and interpreting data. The course delivers information in a 'just-in-time' fashion[20] and requires students to address the full life cycle including complexities such as cut off flows (inputs not accounted for), systems with process alternatives, processes that create more than one product/co-product and closed loop recycling (secondary material is fed back into the system).

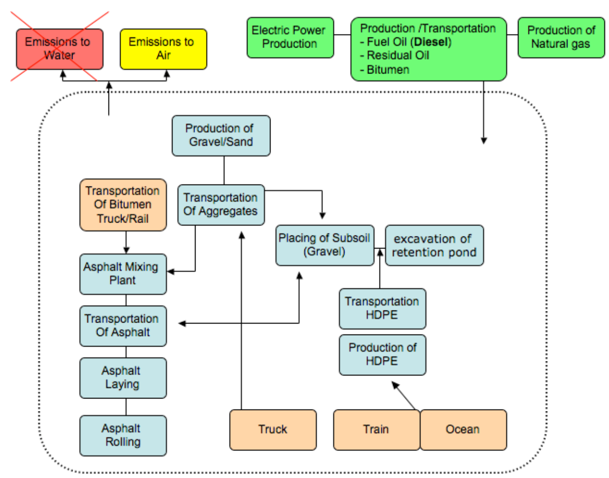

Figure 3: LCA of pavement process flow diagram by J. Ramberg in ME515.

Graduate students from the College of Built Environments who have taken this class have analyzed steel reinforcing bars, façade systems and concrete and results of the research has contributed to faculty led research efforts.

Sustainability and Design for Environment
J. Cooper at University of Washington

Sustainability and Design for Environment (ME 415/CEE495/ENVIR415) has engaged built environment, construction management, and engineering, science, policy, and business students since 1998[21] in the design of sustainable systems. The initial lecture-laboratory format evolved into an interdisciplinary team design-project course for seniors and graduate students currently serving over 50 students annually. Co-listing of the course in engineering and the UW College of the Environment ensures wide interdisciplinary participation.

Class lectures[22] progress from descriptions of methods for quantifying life cycle materials and energy use and waste for a baseline design to the application of resource conservation, pollution prevention, the integration of green technologies (e.g., recycling and alternative energy sources) throughout the life cycle, and the use of the concepts of industrial ecology for encouraging co-product exchanges with other life cycles. Based on these sustainability concepts, teams improve the baseline design and report reductions in environmental, economic, and social metrics and identify enabling technologies and policies.

In recent years, student teams have investigated improvements to high-rise buildings, schools, stadiums, golf courses, roads, suburban neighborhoods, and home heating, water, and lighting systems.

Whole Building Life Cycle Assessment
Rob Sianchuk at University of British Columbia

Whole Building Life Cycle Assessment (CIVL 498C) is an upper level course offered through the UBC Civil Engineering Department. There have been three consecutive offerings since 2009 which have been attended by both architecture and engineering students from various specializations including civil, mechanical, materials and environmental.

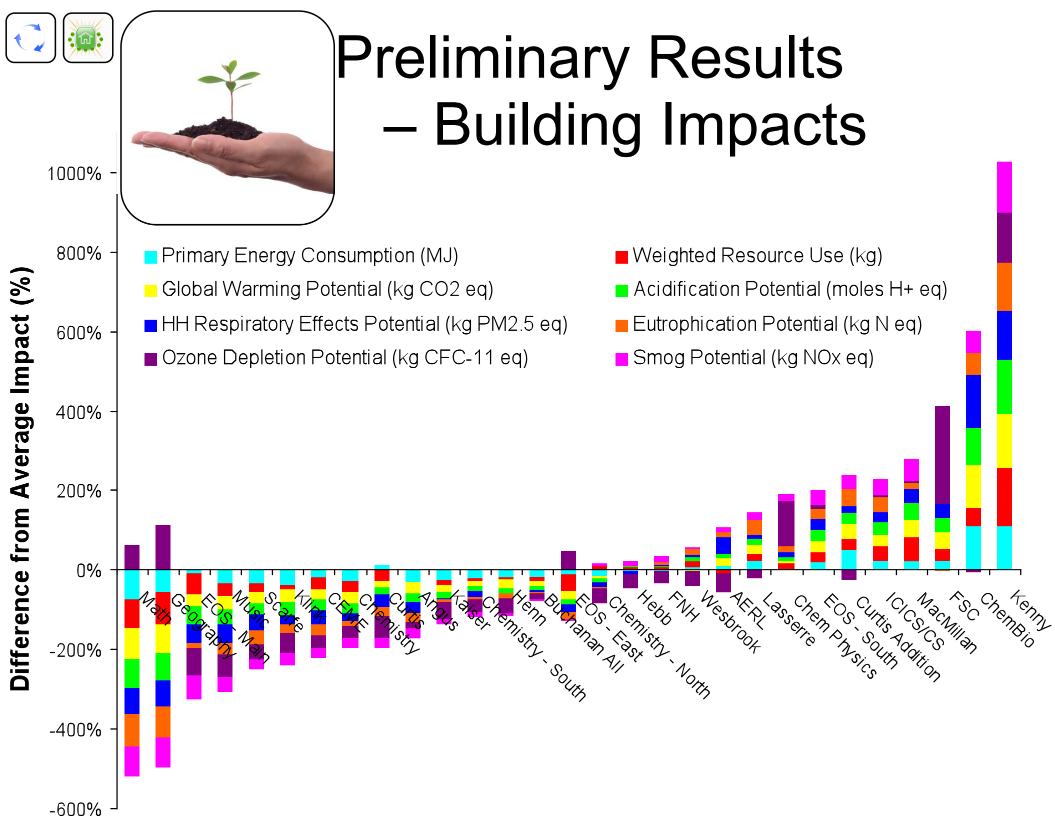

Figure 2: Inventory of buildings on UBC campus with difference from average impact. Buildings on the left hand side of the chart tend to be wood frame structures. Results compiled from multiple years of the Whole Building Life Cycle Assessment class.

Students engaged in CIVL 498C learn about life cycle assessment (LCA) and apply it to study the environmental impacts of buildings at their home campus, UBC Vancouver. The LCA education provided in the course focuses on foundational concepts established in ISO 14040, 14044 and, more recently, 21931-1, with complementing lessons in the state of knowledge and activities in building LCA, modeling methods, and uncertainties present in LCA. This education is paralleled with students being exposed to OnScreen TakeOff and the Athena Environmental Impact Estimator in order to equip them with the tools to gain experience operationalizing LCA through their final projects – an ISO compliant LCA study of an existing UBC building.

Compiling student results to date, cradle-to-gate (resource extraction to building construction) LCA studies of 52% of the academic floor area and 51% of the student residence floor area at UBC Vancouver campus have been modeled by CIVL 498C students. One of the primary applications these studies has been contributing critical impact benchmark data to catalyze the development of performance based sustainable construction assessment criteria for construction activities at UBC in accordance with ISO 21931-1, which asserts that both LCA and benchmarks are required to assess the environmental performance of buildings. A second major application has been the immense public outreach that has been possible with the CIVL 498C students' final projects, as they have proven to be valuable assets to engage and educate academics, industry and government in LCA through, for instance, public final presentations put on by the students (YouTube search 'Whole Building Life Cycle Assessment').

OPPORTUNITIES AND CHALLENGES

The case studies presented above have identified specific opportunities and challenges for integrating LCA into architectural education. Life Cycle Assessment methodology provides a rigorous framework to quantify and assess the environmental (and other) impacts of buildings and the materials and products used to build them. The authors have found students to be engaged with the subject and interested in gaining a better ability to quantify differences between materials and systems. LCA provides structure to integrate discussions about systems based thinking as students must define the goal and scope of the study (explicitly stating what is omitted) and address the limitations of time, data availability, data quality and uncertainty.

In teaching LCA within a relatively short (10-15 week) timeframe, the four phases of an LCA (noted above) can be covered to varying levels of detail and specificity. The first (goal and scope definition) and last (interpretation) steps are critical to develop rigorously in order to provide students with an understanding of the core concepts needed to evaluate and use LCA results. This is critical for architects and engineers looking to integrate LCA data into design and construction practice and could be considered the 'first principles' of LCA.

Preparing the inventory analysis and impact assessment presents more significant challenges and methods for completing this step vary widely amongst the courses described here. The first challenge is in attaining realistic quantities of material and energy used in creating a specific product. The second challenge is developing the data to enable a meaningful impact assessment.

The courses described in the paper use varying combinations of the above methods to develop the inventory analysis and impact assessment. See Table 1 for a summary of the methods used in the courses presented here.

The following four methods address the challenge of estimating material and energy use:

1. <u>Estimated by approximation</u>

For full building analysis students can use tools such as the Athena EcoCalculator to translate a building of known geometry and construction type to determine approximate material quantities and the resulting environmental impacts. This has the advantage of limiting the scope of data collection and analysis required by the students and the disadvantage of students feeling uncomfortable with 'average' data being used to represent specific conditions. This method provides useful and quick results appropriate for use in schematic design studies.

For component analysis students can use published examples of similar construction types and develop estimations of the quantities of materials and energy required to build the selected component. General industry data can be used to extrapolate to the specific conditions of the project.

	UW ARCH 404	UW ARCH 498	UofO ARCH 607	UofO ARCH 4/507	UW ME 415 +	UW ME 515	UBC CE 498C
Material Quantities							
Student design-estimation	■			■	■	■	
As built design documentation		■					■
Student assembled		■			■	■	■
Student field documentation							■
Energy Use Quantities							
Estimated by approximation	■				■	■	
Student created energy model	■				■	■	
Design energy model		■					
Actual energy use data		■			■	■	
Not included			■	■			■
Life Cycle Inventory Data							
BEES						■	
Athena	■	■	■	■		■	■
US NREL LCI Inventory		■	■	■		■	
Eiolca.net (Carnegie Mellon)		■			■		
EcoInvent			■	■		■	
Others: see web resource			■	■	■	■	
Methodology							
Process	■	■	■	■	■	■	■
Economic Input-Output		■			■		
Hybrid		■	■	■	■		
Reference Texts							
A life cycle approach to buildings	■	■	■				
The Ecology of Building Materials				■			
The Computational Structure of LCA						■	
Software							
Target Finder	■	■					
Rocky Mountain Institute Green Footstep		■					
Athena EcoCalculator	■	■	■				
Athena Impact Estimator		■	■				■
SimaPro							
EIOLCA.net		■			■		
Excel		■	■			■	
Matlab						■	

Table 1: Summary of data, methods and tools used in presented courses.

2. Attain primary construction quantity data
When analyzing a built project, construction cost estimates and material quantity take offs can be attained (either by the construction team or generated by students) to develop an inventory of building materials. Depending upon the interests and schedule of the design or construction team and the level of detail desired the effort to attain this data can vary widely. Some owners are uncomfortable sharing the financial details of a project and similarly some general contractors do not want to release detailed information that may be considered proprietary.

3. Develop use phase model
Students can use a variety of energy modeling methods to evaluate and predict the energy required to operate (heating, lighting, equipment etc) the building. Depending upon the technical abilities of the students, these results can vary widely in quality however they are satisfying to student teams looking to capture the 'real' impacts of unique projects.

Industry average data coupled with anticipated building occupancy and use can be used to approximate water and waste usage.

Connecting to land use planning models and transportation data would be possible to integrate the regional impacts of the buildings use however none of the classes noted above have included this level of analysis.

4. Attain primary energy use data
Most higher performance buildings are developed with an energy use strategy. Attaining this data from the design team provides an effective way to capture operational impacts. For built projects attaining the actual energy used is also possible but more challenging as not all design teams have access to this data.

The following methods address the challenge of developing meaningful impact assessments.

1. Use existing (simplified) data resources
The Athena EcoCalculator and Impact Estimator internalize much of the complex data collection required for typical building components and assemblies. Many assumptions and approximations are by necessity included in this tool and are not all transparent to the users. This simplification is effective in enabling students to attain fairly comprehensive results quickly.

Summary data sources (such as the Bath ICI database, BEES and as found in different texts) can provide impacts per unit quantity for select building materials. These are useful to enable rapid comparisons between materials and the ability to estimate total impacts from a built up assembly.

2. Use I/O or Hybrid method
Leveraging national input/output databases enables a relatively rapid/comprehensive analysis of systems to translate economic data (such as a cost estimate) to environmental impact. Using a hybrid method that combines the comprehensive, yet very general, results of an input/output analysis with more specific (process based) data from relevant components enables the analysis to focus on known and/or significant impacts while maintaining a comprehensive scope.

3. Require students to find available data
As the U.S. Life Cycle Inventory Database is not sufficiently populated to analyze most products, many other data sources can be accessed to compile a comprehensive impact assessment. Requiring the students to attain primary data has the advantage of exposing them to the complexities of integrating data and challenges in capturing uncertainty and variation into an LCA. Appropriate for graduate/specialized study this method would be challenging to implement in larger/more-generalized courses, as students require significant mentorship to find, evaluate and incorporate the data.

4. Use LCA software/databases
Software has been developed (e.g. SimaPro, Gabi) to enable LCA practitioners to interface with international databases and create comprehensive Life Cycle Inventories. These tools have the advantage of utilizing more comprehensive datasets formatted to aid in developing LCI data and potentially could bridge between the complexities of compiling LCI data and the simplifications of building industry tools. The 'Introduction to LCA in Building Design' course in development at the University of Oregon will explore the potential and challenges

of using these tools within the building design process.

CONCLUSIONS: RECOMMENDATIONS FOR ARCHITECTURAL EDUCATORS

Life Cycle Assessment was developed as a tool to enable process improvement not a singular analysis method. An LCA for a product produced on an assembly line can directly inform decisions for future manufacturing methods and process innovation as a single company looks to improve performance. However, most buildings are not mass-produced and translating the knowledge and opportunities identified in the analysis of a singular building to improvements in the design, construction and operation of other distinct buildings is a unique challenge.

Analyzing buildings helps to identify the magnitude of the challenge and motivate action. Architectural educators however, should focus on how to utilize LCA results and integrate LCA methods into the design process. To do so, we must first advance industry knowledge and expertise. Analysis of components, systems and buildings is an effective way to do this. However, methods to integrate this analysis into building design and construction practices must still be advanced if we are to inform and impact practice. While LCA provides the promise of delivering high quality information to inform decisions and help reduce the environmental impact of buildings, significant research and development is still required to provide the data, tools and methods needed. The authors have found that these teaching efforts help support our related research efforts in life cycle design, LCA standardization, design for disassembly and provide case studies for education within both the LCA and building industry professions.

Courses in building energy performance, materials and methods of construction and structures could all benefit from integration of a component of LCA data and method to provide context and information to help inform the assessment of design options. For example, structures can be evaluated by carbon footprint as well as weight and strength and the tradeoff between higher performing yet higher embodied impact assemblies could be quantified in detailing course. Dedicated courses such as described here provide the time needed to cover the details and execution of an LCA in sufficient detail to capture the rigor and nuance in a comprehensive LCA. Using life cycle thinking to conceptualize buildings in the design phase provides the opportunity to establish performance objectives, target high impact areas and frame design criteria to include issues such as material sourcing, deconstruction/re-use, life-span, durability and maintenance.

Given the scale of the economic, social, and environmental challenges we currently face, educators have a unique challenge to integrate new data and tools to improve teaching and practice. Life Cycle Assessment provides structure and information to understand and evaluate the impacts of buildings in a comprehensive manner. As architects, we must develop methods to effectively and efficiently integrate this knowledge into design to help enable quantifiable improvements to the quality and environmental impact of the buildings we design.

NOTES

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