Summary Report

End-of-Life Modeling and Data in North American Whole Building Life Cycle Assessment Tools

APRIL 2024

Carbon Leadership Forum

About the Carbon Leadership Forum

The Carbon Leadership Forum accelerates the transformation of the building sector to radically reduce the greenhouse gas emissions attributed to materials (also known as embodied carbon) used in buildings and infrastructure. We research, educate, and foster cross-collaboration to bring embodied carbon of buildings and infrastructure down to zero.

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CONTENTS

EXECUTIVE SUMMARY

This document summarizes the Carbon Leadership Forum (CLF) research on end-of-life (EOL) modeling for a selection of building materials in whole building life cycle assessment (WBLCA) tools conducted as part of a larger project in collaboration with the National Renewable Energy Lab (NREL), Building Transparency (BT), and Skidmore, Owings & Merrill (SOM.) The overarching **project goals** are:

1. Improve EOL modeling in WBLCA tools by exploring data gaps and current tool capabilities.
2. Explore opportunities for developing and testing an open-access EOL database. This can potentially enable WBLCA tools to draw from this database and better harmonize the modeling of EOL impacts.

The recommendations, limitations, and future research ideas are based on: 1) a review of EOL data and modeling functions for three North American WBLCA tools, 2) direct interviews with North American WBLCA tool providers, and 3) a survey and an online workshop with experienced WBLCA tool users.

The key **recommendations** related to data and tools are elaborated upon and include the following:

- Develop an open-access EOL database of LCA models (i.e., life cycle inventory (LCI) data and emission factors for the North American geography). Note all three tool developers expressed interest in aligning with and/or using such a resource.
- Develop regional default EOL management rates for North America.
- In WBLCA tools:
    - Acknowledge future uncertainties in EOL practices.
    - Continue and/or enhance transparent methodology documentation.
    - Enhance customization, scenario comparisons, and reporting to aid interpretation and design.
- In Stage C EOL models, prioritize filling data gaps (e.g., C1: demolition/deconstruction, C2/C3: reuse transport and processing for all materials).

The high-priority EOL functions that LCA tool users requested are listed below. The workshop helped identify data needs as well as potential available data to support these functions.

1. Scenario-based EOL modeling (i.e., best case, worst case, and business-as-usual scenarios)
2. Ability to customize EOL management rates
3. Choice of default EOL management rates by region
4. Customization of Module D modeling (include or exclude, change parameters, etc.)

The **limitations** of this study are also acknowledged and summarized below:

- The scope of this research is limited to only eight categories of construction materials.
- Findings and recommendations are primarily based on input from building LCA practitioners and WBLCA tool providers, with limited review of academic literature.
- The survey results and workshop participation were limited in size and may not accurately depict the opinion of the North American building LCA practitioners.
- WBLCA tool review in this research is limited to three major providers.

Finally, **future research** highlighted through this work includes the following:

- Expand the review of published literature and existing public and private LCI databases to identify data gaps related to EOL modeling.
- Prioritize data gaps by investigating the relative contribution of individual C Module impacts at a building scale using a large sample of WBLCA data and material quantities.
- Conduct further research on harmonizing Module D accounting across WBLCA tools.
- Carry out further comparisons and recommendations on biogenic carbon accounting at the end of life.
- Develop material service life defaults for North American materials.

INTRODUCTION

This document summarizes the CLF research on EOL modeling for a selection of building materials in WBLCA tools. The overarching goals of the project are to:

1. Improve EOL modeling in WBLCA tools by exploring data gaps and current tool capabilities.
2. Explore opportunities for developing and testing an open-access EOL database.

This report presents findings and conclusions from research into project goal #1.

What is End-of-Life?

For this project, the EOL focus is primarily on "Stage C" in life cycle assessment (LCA) terminology. Stage C comprises four life cycle modules (see **Figure 1**):

- Module C1- Building demolition or deconstruction.
- Module C2- Waste transportation.
- Module C3- Waste processing.
- Module C4- Landfilling waste.

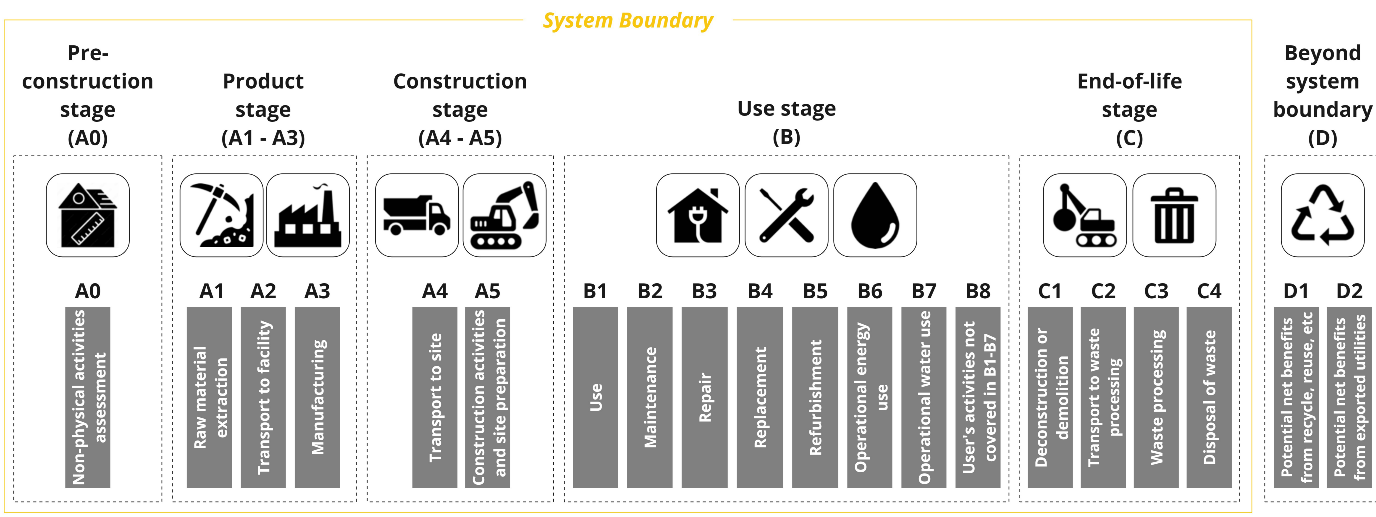


Figure 1. Life cycle stages and modules included in a life cycle assessment (LCA) framework per ISO 21931-1

Although this research centers on tailoring Stage C inputs, it must be mentioned that activities in Stage C significantly influence Module D. Exploring the potential advantages of recycling, reusing, and energy recovery highlights the intricate linkages between these stages. It becomes challenging to address one stage independently without investigating its relationship with the other due to its interconnected nature. Additionally, Module A5 warrants attention for its inclusion of Stage C impacts related to on-site waste handling during construction. Module A5 can also include the waste impacts from existing buildings on-site, as outlined in ISO 21931-1 and EN 15978 standards. Notably, the recent RICS (Royal Institution of Chartered Surveyors) standard release, guiding WBLCA in the UK, introduced Module A5.1.[1] This new addition accommodates the separate reporting of EOL impacts from any existing buildings on-site that were demolished before new construction starts. Exploring how existing buildings on-site are handled today will be an important aspect of further discussions for which no definitive modeling guidance exists for North American LCA standards as of March 2024.

Finally, it's important to recognize that depending on the end-of-life pathway and allocation approach chosen, the benefits shown in Module D may also reflect on the potential benefits that can be realized during Stage A of the next lifecycle of the material. In the case of recycling or reuse, Module D reflects the potential substitution benefits of using recovered material to offset virgin material production. Therefore, WBLCA tool users should not sum Stages A-D results since it would result in double counting of potential benefits that are outside the system boundary. However, it should be recognized that Module D plays an important role in informing efforts to design for circularity, reuse, disassembly, and recycling.

Why Harmonize EOL Data in WBLCA Tools?

The growing landscape of policies mandating WBLCA reporting and setting global warming potential (GWP) limits calls for the need for accurate, transparent, and harmonized data within a given geographic context. Standardized defaults for EOL management rates in tools become vital to ensure policy adherence and avoid situations where compliance hinges on incomparable, unreliable, or eccentric EOL assumptions.

Another reason to harmonize EOL impact data is that despite the diverse range of manufactured building products, they often follow common EOL pathways for recovery or disposal. This uniformity in EOL pathways can result in similar EOL impacts within a geographic region.

It is also important to harmonize EOL data across the material and building scales. The disclosure of product LCA results through environmental product declarations (EPDs) can serve as an information source for WBLCA tools. Thus, as EPDs increasingly include additional life cycle stages, the harmonization of EOL modeling between tools and EPDs becomes essential for reliability and consistency. Appendix A outlines some EOL default recovery and disposal rates in North American product category rules (PCRs).

To achieve harmonization, one key element is common national and sub-national default EOL recovery and disposal rates that all tools can use. In this report, EOL recovery and disposal rates are referred to as "EOL management rates." Although this data is limited and needs additional research to fully establish default rates, Appendix B provides an estimation of recovery and disposal rates for the United States as a starting place for additional research. Other key elements need consideration, such as common background LCI data related to energy and fuel use impacts, alignment of calculation methodologies and scenarios to define underlying assumptions for items such as transportation modes and distances and establishing common impact offsets for Module D.

EOL MODELING IN WBLCA TOOLS

Building LCA tools such as tallyLCA, One Click LCA, and Athena Impact Estimator offer some features and optional inputs for calculating EOL impacts. This section discusses how each of these three prominent LCA tools develop scenarios to consider EOL. This effort involves two approaches to collect information and perform research:

- **Interviews with tool providers.** To fill the information gaps from the tool review effort, the CLF researchers contacted the three tool providers to seek additional input regarding several aspects of EOL modeling in their tool.
- **Tool review.** Tool environments, functions, data sources, and manuals (when available) are first reviewed to understand how WBLCA tools model EOL.

Interviews with WBLCA Tool Providers

A series of interviews with the three major WBLCA tool providers (i.e., One Click LCA, tallyLCA, and Athena Impact Estimator) were conducted to gain insights about 1) the current status of how these tools model end-of-life, 2) the existing data availabilities and gaps in end-of-life modeling, and 3) challenges and potential solutions to improving end-of-life modeling and data. To be consistent, we asked the same questions from all three interviewees. Individual responses are further kept anonymous to preserve confidentiality. Our findings are summarized below:

1. Most critical data gaps
    - Lack of market-specific EOL data within the United States
    - Need for improved default EOL management rates
2. Most uncertain aspects of EOL data
    - Challenges in predicting future EOL practices
    - Regulatory changes
    - Material-specific EOL management rates across different countries
3. Modeling of reuse
    - Reuse is represented as an EOL scenario for new materials/products.
    - When modeled, the impact of reusing existing materials in new projects affects A1-A3 following the avoided burden method.
    - Post/pre-processing impacts that affect the qualification of reuse are not adequately addressed.
4. Distinction of demolition and deconstruction in Module C1 modeling
    - Customization based on project-specific data for distinguishing between demolition and deconstruction seems feasible. However, there is limited reported demand for such customization in practice.
5. Ability to customize Module C3 processes
    - Direct modification of specific processes in Module C3 is currently unavailable.
6. Region-specific EOL inputs (e.g., landfilling emission factors, default EOL management rates)
    - While acknowledging potential feasibility, challenges arise in integrating complex functions.
    - Limited reported demand for region-specific features in the tools.
7. Customization of multiple EOL scenarios for a given material (e.g., 50% landfill and 50% recycled)
    - Tools consider providing functionality for multiple EOL scenarios but implementation/design is pending.
8. Documentation of Module D modeling (e.g., substitution method, biogenic carbon treatment, etc.)
    - Existing guides, such as the IE4B user guide[2] and NRC guidelines, offer detailed insights into Module D calculation methods.
9. Willingness to use open-access EOL database
    - Open to using external databases, prioritizing quality and reliability.
    - High-quality data is essential in setting standard defaults across different WBLCA tools and EPDs.

WBLCA Tool Review

Table 1 provides a comparison of the three WBLCA tools reviewed here. The main points of comparison are the geographic coverage of the tools, primary LCI data sources, the granularity of LCA stages modeled, adjustability features of Stage C modules and Module D, and the choice of EOL management scenario. **Table 2.** further summarizes the range of EOL emission factors and management rates from the three most commonly used WBLCA tools, tallyLCA, Athena Impact Estimator for Buildings, and One Click LCA. The following sections dive deeper into each tool and its underlying LCI data for EOL modeling. The extent of information included in the following sections varies depending on availability.

Table 1. Differences in EOL modeling and reporting in WBLCA tools.

Feature	Athena v5.4	One Click	tallyLCA
Geographic Coverage	US/Canada	Global	US
Primary LCI Data Source(s)	Various	ecoinvent/EPDs	GaBi
LCA Stages Modeled			
C1 Deconstruction/Demolition	Reported	Reported	n/a
C2 Waste Transport	Reported	Reported	Combined
C3 Waste Processing	Combined	Reported	
C4 Waste Disposal		Reported	
D EOL Burdens/Benefits	Reported	Reported	Reported
LCA Stage Adjustability			
C1 Deconstruction/Demolition	Not adjustable	Structure type/GFA input	Not modeled
C2 Waste Transport	Not adjustable	Mode/distance	Not adjustable
C3 Waste Processing	Not adjustable	Not adjustable	Not adjustable
C4 Waste Disposal	Not adjustable	Not adjustable	Not adjustable
D	Not adjustable	Not adjustable	Not adjustable
Ability to Choose EOL Management Option			
Reuse	n/a	✓	n/a*
Recycling	n/a	✓	n/a
Incineration	n/a	✓	n/a
Landfilling	n/a	✓	n/a
Use EPD's EOL parameters	n/a	✓	n/a
Combination of EOL scenarios	n/a	n/a	n/a

n/a: *not available*

** The use of a reused material in a new project is an option in tallyLCA.*

Table 2. Synthesis of models (biogenic carbon is included in GWP numbers).

Material	Reused	Recycled	Incinerated	Landfilled	GWP Range ($kgCO_2e/kg$)	
					C*	D
Steel (structural)	0%	70%-98%	0%	2%-30%	0.001 to 0.043	-2.200 to -0.757
Concrete	0%	50%-60%	0%	40%-45%	0.006 to 0.040	-0.026 to 0.001
CLT	6.1%	2.9%-14.5%	18.4%-22%	63.5%-72.6%	0.035 to 1.160	-1.730 to 0.093
Glulam	6.1%	2.9%-14.5%	18.4%-22%	63.5%-72.6%	0.036 to 0.921	-1.730 to 0.046
Asphalt Shingles	0%	0%	0%	100%	0.005 to 0.044	-0.044 to 0.001
Fiberglass Insulation	0%	0%	0%	100%	0.006 to 0.132	-0.003 to 0.000
Glass	0%	0%	0%	100%	0.008 to 0.045	-0.013 to 0.000
Drywall	0%	0%	0%	100%	0.007 to 0.044	-0.002 to 0.000

** Stage C impacts may or may not include all modules*

TallyLCA

TallyLCA is a plug-in tool that uses Revit's building information model for estimating material quantities and enables users to link environmental impact data from its material library. Our initial synthesis of how tallyLCA handles EOL is limited. TallyLCA provides details about end-of-life modeling assumptions for each material entry (e.g., EOL scenarios are clearly stated for each product). For the most part, tallyLCA uses the EPA's waste reduction model (WARM) for the US construction and demolition waste treatment methods. EOL emission factors are, however, reported for the combination of EOL scenarios and are not reported separately.

Athena Impact Estimator for Buildings (v5.4)

Athena's tool is a stand-alone software that takes different forms of project inputs (e.g., bill of materials) to create LCA models for buildings. We use Athena's User Manual to extract information regarding EOL modeling.[2] The manual, however, lacks detailed LCI data while the tool developer provides a variety of resources used to create its LCI database, with the majority being limited to cradle-to-gate boundaries. It must be noted that the tool has gone through substantial updates in its most recent version (v5.5 or later) where more EOL functions are included.

One Click LCA

One Click LCA for buildings offers both a web-based and a Revit plug-in tool. It can either extract material quantities and properties from Revit when using the plug-in, or create manual entry of material quantities and properties for different design stages of a building within the web app. It can also import building designs and materials from other sources (e.g., Excel sheets). The One Click LCA version examined here is the Life Cycle Carbon for North America tool.

One Click LCA treats EOL in three different ways:

- Material-locked: material type-specific scenario.
- Market scenarios, user-adjustable: Set of EOL scenarios available for material type. The default option is chosen based on the standard practice on the market. Users can adjust the options per item. Users can also choose the EPD EOL scenario for specific products if they so wish.
- EPD EOL scenario, user-adjustable: This uses the EOL scenario defined in the EPD (if defined). Users can also choose market scenarios for specific products in this case if they so wish.

WORKSHOP: EOL MODELING IN WBLCA TOOLS

Introduction

End-of-life modeling of materials, assemblies, and buildings within WBLCA tools varies in scope, methods, and the ability to customize scenarios. This workshop explored how architects, engineers, and consultants currently utilize EOL modeling inputs and outputs to influence building design. The workshop is part of a broader project to improve EOL modeling in WBLCA tools and explore open-access EOL impact data. In preparation for the workshop, CLF conducted a limited literature review, several interviews, and a pre-workshop survey. The online workshop was held virtually on Zoom and consisted of breakout discussions and activities using online collaboration tools.

Goal of the Workshop

The primary goal of the workshop is to gather input on the challenges, opportunities, and desired end-of-life modeling functionality in WBLCA tools. It is worth noting that despite the scope of this project being limited to only eight building materials (i.e., concrete, steel, asphalt roofing shingles, glass, cross-laminated timber (CLT), glued-laminated timber (glulam), drywall, and fiberglass insulation), the scope of the workshop was broader and considered the EOL of buildings and materials as a whole.

Pre-Workshop Survey

This section provides a summary of survey results taken as part of the preparation for the workshop. The survey was initially distributed on 10/11/2023. There were a total of 20 questions: 12 multiple choice questions and 8 free form questions. The survey received 22 responses. Over three-quarters of respondents worked in firms with more than 50 employees and had the majority of their projects located in the U.S., the West Coast in particular. The majority of survey takers identified themselves as sustainability leads or LCA analysts, where about half of them indicated more than 5 years of experience with WBLCA tools where informing design was indicated as the primary purpose of using WBLCA tools. The use of professional LCA tools and EOL modeling outside of WBLCA tools were areas in which respondents indicated less familiarity. Appendix C provides a detailed summary of survey responses.

The following summarizes the key findings and themes from the survey responses, primarily derived from the free-form questions:

- **Influence on design:** EOL considerations primarily impact designs for disassembly and modular structures to facilitate easier maintenance.
- **Challenges of EOL modeling:** Focus on the time value of carbon, mass timber recovery, and uncertainties regarding future EOL practices and market trends. Tools might oversimplify aspects like reuse and fail to accurately model the processes involved, leading to discrepancies in reporting and overlooking of emissions related to reuse.
- **Challenges in lack of standards:** Lack of standardized EOL assumptions and methodologies leading to varied reporting tools, material-specific assumptions, and uncertain accounting for credits/benefits from Module D.
- **Design challenges:** Emphasis on designing for deconstruction/disassembly to enable reuse, particularly essential in renovation projects and the use of bio-based products.
- **Complexities of reuse:** Challenges in tracking, modeling, and assessing the environmental impact of different types of reuse, especially for bio-based materials and distinguishing between material, product, and building reuse.
- **Need for data transparency and accuracy:** Desire for transparent data sources, scenario-based EOL analysis, and a standardized approach to assumptions for better harmonization among tools.

Workshop Structure and Findings

A virtual workshop was held in November 2023. Around 35 targeted invitations were sent. Potential participants were selected based on the project team's knowledge of the building industry practitioners who are experienced users of WBLCA tools. A total of 31 people participated in the workshop (see the Acknowledgments Section for a full list of participants). The majority of participants were architects, engineers, and consultants who work for private companies. The overarching goal of this workshop was to explore the experience of WBLCA tool users with EOL modeling and investigate opportunities and challenges for improving EOL modeling functions. All responses were kept anonymous.

Workshop Design and Execution

The workshop started with a presentation to review key findings from the literature review and survey efforts. That is followed by three group activities. All activities were designed and executed in Miro Boards (see Appendix D for results).

Summary of Findings

Activity 1: High-priority EOL functions in WBLCA tools

A list of potential EOL functions in WBLCA tools was identified through a review of the three major WBLCA tools, interviews with WBLCA tool providers, and a review of pre-workshop survey responses. In a workshop activity, participants were asked to identify each EOL function as high priority, somewhat important, or low priority. **Figure 2** shows the priority assessment summary analysis of workshop responses. The list of selected EOL functionalities in the order of their priority and some of the comments related to each received in the workshop can be found in Appendix D.

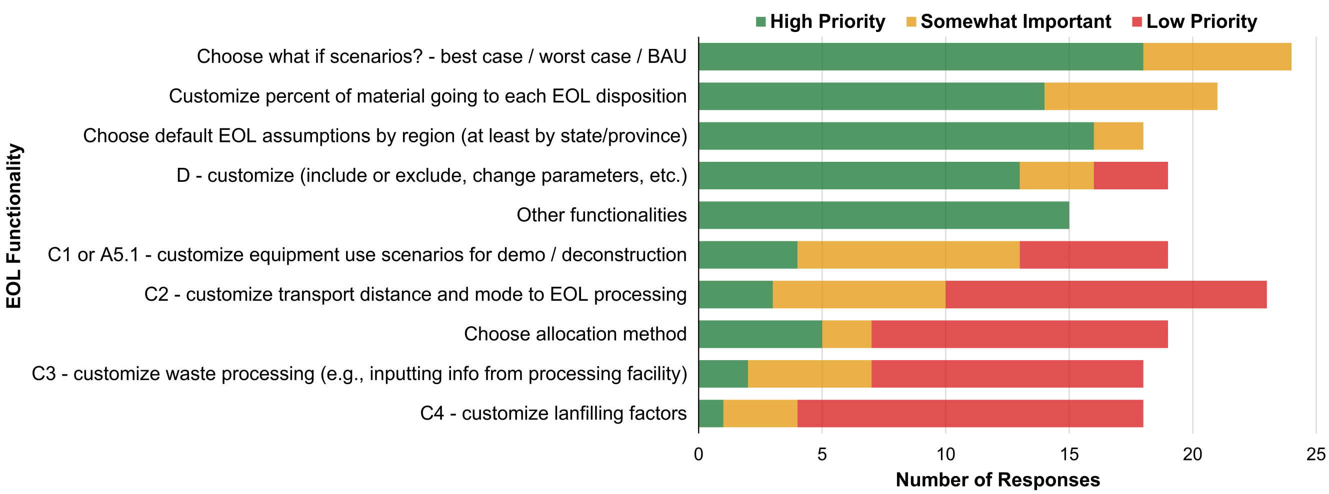


Figure 2. Analysis of EOL function ranking results with the highest priority function on the top and the lowest priority functions on the bottom.

Activity 2: Data needs and data availabilities for the top priority EOL functions

The top ranked EOL functions in WBLCA tools were selected for further discussion (see the ranking in the previous section). Participants were asked to identify data needs and data availability for each of the highly prioritized functions. The goal of this workshop activity was to understand the breadth and depth of data/information needed to enable the proposed functions and whether the data is already available (we asked participants to identify data sources if available). Verbal responses from workshop participants were then analyzed and categorized into common themes per specified EOL function. **Table 3** summarizes the result of analyzing individual responses for each of the selected EOL functions. It is worth noting that Table 3 solely represents the opinion of workshop participants with minimal modifications.

Table 3. Workshop activity 2 results: participants' insights on what data are needed and are available to enable the top priority EOL functions identified in activity 1.

EOL Function	Data Needs	Available Data
1. Choose what if scenarios? - best case / worst case / business-as-usual	• Regional BAU pathways per material • Variability between best and worst case impacts • Understanding of tech changes • Future scenario projection • Definition clarification • Guidance on responsible use • Scenario preset data	• Grid decarbonization scenarios • Future EV adoption models • Limited scenario modeling • In-house models • Conversations with owners/operators • Salvage/reuse indication in tools • Grid decarbonization scenarios • Future EV adoption models • Limited scenario modeling • In-house models • Conversations with owners/operators • Salvage/reuse indication in tools
2. Customize percent of material going to each EOL management option	• Business-as-usual and future EOL management rates (per region) • Lessons from pre-demolition audits and waste streams • Default values development guidance • Realistic data on recycling rates • Material-specific data • Consistency across tools • Uncertainty estimation	• Workarounds developed • Diversion rates • Historic EOL scenario data • C&D reports • Manufacturer buy-back programs • Existing policies • Extent of practitioners' control • Some regional policies and data
3. Choose default EOL assumptions by region	• Regional defaults based on waste statistics • Data on state/province EOL trends • Clearer spatial resolution • Impact of state/local regulations • Circular economy uptake • Granular defaults by region	• Data on wood disposal (North America vs Europe) • Municipal waste info • Some state waste tracking • EPA WARM data • Limited capabilities for customization • Limited transparency on waste data
4. D - Customize (include or exclude, change parameters, etc.)	• Harmonization of treatment methods • Granular data output • Modules completion within EPD • Standardization • Take Back program inclusion	• Contractor input • Project-specific insight • Limited customization capability

Activity 3: Real-world EOL modeling stories, challenges, and solutions

Activity 3 focused on real-world examples of project challenges and solutions. We explored three common themes: 1) deconstruction and/or reuse; 2) biogenic carbon and wood products; and 3) accounting of existing building on-site. Lack of tool functionality, insufficient input data available to the practitioner, and concerns with the service life uncertainty of reused materials were among the major challenges with modeling deconstruction and material reuse. Regarding biogenic carbon and wood products, the major challenges reported were the lack of granular data to differentiate different wood products, unclear Module D accounting methods, and complicated decision-making when comparing results with and without biogenic carbon. Finally, the frequently discussed challenges in accounting for the existing building on-site were the inability to distinguish demolition and deconstruction within WBLCA tools, lack of granular exported waste data, and issues with modeling reuse in WBLCA tools and its impact on rebuild vs. renovation decisions. **Table 4** further provides a summary of challenges and solutions identified from the workshop responses for each common theme under discussion.

Table 4. Summary of challenges and proposed solutions by workshop attendees related to three discussion topics: 1) deconstruction and/or reuse, 2) biogenic carbon and wood products, and 3) accounting of existing buildings on-site.

Theme	Challenges	Solutions proposed by workshop attendees
Deconstruction and/or reuse	Uncertainty in quantifying reused material quantities and selecting EPDs for materials that are no longer available	• Waited for material removal to ensure accurate data • Discussed with structural engineers to create an accurate picture of existing conditions • Used industry-wide EPDs with larger margins of error for unknowns
	Difficulty in accounting for material differences and service life adjustments	• Proposed a time value of carbon to address material service life differences • Suggested implementing custom fields to adjust service life for reused materials' first replacement cycle
	Complexity in modeling salvaged materials	• Shifted Stage C impacts from the old building's material into the new one • Developed guidance for salvaged material impact calculations • Applied generic end-of-life data where specific data was unavailable
	Quantification challenges for easy assembly / disassembly and module reuse	• Roughly estimated emissions reductions by comparing a conventional building with a modular building • Acknowledged challenges in accounting for ignored Module D impacts • Suggested comparing construction/deconstruction durations
	Tool limitations for comprehensive analysis	• Conducted manual post-processing to expand system boundaries • Suggested starting LCAs by considering A0 impacts
	Insufficient data on building deconstruction and EOL process inputs	• Suggested partnering with the industry to calculate and validate EOL process inputs • Proposed developing bespoke calculators for rough estimates
Biogenic carbon and wood products	Time scale discrepancy in carbon accounting from fossil and biogenic sources (Stages A to C vs. Module D)	• Emphasized separating biogenic carbon storage from emissions, highlighting its value and the need for owners' informed decisions on procurement and EOL impact valuation
	Decision-making dilemma: new construction vs. renovation	• Modeled demolition impacts for the existing timber building, considering uncertainties for future projects requiring quicker decisions
	Limited EOL scenario choice (e.g., incineration vs recycling)	• More unconventional EOL scenarios and impacts from the WARM model were sought
	Differences in Module D accounting method across different tools	• Informed the client by demonstrating the potential sources of differences across tools and left the decision making to the client
	Similar Module D and Stage C accounting for different wood products	• No solution was found
Accounting of existing building on-site	Avoided emissions from reuse are not captured by the WBLCA tool	• Ran two different models to estimate avoided emissions from reuse: one with all new materials and one with reused materials
	Broad categorization of waste products disables accurate LCA modeling	• Made assumptions on the split of waste materials, especially for metals (e.g., type of steel, aluminum)
	Comparison of rebuild vs. renovation alternatives	• No solution proposed; with a suggestion to develop reliable EOL data
	Lack of existing building models to compare renovation and rebuild scenarios	• Used the carbon intensity of a new building scenario and applied that to the existing building
	Accounting for reuse without accounting for demolition is misleading	• Suggested a process for accounting for pre Stage A impacts
	Distinction between demolition and deconstruction in a partial reuse and replacement case	• Created a totally separate inventory for demolished materials, extracted Stage C impacts, and added them back to the proposed design case
	Difficulty in estimating the impacts or benefits of reuse	• Used CLF benchmark data to roughly estimate the benefit of reuse in the baseline model

CONCLUSIONS

The following recommendations, limitations, and future research ideas are based on 1) a review of EOL data and modeling functions for three North American WBLCA tools by CLF staff; 2) direct interviews with N. American WBLCA tool providers; 3) a survey of 22 experienced WBLCA tool users; 4) an online workshop with 23 experienced WBLCA tool users; and 5) a limited literature review of EOL pathways and data for a set of eight different construction materials.

Recommendations

- Develop or contribute to an **open-access database** with LCI data, LCA models, and impact factors for the North American geography (national + subnational) to aid in the harmonization of EOL modeling in WBLCA tools.
  - EOL methods and data are not harmonized across WBLCA tools. All three North American WBLCA tool providers expressed interest in using a robust, harmonized, and transparently documented EOL database of impact factors as input data for their WBLCA tools.
  - The main driver for harmonization is the growing landscape of policies mandating WBLCA reporting and setting limits, which demands accurate, transparent, and harmonized data within a given geographic context.
  - Additionally, the disclosure of product LCA results through environmental product declarations (EPDs) serves as a growing information source for WBLCA tools. As EPDs increasingly include additional life cycle stages, the harmonization of EOL modeling between tools and EPDs becomes essential for reliability and consistency.
- Develop regional **default EOL management rates** for North America
  - Regionalized (national + sub-national) default management rates reflecting material-specific waste disposal and recovery data are crucial for accurate EOL assessments. This is foundational for WBLCA modeling to be used effectively in policy. This work can be accomplished through a detailed literature review and targeted interviews with waste regulators and waste processors in a variety of geographic regions.
- In WBLCA tools, acknowledge **future uncertainties** in EOL practices
  - Develop additional default modeling and reporting EOL scenarios like "best case" and "worst case." These scenarios can be useful to designers to understand the variability and magnitude of EOL results and acknowledges the inherent uncertainty in EOL modeling for a process that may not take place until 60 or more years into the future. Tools should strive to incorporate "what if" scenarios that represent future improvement in EOL recovery and consider discounting approaches to future impacts/benefits to aid decision making.
- In WBLCA tools, continue and/or enhance **transparent methodology** documentation
  - LCI data sources and methods used to calculate impacts for individual materials, processes, and modules should be transparent and well documented with help menus where appropriate. Documentation should include both the author and date of the data sources. Method transparency, alignment, and education are particularly important for reused materials/components, biogenic carbon, and Module D impacts.
- In WBLCA tools, **enhance customization, scenario comparisons, and reporting** to aid interpretation and design
  - Tool users want the ability to customize EOL scenarios within reasonable boundaries for the study. Flexible tool functions are essential for accommodating diverse EOL possibilities, and ensuring more accurate assessments. However, in a policy context, there should be stricter scenario parameters to ensure comparability.
  - Comparisons of default and/or custom EOL scenarios are helpful aids for interpretation and design. Scenario comparison *within* the tool can help workflow and reduce post processing of LCA results. To the extent feasible, tools should consider additional reporting features that incorporate scenario comparison.

    - Enhanced reporting and modeling functions for material and building reuse are essential to inform design strategies. It is recommended that reuse modeling be improved at the assembly and building scale with enhancements to scenario comparisons with and without reuse. More defined Modules C2 and C3 for material scale reuse can also increase confidence in the accuracy and usefulness of the results to inform design. Additional considerations should be made regarding the modeling and reporting of biogenic material reuse since biogenic emissions are often reported in Stage C - even for materials leaving the system for reuse.
    - Reporting and accounting for the impacts associated with demolishing or preparing existing building fabric needs clearer guidance and reporting frameworks, like the RICS v2 standard that created a new sub-module, A 5.1, to distinctly report the EOL impacts of building/materials being removed from the site before new construction begins.
    - Finally, separate reporting of biogenic carbon is recommended.
- In Stage C EOL models, **prioritize filling data gaps**
    - Refine/enhance Module C1 - demolition/deconstruction.
        - Conduct further research and or primary data collection on the impacts of mechanical demolition for North American buildings by type, area, method, and equipment.
        - Conduct further research and/or primary data collection on the impacts of deconstruction for North American buildings by type, area, method, and equipment.
    - Reuse pathways for all materials lack reliable data. Collect data to inform default material transport (C2), processing (C3), and losses/disposals (C4) of salvaged materials to prepare them for reuse in buildings. This will directly help inform burdens/credits (Stages C, D, A) given for reused materials based on better transport, processing, loss, and preparation for installation data at the material and building scales. Finally, functional equivalence of reused materials compared to their virgin material replacements needs to be further evaluated.

Limitations

The limitations listed here are only reflective of the recommendations made above. In most cases, this research was limited based on available time and resources dedicated to this project. Specifically, the limitations of the recommendations made in this report include:

- **Survey responses**
    - The survey had only 22 respondents and may not be representative of the entire population of WBLCA tool users. CLF prioritized experienced North American WBLCA tool users that are architects, engineers, and consultants. We are likely missing some perspectives with the small sample size and may learn additional perspectives if we engaged more practitioners and/or a wider international community of tool users.
- **Workshop participation**
    - The workshop included 23 WBLCA tool users and 8 project team members. We limited the number of people to keep the workshop manageable, productive, and interactive for the participants. Additional perspectives may be gained through an expansion of the workshop with additional participants.
- **Data gap analysis**
    - The data gap analysis is based on a limited direct literature review and the method is not standard. The CLF team did not explore public and private LCI databases to examine data gaps directly but did indirectly assess data gaps through tool evaluation, tool users (survey and workshop), and direct interviews with tool providers. Only data gaps that have a high degree of confidence are presented as priorities to fill in our recommendations. Additional reflections on data gaps are covered in the Future Research section.

- **Scope of materials**
  - This project only focused on eight construction materials that included steel, concrete, glulam, cross laminated timber, asphalt roofing shingles, fiberglass insulation, gypsum drywall, and glass. Robust WBLCA modeling will require clear EOL guidance for all of the other material categories required to construct and maintain a functioning building.

Future Research

Many of the recommendations above would require additional research to accomplish. This includes but is not limited to a detailed evaluation of existing LCI data for EOL processes, research into regionalized EOL recovery rates, developing and testing discounting approaches to aid decision making, enhancing the quality of Module C1 data, and improving data on material reuse for all Stage C modules. In addition to these research needs, there are other future research directions uncovered in this project that can more broadly support the improvement of EOL modeling in WBLCA tools.

- **Data gaps assessment and prioritization**
  - Conduct a more comprehensive literature review, assess existing public and private LCI databases, and interview waste processors to highlight Stage C data gaps. Our initial data gap assessment (of eight materials) suggested that glulam, CLT, and glass have the largest data gaps for Stage C. It also suggested that the majority of data gaps are from C1 and C3 Modules while the benefits beyond material life cycles (Module D) pose challenges to model completeness and quality. From an EOL pathway perspective, the initial research suggests evaluation of *reuse and incineration (especially wood)* scenarios also suffer from a shortage of available data.
  - One approach to prioritizing data gaps, is a contribution analysis to total GWP and other impact categories by individual lifecycle modules at a building scale. Material specific contributions to Stage C impacts can also be investigated with an appropriate set of material quantity data from a sample of real buildings. There are multiple sources of real building quantity data that could be utilized for this research.
- **Module D methods and assumptions**
  - Module D reports the benefits and burdens beyond the system boundary for decisions made during Stage C. Credits are often given for displacing a fuel or material feedstock during the production of new materials. Additional research can investigate the methods and assumptions used in existing WBLCA tools for applying substitution credits for functionally equivalent materials. The research can make recommendations on common methods and assumptions in a given geography. ISO 21930 and EN 15804 have guidance on modeling assumptions but specific substitution credit approaches that reflect local reuse and recycling practices are still lacking.
- **Refinement and standardization of terms/definitions**
  - The research team reviewed definitions for terms like reuse, recycling, incineration, and landfilling, but also found some differences in terminology among WBLCA tools. Defining key terms can help harmonize modeling approaches and results interpretation between different WBLCA tools.
- **Biogenic carbon**
  - Although biogenic carbon was not an explicit focus of the research, the survey and workshop results indicated an interest among WBLCA tool users for better documentation, alignment, and reporting of biogenic carbon. The research team could investigate the implications of separating fossil, biogenic, and land use / land change based carbon reporting for an impact factor database and evaluate the alignment of methodologies in tools. Additionally, there are challenges with biogenic carbon accounting related to recycling and reuse. Since recycling and reuse leave the system boundary, biogenic carbon is sometimes reported as an emission in Stage C within the tools reviewed. This can be counterintuitive and unhelpful in informing design decisions related to design for deconstruction / reuse. A more thorough review of the existing-tool treatment of biogenic carbon at EOL is needed. The research can recommend

a harmonized method that's aligned with standards and can better inform design decisions. In some cases, results reporting may be required in one format for policy or standard compliance, but the tools can allow for more informative scenario comparison *within* the tool environment, as recommended above.

- **Expanded tool comparison**
  - This study evaluated three prominent WBLCA tools that are commonly used within the North American market. The evaluation entailed a comparison across the three tools in their underlying EOL data, assumptions, and methodologies. However, tools are being updated periodically to improve modeling accuracy, functions, and background data and methods. Only with a more robust framework for comparison given transparent tool manuals can it be possible to achieve harmonized LCA results to enable policy implementation at scale. Such effort is subject to future research.
- **Material service life database**
  - EOL impacts of buildings are also driven by the number of times certain materials need to be replaced during their whole lifecycle. Most WBLCA tools rely on assumed and fixed replacement rates for materials which may vary across regions, building types, etc. Development of a regionalized database for material service lives based on primary data (e.g., collected from buildings) can further help harmonize LCA models across different WBLCA tools.

APPENDIX A: EOL MANAGEMENT RATES IN PRODUCT CATEGORY RULES

Review of Product Category Rules

Product category rules (PCRs) provide the rules needed to conduct LCAs of products for disclosure through an EPD. In this appendix, **Table 5** shows that many of the materials studied in this project allow reporting of Life Cycle Stage C. We will likely see more PCRs allowing full life cycle reporting in the future. Many of these PCRs also provide default values for EOL management rates.

Table 5. PCR coverage of EOL modeling for the selected materials.

Material	PCR Source	PCR includes Stage C?	PCR includes default EOL management rates?
Steel	Steel PCR (2020)	✓	✓
Concrete	Concrete PCR (2022)		
CLT	Structural Wood Products (2019)	✓	✓
Glulam	Structural Wood Products (2019)	✓	✓
Asphalt Shingles	Asphalt Shingles PCR (2021)	✓	✓
Fiberglass Insulation	Fiberglass Insulation PCR (2023)	✓	✓
Glass	Flat Glass (2020); Processed Glass (2016)		
Drywall	Drywall PCR (2020)	✓	

EOL Management Rates in Part A Product Category Rules (UL + Smart EPD)

Table 6 is a snapshot of the default end-of-life management rates outlined in both the UL Environment and Smart EPD program operator Part A PCRs. Unfortunately, not much detail is available for the North American market. As we refine EOL modeling and data in WBLCA tools, we should also try to harmonize those EOL assumptions with PCRs and EPDs, which may serve as input data for WBLCA tools.

Table 6. Default end-of-life management rates in UL Environment and Smart EPD.[3]

World Market	Country	Material	Recycling Rate	Landfill Rate	Incineration Rate
North America	United States	Aluminum	95%	5%	0%
		Structural steel	97%	3%	0%
		Steel rebar	59%	41%	0%
		All other metals	74%	26%	0%
		Other materials	0%	100%	0%
	Canada	Aluminum	95%	5%	0%
		All other metals	85%	15%	0%
		Other materials	7%	93%	0%
	Mexico	Metals	10%	90%	0%
		Other materials	0%	100%	0%
Latin America	Brazil	All	0%	100%	0%
Europe	EU	All	50%	37%	13%
North Asia	China	All	5%	95%	0%
	Japan	All	53%	4%	43%
	Korea	All	83.9%	9.4%	6.1%

APPENDIX B: EOL MANAGEMENT RATES FOR THE UNITED STATES

Default EOL management rates at a national, state, and regional scale are important for the harmonization of EOL modeling in WBLCA tools. They are equally important in EPDs and PCRs. While further research is needed at both the national and regional scales, **Table 7** below outlines estimated EOL management rates for the eight study materials being reused, recycled, incinerated, and landfilled in the United States.

Table 7. Estimated end-of-life management rates for the selected construction and demolition waste materials in the United States (numbers mostly pertain to 2015).

Material	Reuse	Recycle				Incineration	Landfill
		Compost and Mulch	Manufactured Products	Aggregate	Soil Amendment		
Steel[7]	unknown	-	85%	-	-	-	15%
Concrete[7]	unknown	-	8%	75%	-	-	17%
CLT[7]	unknown	7%	3%	-	-	20%	70%
Glulam[7]	unknown	7%	3%	-	-	20%	70%
Asphalt Shingles[7]	unknown	-	14.2%	0.6%		0.2%	85%
Fiberglass Insulation[4]	unknown	-	-	-	-	-	100%
Glass (flat glass)*	unknown	-	unknown	unknown	-	-	unknown
Drywall[7]	unknown	15%	2%	-	-	Limited	83%

** There is limited data on flat, processed, and insulated glazing unit recovery pathways for the United States. The State of Oregon recovery[8] and disposal data[9] indicates a 7% recycling rate for flat glass.*

The development of default EOL management rates at the national, state, and regional levels is a key step in developing harmonized EOL impact factors for WBLCA tools and is a primary recommendation in this report. For example, the State of Oregon has long-term material recovery and disposal studies at the state scale and has already developed EOL impact factors (combining Modules C2, C3, C4, D) to help inform local waste management decisions.

At least some of Oregon's work can help inform the development of EOL impact factors at other geographies since they have made their impact factors publicly available via GitHub[10] (documenting LCI processes + sources) and have published an online calculator[11] utilizing those factors to inform waste management decision making.

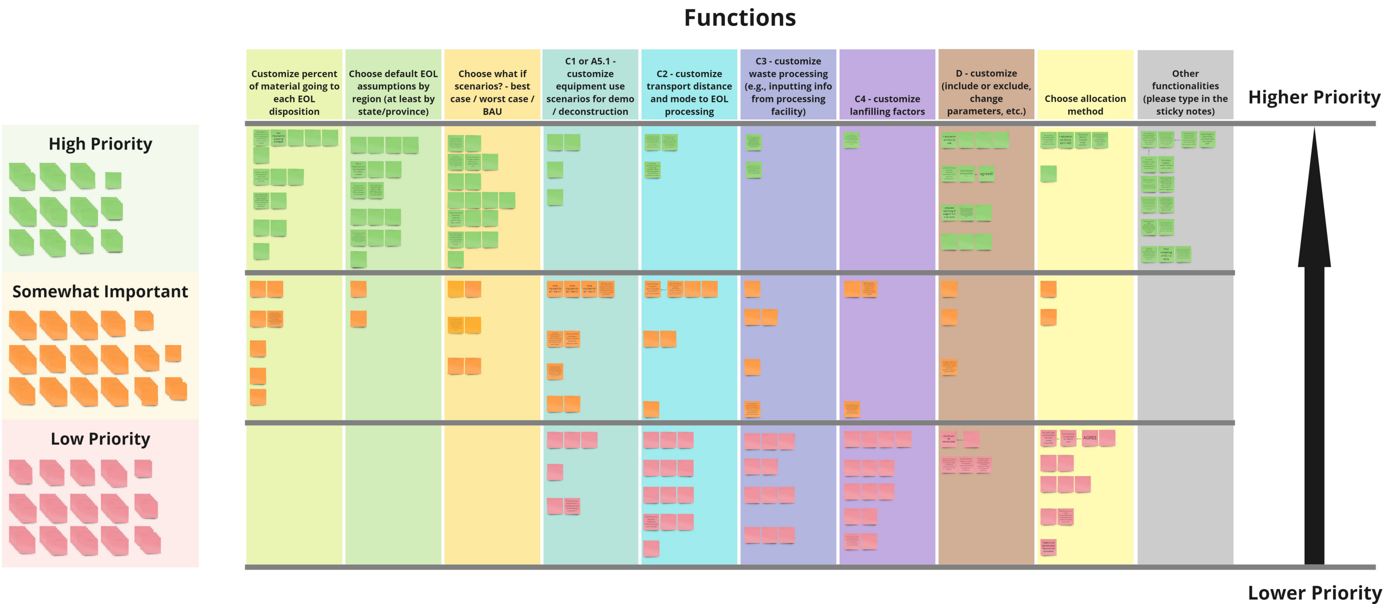
APPENDIX C: SUMMARY OF SURVEY RESPONSES

Table 8. Summary of survey questions and responses.

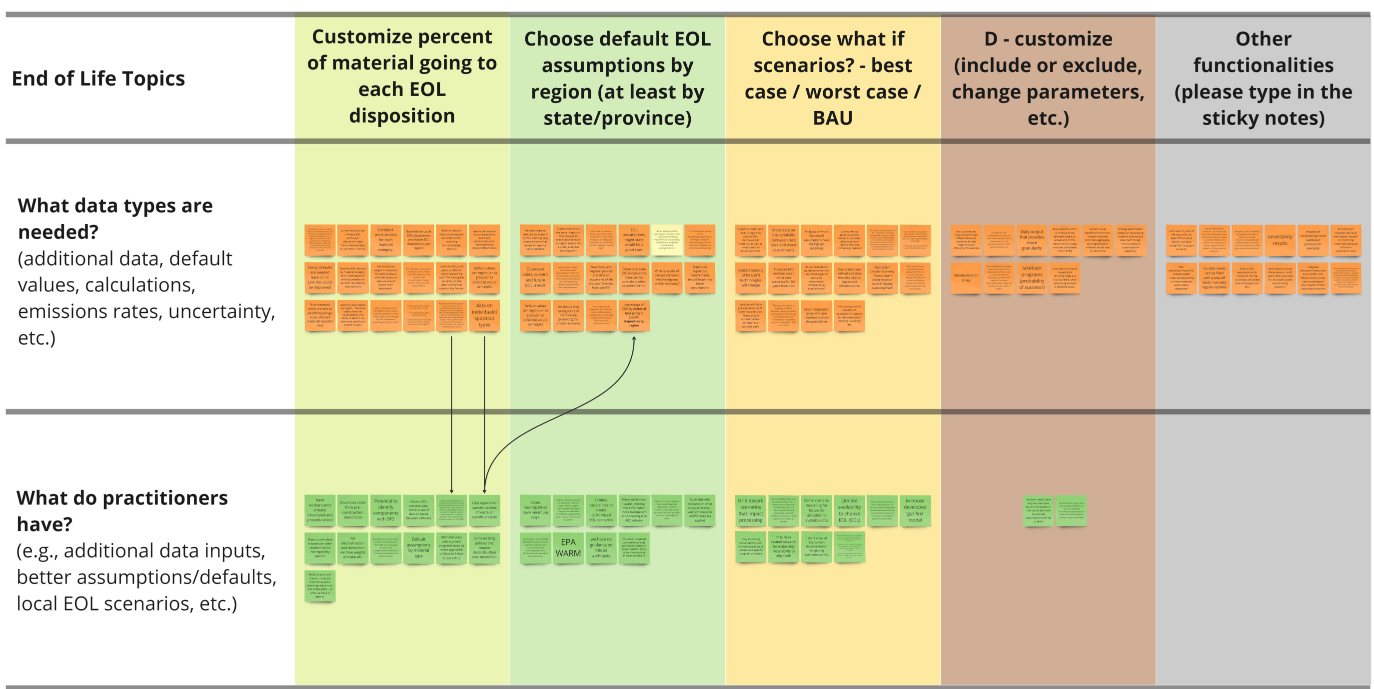
Questions	Summary of Responses
Q1. Where are most of your projects being constructed?	The majority worked on projects located in the US (more than three-quarters), most of which were on the West Coast.
Q2. What best describes your role at the company you work in? (check all that apply)	The majority identified themselves as sustainability leads or LCA analysts.
Q3. What's your firm's size?	Over three-quarters of respondents worked in a firm with more than 50 employees.
Q4. On a scale of 1 to 5, how familiar are you with the following? (1: little knowledge, 5: proficient/expert)	Primary LCA modeling using professional tools and EOL modeling outside WBLCA tool environments seem to be the areas where respondents had the least experience.
Q5. How long have you been performing whole building LCA?	More than 95% of respondents indicated that they have been using WBLCA tools for more than 1 year. About half of the respondents had more than 5 years of WBLCA tool experience.
Q6. What is your main motivation to perform a WBLCA?	The majority (50%) indicated that their use of these tools was in informing design.
Q7. Which of the following LCA tools have you used?	Among WBLCA tools, tallyLCA, One Click LCA, and Athena seem to dominate while EC3, CARE, and EPIC are used more frequently for other purposes.
Q8. Which of the following WBLCA tools are you using the most at your company?	Among WBLCA tools, tallyLCA and One Click LCA are being used almost equally the most.
Q9. How do you rank the following WBLCA tools in terms of EOL modeling functionality?	Almost none of the respondents were fully satisfied with EOL modeling in these tools. However, One Click LCA seems to provide the most comprehensive functions after tallyLCA and Athena.
Q10. What tools do you use besides WBLCA and professional LCA tools for EOL modeling?	While the majority did not use any other tools, those who did have used EPA WARM.
Q11. Have you ever encountered projects where you had more information about EOL than you were able to input into the WBLCA tool?	Almost three-quarters of respondents indicated that existing WBLCA tools could not accept the additional information that practitioners had about the EOL of materials.
Q12. Do you think designers should be able to customize EOL scenarios in WBLCA tools?	Although none of the respondents answered "No" to this question, the majority had doubts about giving full customization functionality.
Q13. Do EOL considerations influence your design decisions? If so, how?	Yes (50%): design for circularity, modularity, carbon reduction through waste minimization, biogenic carbon, alternative comparison. No (41%): not a major driver, limited data, EOL is beyond their control.
Q14. What are your biggest concerns about EOL assumptions in WBLCA tools?	1) Data quality, transparency, and granularity, 2) licensing limitations, 3) unknown future EOL scenarios, 4) standardization, 5) accuracy and validation.
Q15. What aspects of EOL modeling would you like to be improved in WBLCA tools?	1) Customization and flexibility, 2) data transparency, 3) deconstruction modeling, 4) results' granularity, 5) regionalized data, 6) realistic assumptions, 7) EOL what-if scenarios, 8) discounted emissions modeling, 9) material-specific modeling, 10) biogenic and circularity
Q16. Do you have any concerns about how biogenic carbon and/or concrete carbonation are currently reported in the tools you use? If yes, please explain.	Biogenic carbon: lack of standardization, separate reporting, default settings and lack of transparency, lack of knowledge, data quality. Carbonation: limited reporting, lack of transparency and clarity, more research is needed.
Q17. How do assessments of Module D influence your design decisions?	A variety of responses received, ranging from limited influence, suggestion of omitting Module D from calculations, separate reporting of Module D impacts, higher influence of upfront carbon in decisions, use of Module D impacts for alternative comparison, and finally a lack of understanding of what Module D is.
Q18. What is your opinion about material and/or building reuse modeling in WBLCA tools?	Lack of functionality in tools, ambiguity in methods, need for clear guidance, challenges with inputting real-world data, importance of updating standards.

APPENDIX D: WORKSHOP RESPONSES

Activity 1 Responses: High-priority EOL functionalities in WBLCA tools



Activity 2 Responses: Data needs and data availabilities for the top priority EOL functions



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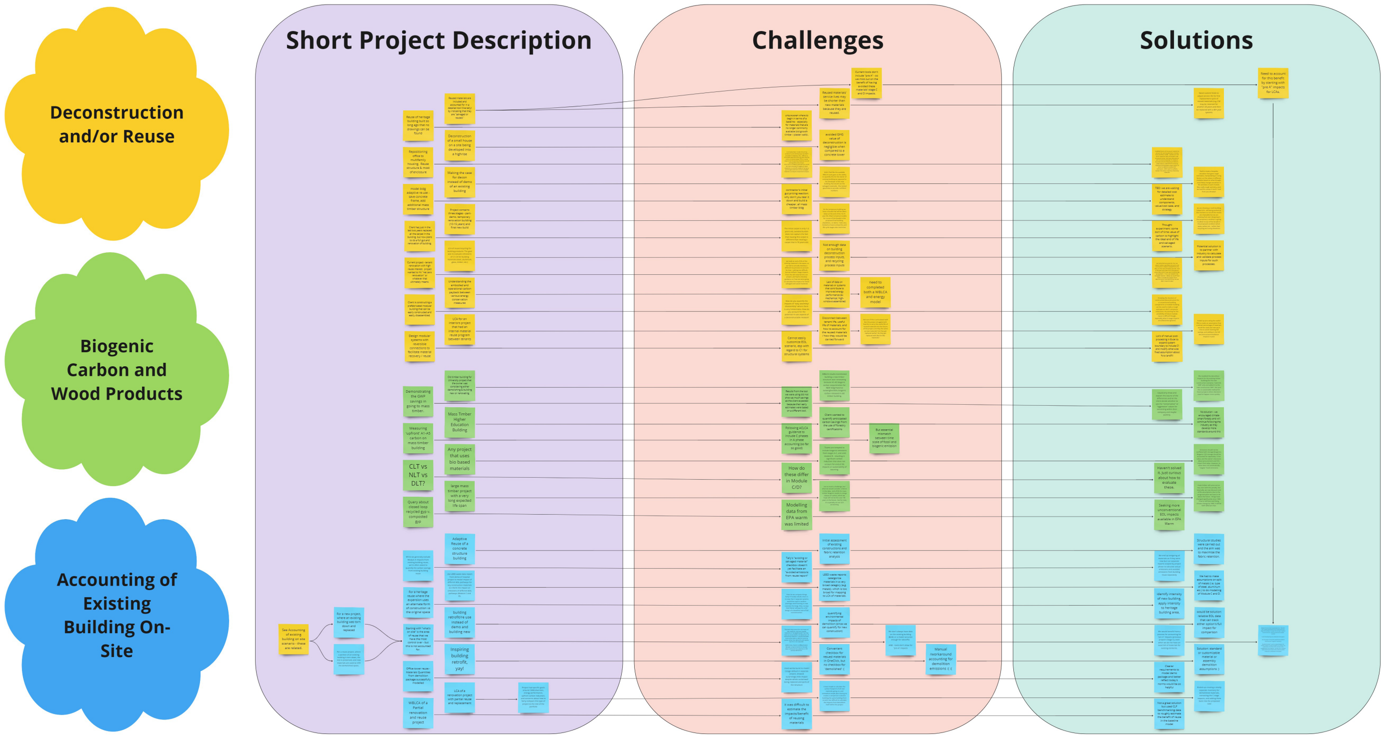
Activity 3 Responses: Real-world EOL modeling stories, challenges, and solutions



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