The Carbon Balance:
Design for Embodied Carbon Measurement of Existing Buildings

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Abstract

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The balance of greenhouse gas (GHG) emissions attributable to the built environment is significantly affected by the decision to either preserve an existing building or demolish it in favor of new construction, concurrently forcing a valuation of the building's historic or cultural importance. While assessment of GHG emissions in the built environment has matured, data collection and material reporting methodologies remain highly varied. Standardization of carbon accounting measures and metrics for existing buildings could improve the ability to compare the carbon impacts and benefits of building reuse, providing increased quality, accuracy, and reliability in decision-making. This thesis seeks to align contemporary building documentation and carbon measurement tools into a single workflow, exploring a streamlined approach to assess the embodied carbon value of existing buildings and which emphasizes the importance of standardized data collection methods. A clearly defined workflow alongside standardization could improve the quality of information guiding design decisions and considerations in building reuse, offering a more sophisticated tool for carbon accounting and performance monitoring of the built environment.

Acknowledgements

Sincere gratitude to David Strauss in service as my committee chair, for his commitment to me, his professionalism, for speaking plainly and with humanity, for his practical insights as a principal for SHKS, and for the great depth of intellect in support of the production of this thesis. David always found a way to ground the conversation, recenter my focus, and provide clarity on intent.

Gratitude as well to committee members Kate Simonen and Kathryn Rogers Merlino, each whose work has served as a baseline informing my greater interest in embodied carbon and building reuse, whose invaluable review and feedback challenged me to elevate my thesis research.

A critical connection I made during the process of investigation was to meet James Harbin, Director of Construction Technology with JTM Construction, who graciously provided his time, knowledge, and use of state-of-the-art survey and reality capture tools.

Special thanks to my former mentor and City Architect, Randy Goodwin, for his inspiration, spirit of generosity, his friendship, and for sharing his wealth of professional knowledge in architecture and public works.

Most importantly, I would like to express deepest gratitude to my family, to my wife and son, to my mother and my late grandfather. They all have my love and deserve the best of my attention and supported me as I directed that attention to the work of this thesis.

Estamos a bastante

List of Abbreviations

AEC	Architecture, Engineering, and Construction
AHCP	Advisory Council on Historic Preservation
BAU	Business as Usual
BIM	Building Information Modeling
BTU	British Thermal Unit
CARE	Carbon Avoided Retrofit Estimator
CLF	The Carbon Leadership Forum
CO2	Carbon Dioxide
CO2eq	Carbon Dioxide equivalent
EC	Embodied Carbon
EC3	Embodied Carbon in Construction Calculator
EOL	End of Life
EPD	Environmental Product Declaration
GHG	Greenhouse Gases
GPR	Ground Penetrating Radar
HRS	Hours
ILFI	International Living Future Institute
LBC	Living Building Challenge
LCA	Life Cycle Assessment of Buildings
LiDAR	Light Detection and Ranging
NTHP	The National Trust for Historic Preservation
OP	Operational Carbon
RICS	Royal Institution of Chartered Surveyors
SLAM	Simultaneous Localization and Mapping
SF	Squar Feet
UK	The United Kingdom
UN	The United Nations
US	The United States of America
USGBC	U.S. Green Building Council
WBLCA	Whole Building Life Cycle Assessment
WLCA	Whole Life Carbon Assessment

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CHAPTER 1: Introduction & Problem Statement

Today, there is an urgent obligation to mitigate the worst outcomes of human-caused climate change. Continuous refinement of methods for measuring climate-warming greenhouse gas emissions is essential to ensure humanity can meet “the needs of the present without compromising the ability of future generations to meet their own needs”.[1] Perhaps one of the most critical areas for these measurements are emissions stemming from processes intertwined with the construction and preservation of the built environment.

Albert Einstein famously said, “Not everything that can be counted counts and not everything that counts can be counted.” In the same vein, everything counted in a different manner cannot be compared. Concepts of uniform weight and measures have evolved through political and technical iteration over hundreds of years. During the French Revolution, nearly a quarter-million different means of measurement across France were consolidated into what we know today as the meter.[2] More recently, in 2019, the Kibble Balance—an electro-magnetic measurement tool—replaced what was previously a physical reference for the kilogram (Le Grand K), a metal artifact held in a locked vault in Paris since 1879 that continued to serve as a basis for global measurements for more than a century.[3]

While historic preservation policy has made lasting investments in cultural history and heritage, it has also significantly contributed to the development of climate change research in the built environment. Shortly after the National Historic Preservation Act of 1966 (NHPA) and the creation of the Advisory Council on Historic Preservation (ACHP), the United States experienced a decade of acute social and economic upheaval, including two fossil fuel energy crises. The Oil Embargo of 1973-1974 and the Oil Shock of 1978-79 bookended the decade, inspiring the ACHP to explore new ways of thinking about buildings, energy, and preservation, ultimately influencing how we approach climate change in the built environment today.[4,5]

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[1] *“Report of the World Commission on Environment and Development: Our Common Future.” sustainabledevelopment.un.org, United Nations, 15 Mar. 2009, sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf.*

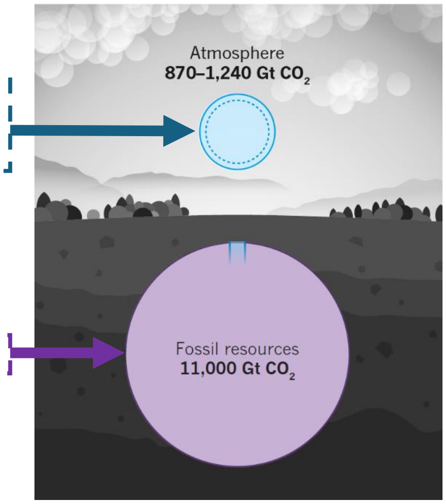
[2] *Bennett, Jay. “Scientists Are about to Redefine the Kilogram and Shake up Our System of Measures.” Smithsonian.Com, Smithsonian Institution, 14 Nov. 2018, www.smithsonianmag.com/science-nature/redefine-kilogram-180970798/.*

[3] *Ibid*

[4] *“Milestones: 1969–1976 - Oil Embargo, 1973–1974.” Office of the Historian, U.S. Department of State, 2017, history.state.gov/milestones/1969-1976/oil-embargo.*

In 1979, in response to a decade of US energy dependency and market failures, the ACHP introduced a novel concept of measuring the value of the embodied energy of existing buildings—or the energy already expended to produce building materials and during construction or renovations—against the energy expended in the demolition of the existing building and subsequent new construction.[6] Providing evidence through measurement encouraged a new focus on building performance and reuse, demonstrating the potential to incur greater energy costs by prioritizing new construction over preservation.

While aspects of the ACHP research were rooted in energy self-determination, it also addressed methods of measurement and called into question practices that lead to poor building performance.[7] The ACHP report greatly contributed to analogs developed since and in practice today, informing contemporary research and remaining highly relevant amidst the urgency associated with our modern understanding of the causal relationship between energy production and consumption, greenhouse gas emissions, and environmental and social impacts from climate change. Contemporary research indicates the capacity of Earth's atmosphere cannot accommodate even a tenth of the potential emissions from known fossil fuel reserves before exceeding limits set forth by the Paris Climate Accord in 2015. The Paris Agreement seeks to prevent a global temperature rise over 2 degrees Celsius above pre-industrial levels, beyond which climate scientists believe impacts would create serious risks to human life.[8]



2050 emissions cap to avoid 2°C increase in temperature above pre-industrial times.

Emissions stored in known fossil fuel reserves as of 2015.

FIGURE 1 - ATMOSPHERIC CARBON CAPACITY VS FOSSIL FUEL RESOURCES. JAKOB, MICHAEL, AND JÉRÔME HILAIRE. "UNBURNABLE FOSSIL-FUEL RESERVES." NATURE NEWS, NATURE PUBLISHING GROUP, 7 JAN. 2015,

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[5] *Richards, Heather. "What the 1970s Teaches about Today's Energy Crisis." E&E News by POLITICO, 15 Apr. 2022, www.eenews.net/articles/what-the-1970s-teaches-about-todays-energy-crisis/.*

[6] *ACHP, Advisory Council on Historic Preservation, 1 Jan. 1979, www.achp.gov/digital library-section-106-landing/assessing-energy-conservation-benefits-historic-preservation. Building and Environment.*

[7] *Richards, Heather. "What the 1970s Teaches about Today's Energy Crisis." E&E News by POLITICO, 15 Apr. 2022, www.eenews.net/articles/what-the-1970s-teaches-about-todays-energy-crisis/.*

[8] *Jakob, Michael, and Jérôme Hilaire. "Unburnable Fossil-Fuel Reserves." Nature News, Nature Publishing Group, 7 Jan. 2015, www.nature.com/articles/517150a.*

In 2011, the National Trust for Historic Preservation's (NTHP) published *The Greenest Building: Quantifying the Environmental Value of Building Reuse*[9], building on the seminal 1979 ACHP report. The NTHP study utilized a Life Cycle Assessment (LCA) methodology to quantify a carbon value for building typologies across North American climate zones.[10] At the time of its publication, the NTHP report documented LCA studies that indicated greater carbon dioxide emission (CO2) reductions from building reuse compared to demolition and new construction.[11] While the report's most quantifiable evidence relied on LCAs, it also acknowledged that building "LCA [was] still in its infancy", a fact which has since garnered modern skepticism in the validity of precision produced by the report.[12]

Since 2011, LCA research has continued to mature, especially in understanding embodied carbon or the processes of materials extraction, refinement, construction, and demolition, providing further evidence that building reuse is often the superior choice compared to new construction in the pursuit of GHG emissions reductions (Fig 2). Research has placed less emphasis on near term impacts of individual building's operational carbon, or GHG emissions generated from a building's energy use, and re-emphasized the need to prioritize and innovate in the preservation of existing buildings, such as was made in the NTHP's *The Greenest Building*, to reduce new and retain existing embodied carbon (EC) in the built environment.[13]

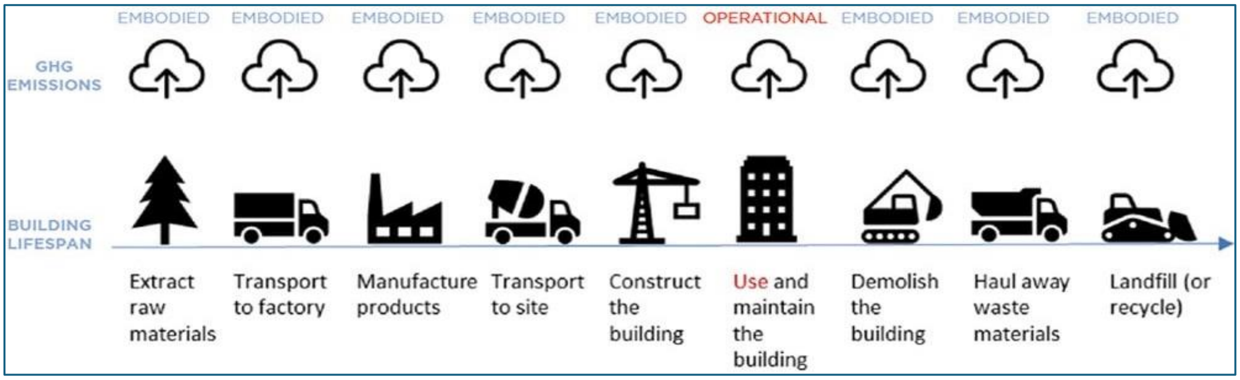

FIGURE 2 - LCA EMBODIED AND OPERATIONAL FLOW CHART DIAGRAM. "THE EMBODIED CARBON REVIEW: EMBODIED CARBON REDUCTION IN 100+ REGULATIONS AND RATING SYSTEMS GLOBALLY." C40KNOWLEDGEHUB.ORG, C40, JAN. 2021, WWW.C40KNOWLEDGEHUB.ORG/S/ARTICLE/THE-EMBODIED-CARB.

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[9] *Frey, Patrice. "Quantifying the Environmental Value of Building Reuse." LivingFuture.Org, National Trust for Historic Preservation, 2011, living-future.org/wp- content/uploads/2022/05/The_Greenest_Building.pdf.*

[10] *Ibid*

[11] *Ibid*

[12] *Ibid*

[13] *Ibid*

Clarity of EC measurement frameworks has improved since the publication of *The Greenest Building*. Progress has been made by organizations such as the Carbon Leadership Forum (CLF) to simplify methods for documenting and communicating the emissions processes (Fig 3).[14] This is essential to inform decision making and improve the effectiveness of emissions reduction strategies, enabling practitioners to identify the most impactful strategies to be prioritized, monitor building performance, and support progress on emissions reduction targets.

Building LCA estimation tools such as Athena, Tally and The Embodied Carbon in Construction Calculator (EC3) rely on LCA databases and product specific LCA results reported in environmental product declaration (EPD) databases to compare materials for their environmental impact value.[15,16,17,18] However, these tools and methods for measuring the embodied carbon of existing buildings are often bespoke and can be time-and cost-prohibitive and are not specifically designed to evaluate existing buildings.[19,20,21,22] Standardization of data collection and analysis tools into a single workflow could support improved efficiency, accuracy, and scalability of LCA assessment of existing buildings. Architect Larry Strain, working with the CLF, emphasized which climate emissions reductions would have the most benefit today by defining the "time value of carbon", asserting that "emissions are cumulative, and because we have a limited amount of time to reduce them, carbon reductions now have more value than carbon reductions in the future."[23] When considering this with Einstein's comments on measures, it can be inferred that what counts most in mitigating climate change is the reduction of embodied carbon emissions. Standardization and efficiency of measurement focused on existing buildings for their embodied carbon value can help identify what should be counted and inform timely decisions in prioritizing emissions accounting in the built environment.

The environmental impact of the materials already in place in existing buildings is typically unaccounted for in broader carbon accounting frameworks. Building reuse could provide substantial emissions reductions by avoiding

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[14] *"Who We Are." Carbonleadershipforum.Org, Carbon Leadership Forum, 7 Apr. 2024, carbonleadershipforum.org/who-we-are/.*

[15] *"LCA for Buildings | Athena Sustainable Materials Institute." Athenasmi.Org, Athena Sustainable Materials Institute, www.athenasmi.org/resources/about-lca/lca-in-construction-practice/. Accessed 15 Apr. 2023.*

[16] *"About: Overview." Tally, choosetally.com/overview/. Accessed 20 May 2023.*

[17] *"EC3 User Guide." Building Transparency, 27 Jan. 2023, www.buildingtransparency.org/ec3-resources/ec3-user-guide/.*

[18] *Adlerstein, Michael. "Assessing the Carbon-Saving Value of Retrofitting versus Demolition and New Construction at the United Nations Headquarters."*

[19] *"LCA for Buildings | Athena Sustainable Materials Institute." Athenasmi.Org, Athena Sustainable Materials Institute, www.athenasmi.org/resources/about-lca/lca-in-construction-practice/. Accessed 15 Apr. 2023.*

[20] *"About: Overview." Tally, choosetally.com/overview/. Accessed 20 May 2023.*

[21] *"EC3 User Guide." Building Transparency, 27 Jan. 2023, www.buildingtransparency.org/ec3-resources/ec3-user-guide/.*

[22] *Adlerstein, Michael. "Assessing the Carbon-Saving Value of Retrofitting versus Demolition and New Construction at the United Nations Headquarters."*

[23] *Strain, Larry. "CLF Time Value of Carbon." Carbon Leadership Forum, 30 May 2017, carbonleadershipforum.org/wp-content/uploads/2017/06/CLF-Time-Value-of-Carbon.pdf.*

demolitions that squander previously expended energy and carbon embodied in a building while preventing generation of new emissions for construction and offering the potential co-benefit of preserving historic buildings. With billions of square feet of existing buildings in the U.S. and even more globally, it is it is essential to refine and

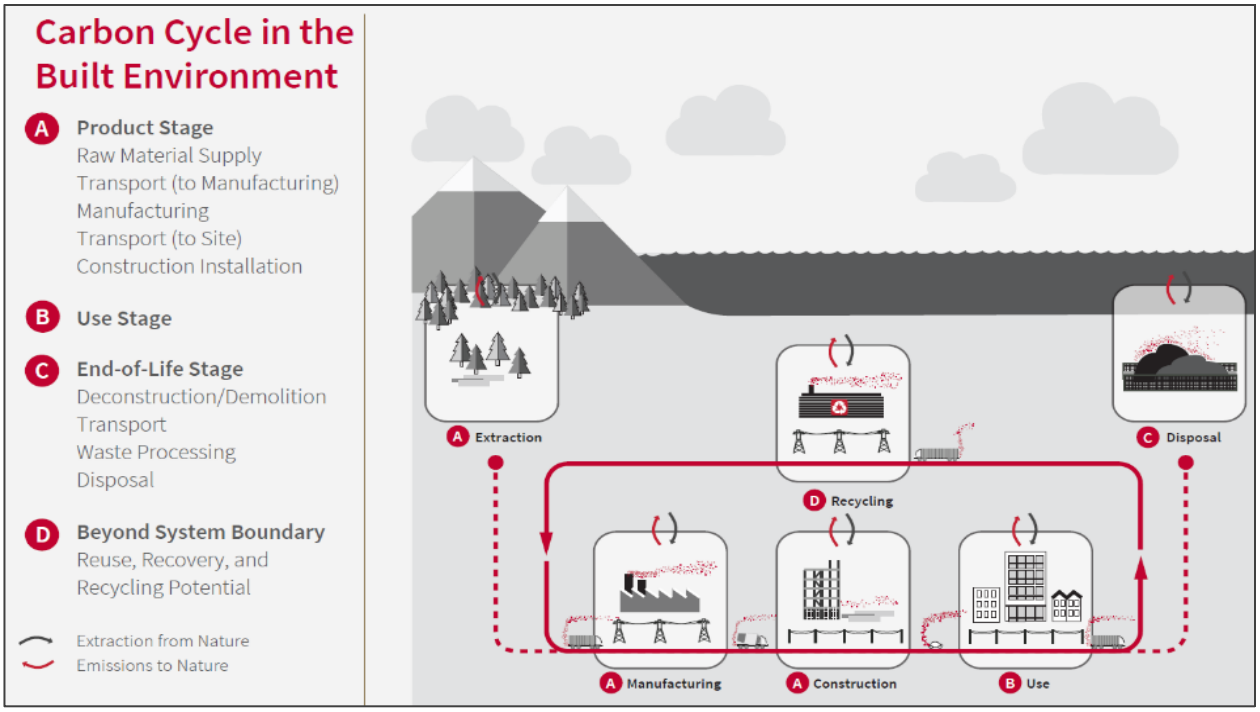

FIGURE 3 - LCA CLASSIFICATION OF SCOPE EMISSIONS DIAGRAM. "AIA-CLF EMBODIED CARBON TOOLKIT FOR ARCHITECTS." CARBON LEADERSHIP FORUM, 8 APR. 2023, CARBONLEADERSHIPFORUM.ORG/CLF-ARCHITECT-TOOLKIT/.

CHAPTER 2: Literature Review, Precedent Analysis, & Case Studies

2.1 MEASURE TWICE: REALITY CAPTURE TOOLS AND TECHNOLOGY

Architectural representation and methods continue to evolve, including those used for assessing and mitigating carbon emissions attributed to the built environment. A key area of evolution is in the tools used to estimate carbon costs, benefits and trade-offs to determine whether to reuse an existing building or to demolish it and construct a new one. In reusing buildings, accurate measurements of existing as-built conditions are required to understand the performance of structural members and identify unrecorded alterations or demolitions.

Photogrammetry and LiDAR are contemporary tools that provide time-efficient, precise measurements of existing buildings.[24] While photogrammetry offers a wider color spectrum and superior visual representation, LiDAR provides more precise measurements and greater opportunities for software analytics, such as segmentation and identification of planar and coplanar structural members, as represented in the point cloud.[25,26] Both tools can assess existing buildings for potential reuse. The following literature review outlines these tools and summarizes the state of the practice for entities conducting LCAs in the consideration of building reuse and preservation.

2.1.1 PHOTOGRAMMETRY

The development of photogrammetry is closely linked to the invention of the camera and photography in early 19th-century Europe.[27] The underlying technology and photographic concept of utilizing mirrors and light for accurate representation in art has been well demonstrated by artists like Rembrandt, who produced highly accurate self-portraits in the 17th century.[28] However, the advent of photography significantly impacted artistic representation, with some critics fearing “that photography would in time entirely supersede the art of painting” and that “…when the process of taking photographs in colors has been perfected and made common enough, the painter will have nothing more to do.”[29] Despite these concerns, the widespread use of photographic methods flourished within the art world and across scientific disciplines, leading to the creation of photogrammetry. The

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[24] *Luhmann, Thomas, et al. “Chapter 1; Introduction.” Close Range Photogrammetry: Principles, Techniques and Applications, Whittles Publishing, Dunbeath, 2014.*

[25] *Ibid*

[26] *Ntiyakunze, Joram, and Tomo Inoue. “Segmentation of Structural Elements from 3D Point Cloud Using Spatial Dependencies for Sustainability Studies.” MDPI, Multidisciplinary Digital Publishing Institute, 8 Feb. 2023, www.mdpi.com/1424-8220/23/4/1924.*

[27] *Luhmann, Thomas, et al. “Chapter 1; Introduction.” Close Range Photogrammetry: Principles, Techniques and Applications, Whittles Publishing, Dunbeath, 2014.*

[28] *Yin, Steph. “The Mirrors behind Rembrandt’s Self-Portraits.” The New York Times, The New York Times, 14 July 2016, www.nytimes.com/2016/07/14/science/rembrandt-old-master-optics-mirrors.html.*

[29] *Teicher, Jordan G. “When Photography Wasn’t Art - Jstor Daily.” JSTOR Daily, JSTOR, 6 Feb. 2016, daily.jstor.org/when-photography-was-not-art/.*

photogrammetric method is defined as "image measurement and interpretation in order to derive the shape and location of an object from one or more photographs of that object."[30]

Photogrammetry was invented as a method in response to increasingly sophisticated architectural work and representation. Developed just a few years after the creation of photography, architect Albrecht Meydenbauer coined the term "photogrammetry".[31] Meydenbauer's initial development of photogrammetry aimed "to avoid the conventional, often dangerous, manual method of measuring façades" in the archiving of Prussian architectural monuments, citing the added benefit of the method "as insurance against the damage or destruction of the cultural heritage."[32] Photogrammetric methods and camera technologies continued to improve, from analog computation in the late 19th century to integration with digital electronics and computation in the mid-20th century, continuing into the modern era of post-processing technologies that enable analysis of visual representations. These advancements allow for the automated generation of 3D models and CAD drawings calculations, and analyses of existing buildings.[33]

2.1.2 LIDAR

The history and development of LiDAR (Light Detection and Ranging) is tied to the development of laser technology for range-finding associated with artillery applications dating back to 1933. This technology evolved for use in aeronautics, environmental science, and space navigation starting in the 1960s.[34] Understanding the fundamentals of LiDAR requires knowledge of its use of laser technology. Since a laser is light, and "[b]ecause we know the speed of light, we can calculate range" by casting and receiving single or multiple reflected laser beams.[35]
A contemporary architectural application of this technology is 3D LiDAR, which generates a "point cloud"—a computer-generated 3D digital representation from hundreds of thousands, or up to millions, of laser measurements taken per second. These measurements are taken across azimuth and elevation positions to create a precise 3D picture of a space.[36] 3D LiDAR can be applied at macro and micro scales, from devices attached to airborne vehicles mapping exterior land and cityscapes, to the precise detailing of architectural elements within

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[30] *Luhmann, Thomas, et al. "Chapter 1; Introduction." Close Range Photogrammetry: Principles, Techniques and Applications, Whittles Publishing, Dunbeath, 2014.*
[31] *Ibid*
[32] *Ibid*
[33] *Ibid*
[34] *McManamon, Paul F. "Chapter 5 - History of LiDAR." Lidar Technologies and Systems, SPIE Press, Bellingham, WA, USA :, 2019.*
[35] *Ibid*
[36] *Ibid*

buildings, providing for precise plan and shop drawing replication. Additionally, design and analytics software continues to innovate, allowing for the complicated calculation, interpretation, and manipulation of point clouds, representing a significant technological leap for efficiency and precision.[37]

2.2 CARBON ACCOUNTING: THE ROLE OF LCA & STANDARDIZATION OF MEASUREMENT

The importance of LCA in understanding embodied carbon (EC) emissions trade-offs between building reuse and new construction has been highlighted in various reports including the 1979 ACHP report, the 2011 NTHP's *The Greenest Building*, and the CLF's 2016 *The Time Value of Carbon*. However, despite some consensus on the value of LCA, its history has been marked by divergent approaches, terminologies, and results, often leading to speculative claims in commercial product marketing.

In the 1990s, the Society of Environmental Toxicology and Chemistry (SETAC) in North America and Europe convened LCA practitioners to initiate efforts on the "continuous improvement and harmonization of LCA frameworks, terminology and methodology".[38] By 1994, SETAC began collaborating with the International Organization for Standardization (ISO) to establish the ISO 14040 and 14044 standards, which continue to guide LCA practices today.[39] However, ISO standards lacked detail, offering "no single method for conducting LCA."[40]

Many organizations have since sought to enhance communication and methodology. Notable examples include the Carbon Leadership Form (CLF), Architecture 2030, and Building Transparency, providing resources defining the role of LCA in the built environment and individual materials at varying levels of specificity.[41]

For instance, the CLF offers guidance for conducting an LCA and adapting it for assessing buildings[42], including:

1) Define Goal and Scope
2) Inventory Materials
3) Perform Impact Assessment
4) Interpret Results
5) Report Results

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[37] *McManamon, Paul F. "Chapter 5 - History of LiDAR." Lidar Technologies and Systems, SPIE Press, Bellingham, WA, USA :, 2019.*

[38] *Ibid*

[39] *Ibid*

[40] *Ibid*

[41] *CLF – Embodied Carbon. "AIA-CLF Embodied Carbon Toolkit for Architects." Carbon Leadership Forum, 8 Apr. 2023, carbonleadershipforum.org/clf-architect-toolkit/.*

[42] *Lewis, Meghan. "Life Cycle Assessment of Buildings (LCA): A Practice Guide." Carbonleadershipforum.Org, Carbon Leadership Forum, 30 Mar. 2024, carbonleadershipforum.org/lca-practice-guide/.*

Digital tools and databases have also been developed to streamline the LCA process in building assessments:

- **Tally**, is an LCA assessment tool for whole buildings, integrating directly into the design process as a "plug-in", for Revit design software.[43] Tally and other LCA software utilize different commercial or non-profit LCA material databases.[44]
- **The Embodied Carbon Calculator (EC3)**, developed within the CLF, assesses the carbon value of individual materials by referencing a database of environmental product declarations (EPDs), developed through industry research and with variable accuracy and reliability.[45]

Tally and EC3 have begun collaborating to align their databases for a more comprehensive and accurate accounting of the potential carbon emissions resulting from the selection of different building materials. This important step in data integration holds promise for further enhancement of GHG and EC measurement in buildings.[46]

While consensus on a single LCA standard and methodology for buildings may not yet exist, the tools and literature of LCA have matured significantly. Interest in understanding the value of building reuse remains strong, and this context could aid ongoing discussions in pursuit of consensus on the standardization of methodologies.

2.3 HISTORIC VALUES: BUILDING PRESERVATION POLICY & PERFORMANCE

The 2011 study by the NTHP, *The Greenest Building: Quantifying the Environmental Value of Building Reuse*, has added depth to the value of existing buildings and historic preservation, echoing the call to action in ACHP's 1979 report on buildings and energy. Both reports urge the public and policymakers to expand their perceptions of which buildings should be preserved and why.

Within the research of the *Greenest Building*, findings asserted that:

> "building reuse almost always offers environmental savings over demolition and new construction. Moreover, it can take between 10 and 80 years for a new, energy-efficient building to overcome, through more efficient operations, the negative climate change impacts that were created during the construction process."[47]

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[43] *"About: Overview." Tally, choosetally.com/overview/. Accessed 20 May 2023.*

[44] *Ibid*

[45] *"EC3 User Guide." Building Transparency, 27 Jan. 2023, www.buildingtransparency.org/ec3-resources/ec3-user-guide/.*

[46] *Tallycat Beta. "Tallycat Beta." Building Transparency, 14 Apr. 2023, www.buildingtransparency.org/tally/tallycat/.*

[47] *Frey, Patrice. "Quantifying the Environmental Value of Building Reuse." LivingFuture.Org, National Trust for Historic Preservation, 2011, living-future.org/wp- content/uploads/2022/05/The_Greenest_Building.pdf.*

The combined effect of the 1979 ACHP call to action and the 2011 study has added urgency to efforts to mitigate climate change. It has also given greater credibility to the potential co-benefits of aligning sustainable and historic preservation policy. In recent years, discussions have contemplated substantive changes to historic preservation policies and the traditional focus of the ACHP and federal, state, and local preservation implementation, which has been critiqued for tending to overly focus on the preservation of aesthetics and on buildings that are that hold more significance to white, wealthy men.[48] This practice has contributed in some cases to the erasure of communities of color and places of importance for women and people with less economic power at varying times in history.

Elected as Chair to the ACHP at the close of 2022, Cornell Professor Sara C. Bronin produced several policy papers in her first year of tenure. Bronin's policy papers underscore the ACHP's obligations and connect with aspects of sustainable policy. Bronin's multi-disciplinary background in preservation, architecture, and law are visible in her analysis of the ACHP's statutory obligations under the *National Historic Preservation Act of 1966*. This act requires the ACHP to "review the policies and programs of federal agencies and recommend… methods to improve their effectiveness, coordination, and consistency."[49]

In response, Bronin developed two policy papers fulfilling this obligation: The *Housing and Historic Preservation Policy Statement* (HHPPS) and the *Climate Change and Historic Preservation Policy Statement* (CCHPPS). Both papers build upon the 1979 ACHP report and the 2011 NTHP report.[50] On March 1, 2024, Bronin delivered to the ACHP a six- hundred-page report analyzing the Federal Historic Preservation standards, informed in part by findings from the HHPPS and CCHPPS. In a subsequent webinar hosted by Bronin providing public guidance on the document,.[51] she explicitly highlights a principle included in both policy documents addressing the nexus of historic preservation and sustainability policies.

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[48] *Ghoshal, Shreya, et al. "Preservation, Sustainability, and Equity: Preservation's Intersection with Sustainability and Equity: A Literature Review." Columbia GSAPP, Columbia University, 2021, www.arch.columbia.edu/books/catalog/826-preservation-sustainability-and-equity.*

[49] *Bronin, Sara. "Exploring the ACHP Chair's Report: Reviewing and Modernizing Federal Historic Preservation Standards." YouTube, Advisory Council on Historic Preservation, 13 Mar. 2024, www.youtube.com/watch?v=t0-UpvfUt_Y.*

[50] *"Advisory Council on Historic Preservation." ACHP.Gov, Advisory Council on Historic Preservation, 2024, www.achp.gov/initiatives.*

[51] *Bronin, Sara. "Exploring the ACHP Chair's Report: Reviewing and Modernizing Federal Historic Preservation Standards." YouTube, Advisory Council on Historic Preservation, 13 Mar. 2024, www.youtube.com/watch?v=t0-UpvfUt_Y.*

From the CCHPPS, Climate Principle 10, states:

> "The federal government should expand and more flexibly apply its guidance on the treatment of historic properties threatened by climate change… [and] should accelerate the development of additional guidance for acceptable treatments of historic buildings, sites, and landscapes facing climate risks. The guidance should extend beyond flooding to the broad range of climate impacts, should incorporate the latest technological innovations and material treatments, and should increase flexibility in retrofitting buildings to be more resilient while preserving their historic character as much as possible."[52]

From the HHPPS, Housing Principle 7, states:

> "The federal government should expand upon its guidance regarding reuse and rehabilitation of historic properties for housing and should encourage flexible yet consistent application of such guidance…The federal government should add to and flexibly apply its guidance on the treatment of historic properties in ways that will incentivize housing development, particularly of affordable housing, and facilitate adapting nonresidential buildings to housing."[53]

These policy statements directly align with each other, illustrating the reciprocal relationship between historic preservation and sustainability policy, recognizing the power of preservation to reduce carbon emissions alongside multiple other goals. Co-benefits could include increased climate resiliency and improved equity outcomes by incentivizing increased creation of affordable housing from existing building stock. The ACHP, with a statutory obligation to existing assets, is well-positioned to set contemporary standards aligning the built environment with building performance that is responsive to the needs of both people and climate change.

The value of embodied carbon in existing structures as a historic preservation technique is clear. Doing so could enhance the value of historic preservation and building reuse through a more complete understanding of the energy invested in the building, the carbon emissions avoided in preserving them, and the social equity outcomes from maintaining services to disadvantaged communities. Precedent studies at the intersection of preservation, climate, and equity estimate "…approximately 125 million existing buildings across the… [US, with] [a]bout 39

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[52] *Bronin, Sara. "Exploring the ACHP Chair's Report: Reviewing and Modernizing Federal Historic Preservation Standards." YouTube, Advisory Council on Historic Preservation, 13 Mar. 2024, www.youtube.com/watch?v=t0-UpvfUt_Y.*

[53] *Ibid*

percent of the[m]—nearly fifty million buildings… [being] at least fifty years old" and lacking consistent maintenance, further exacerbated by an industry preference for demolition and new construction.[54] Overall, historic preservation would benefit from greater precision, standardization, and expediency in accounting for embodied carbon in existing buildings. A culture of resource consumption and wasting can be better combated through a unified approach to quantifying analyses.

2.4 CASE STUDIES

The following case studies provide contemporary examples of practice in photogrammetry, LiDAR, and LCA in preservation and building reuse. Each case study exemplifies the effectiveness of each technology to the intent of the project. This information is meant to provide supporting evidence of how these technologies are employed in the built environment and to serve as a baseline to inform later discussion in this paper.

2.4.1 PHOTOGRAMMETRY

CHURCH OF PANAGIA KARMIOTISSA, CYPRUS, BUILT 13TH-14TH CENTURY CE

In 2021, Cyprus University of Technology researchers wanted to gain greater insight into the historic and cultural value embodied in the Church of Panagia Karmiotissa and did so by employing photogrammetry techniques which utilized a UAV or unmanned aerial vehicle as well as thermal imaging and ground penetrating radar.[55] The researchers found the techniques to be successful, resulting in "3D models and digital elevation models to document and preserve the cultural history of the site", which can be seen in Figure 4.[56]

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[54] *Lindberg, James B. "Reorienting toward Climate and Justice Avoiding Carbon: Mitigating Climate Change through Preservation and Reuse." Preservation, Sustainability, and Equity, 16 Mar. 2022, www.arch.columbia.edu/books/reader/826-preservation-sustainability-and-equity.*

[55] *Shultz, Karsten, et al. "Earth Resources and Environmental Remote Sensing/GIS Applications XII." SPIEDigitalLibrary.Org, Sept. 2021, spie.org/ERS/conferencedetails/earth-resources-environmental-remote-sensing-gis-applications.*

[56] *Ibid*

FIGURE 4 - VARIOUS VIEWS OF 3D MODEL GENERATED FROM PHOTOGRAMMETRY. SHULTZ, KARSTEN, ET AL. “EARTH RESOURCES AND ENVIRONMENTAL REMOTE SENSING/GIS APPLICATIONS XII.” SPIEDIGITALLIBRARY.ORG, SEPT. 2021, SPIE.ORG/ERS/CONFERENCEDETAILS/EARTH-RESOURCES-ENVIRONMENTAL-REMOTE-SENSING-GIS-APPLICATIONS.

2.4.2 LIDAR COVERED BRIDGES (VARIOUS), UNITED STATES, BUILT 1869-1884

To preserve the engineering and architectural heritage of covered bridges in the United States, a collaboration was convened in 2012 across several state and federal agencies. The project utilized precise measurements of covered bridges in Iowa, Minnesota, and Wisconsin employing LiDAR scanning and CAD software.[57] In response to the loss of many covered bridges to extreme weather in New England in 2011, and the increasing likelihood of more extreme weather due to climate change, there was a recognized need to hasten documentation of historic structures in the National Parks Service's Historic American Engineering Record (HAER).[58]

By using advanced LiDAR technology, which emits a laser beam from a rotating mirror toward the area being scanned and calculates the distance to objects in the vertical and horizontal axes for input into a digital 3D point cloud model, researchers estimated "an overall time savings of 100+ person-hours through the use of 3D scanning" compared to traditional methods.[59] For this study, a LiDAR scanner was staged on a tripod at over twenty static locations for each bridge. After verification with tape measurements, the study found that the methodology produced accurate measurements within a 1-2mm margin for error, resulting in precise point clouds and CAD models for analysis and future reproduction (see Figure 5).[60]

Although this relatively recent example of LiDAR technology dates to 2012, technology has continued to advance in the field of 3D reality capture, LiDAR scanning, and software processing tools. Over the past twelve years, there have been significant improvements and efficiency gains in mobile and autonomous scanning of objects. Additionally, the post processing software market has expanded greatly, with the use of machine learning to identify objects automatically and efficiently, enhancing the production of 3D models and as-built drawings.[61]

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[57] *Ross, Robert J., et al. "Use of Laser Scanning Technology to Obtain As-Built Records of Historic Covered Bridges." US Forest Service Research and Development, Aug. 2012, www.fs.usda.gov/treesearch/pubs/41846.*

[58] *Ibid*

[59] *Ibid*

[60] *Ibid*

[61] *Ntiyakunze, Joram, and Tomo Inoue. "Segmentation of Structural Elements from 3D Point Cloud Using Spatial Dependencies for Sustainability Studies." MDPI, Multidisciplinary Digital Publishing Institute, 8 Feb. 2023, www.mdpi.com/1424-8220/23/4/1924.*

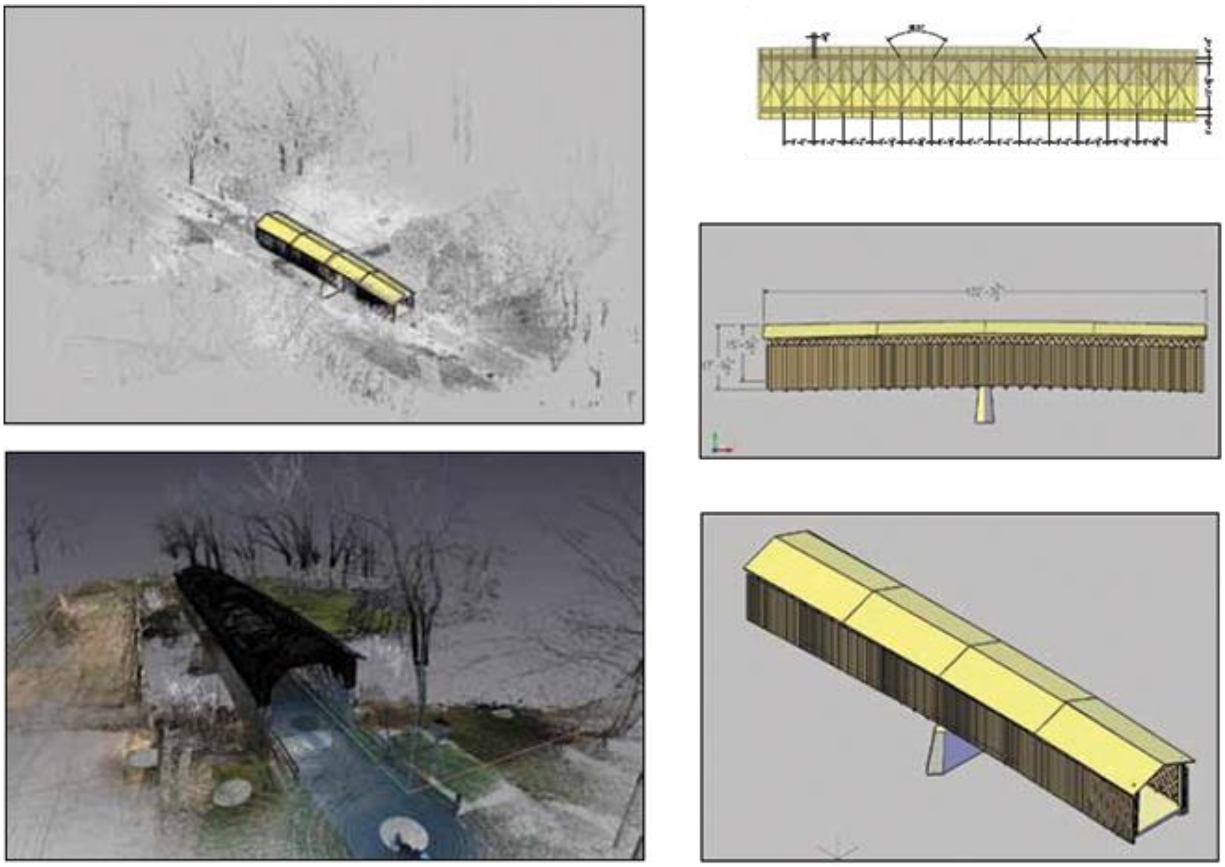

FIGURE 5 - UPPER LEFT, REVIT MODEL GENERATED FROM LIDAR SCAN NESTED IN SITE LIDAR SCAN, BOTTOM LEFT LIDAR SCAN, RIGHT VARIOUS VIEWS OF REVIT MODEL GENERATED FROM LIDAR SCAN. ROSS, ROBERT J., ET AL. "USE OF LASER SCANNING TECHNOLOGY TO OBTAIN AS-BUILT RECORDS OF HISTORIC COVERED BRIDGES." US FOREST SERVICE RESEARCH AND DEVELOPMENT, AUG. 2012, WWW.FS.USDA.GOV/TREESEARCH/PUBS/41846.

2.4.3 ASSESSING BUILDING REUSE AND DECARBONIZATION UNITED NATIONS HEADQUARTERS, NEW YORK

There are fewer examples of embodied carbon assessments for existing buildings compared to new buildings—a discrepancy that reflects the tools and data available to perform such work. However, a comprehensive assessment was conducted by the United Nations (UN) of its Headquarters building in New York City, providing a clear understanding of assessing the embodied carbon of an existing structure.

The UN's capital management staff aimed to determine, through a comprehensive carbon assessment, whether retrofitting the building to contemporary energy standards or constructing an entirely new building would be more beneficial.[62] The team led by Michael Adlerstein, F.A.I.A. outlined the assessment process by listing project deliverables for both retrofit and new construction, which included improvements in mechanical, communications, security, accessibility, amenities, and compliance with modern code requirements.[63]

As a leader in climate change policy and implementation, the method the team used was the Avoided Impacts Approach, in which "[e]mbodied energy is calculated for the demolition of the existing structure and for the proposed construction of a new replacement structure... [or] the carbon that not spent if a renovation is undertaken."[64] The LCA tools used for measurements were ATHENA for embodied carbon and DOE 2.2 to measure operational carbon, or carbon emissions attributed to building operation such as lighting and mechanical equipment.[65]

To identify embodied carbon of existing materials for input into ATHENA, the team examined (Figure 6) "preserved elements (primarily structure, core walls, and opaque envelope) … identified from the CAD plans… [and] take-offs were calculated" by subject matter experts.[66] To estimate the carbon impacts from potential new construction, the team analyzed the Energy Use Intensity (EUI) reported in twelve similarly sized buildings constructed in New York City.[67] The results for the UN Headquarters were profound, estimating that hundreds of thousands of tons of CO2 emissions would be saved and stating that:

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[62] *Adlerstein, Michael. "Assessing the Carbon-Saving Value of Retrofitting versus Demolition and New Construction at the United Nations Headquarters."*
[63] *Ibid*
[64] *Ibid*
[65] *Ibid*
[66] *Ibid*
[67] *Ibid*

> “[i]f the UN complex had been demolished and replaced with new construction of similar size, it would have taken between 35 – 70 years before the improved operating efficiencies of the new complex would have offset the initial outlays of carbon emissions associated with the demolition and new construction process.”[68]

From this perspective, the UN team successfully fulfilled its objective to assess and compare the carbon impacts of retrofitting versus constructing a new building, thereby reducing the overall carbon emissions. While this work is exemplary in measuring the carbon footprint of an existing building, it may not address fundamental questions and needs related to the accuracy and disparate nature of tools and databases used in such assessments.

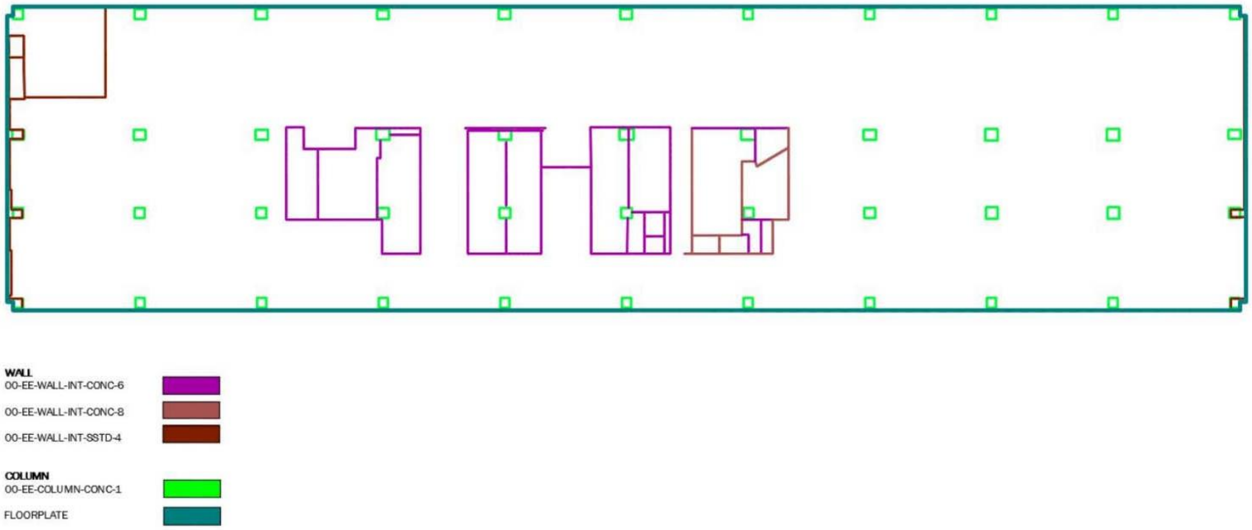

FIGURE 6 – UN RENNOVATION DIAGRAM. ADLERSTEIN, MICHAEL. “ASSESSING THE CARBON-SAVING VALUE OF RETROFITTING VERSUS DEMOLITION AND NEW CONSTRUCTION AT THE UNITED NATIONS HEADQUARTERS.”

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[68] *Adlerstein, Michael. “Assessing the Carbon-Saving Value of Retrofitting versus Demolition and New Construction at the United Nations Headquarters.”*

CHAPTER 3: Methodology

3.1 VISUALIZING THE PROCESS: DESIGN THINKING APPROACH

When thinking about decarbonization strategies, it is useful to visualize an existing building as a single mass of embodied carbon. Additions and subtractions are incurred as a cost, and preservation is viewed as a means of maintaining the building's original carbon investment, thereby avoiding additional carbon generation in demolition and new construction. This visualization approach is informed by an existing framework for analysis in adaptive reuse design produced by Dafna Fisher-Gewirtzman from the Faculty of Architecture & Town Planning, Technion – IIT, Haifa, Israel.[69] Fisher-Gewirtzman developed a diagram of building reuse contrasting existing buildings designs that remove or add mass to form at various scales (see Figure 9).[70]

The value of this framework lies in its ability to identify and communicate separate masses, both existing and new. These masses can then be measured as form and volume, and thus as material, to assess the potential tradeoffs in environmental impact from design choices.

Another framework for visual measurement is the *Shearing Layers* diagram from Stewart Brand's 1994 book *How Buildings Learn: And Fail to Learn*. Brand's book is dedicated to the idea that buildings gain inherent value as they age (Figure 7).[71] The diagram visualizes the life cycle of material systems, enhancing our understanding of material performance and accountancy. In the diagram, line thickness indicates the life cycle, and shading corresponds to different assemblies. For example, structure is represented with a thick line as it lasts longer, while services are depicted with a thin line due to their faster life cycle.

Brand's diagram is a useful visual tool to overlay with quantitative research, such as that from Thornton Tomasetti, which identified the average embodied carbon expenditure of different material assemblies in over six hundred buildings (see Figure 8).[72]

Thornton Tomasetti's bar graph illustrates potential carbon trade-off targets in building reuse when overlaid with Brand's *Shearing Layers* diagram. The simple contrasting forms by Fisher-Gewirtzman, the cycles in Brand's

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[69] *Fisher-Gewirtzman, Dafna. "Adaptive Reuse Architecture Documentation and analysis." Journal of Architectural Engineering Technology, vol. 05, no. 03, 2017, https://doi.org/10.4172/2168-9717.1000172.*

[70] *Ibid*

[71] *Brand, Stewart. "Shearing Layers." How Buildings Learn: And Fail to Learn, Viking, New York, NY, 1994.*

[72] *"Embodied Carbon." Thorntontomasetti.Com, Thornton Tomasetti, 1 Mar. 2024, www.thorntontomasetti.com/capability/embodied-carbon.*

diagram, and Thornton Tomasetti's embodied carbon materials bar graph all contributed to development of my own framework for measuring the value of embodied carbon in existing buildings.

FIGURE 7 – BRAND DIAGRAM. BRAND, STEWART. "SHEARING LAYERS." HOW BUILDINGS LEARN: AND FAIL TO LEARN, VIKING, NEW YORK, NY, 1994. "ADAPTIVE REUSE - ARCHITECTURAL RESOURCES - NY ARCHITECTS & PLANNING FIRM." ARCHRES.COM, ARCHITECTURAL RESOURCES, 11 MAY 2022, WWW.ARCHRES.COM/ADAPTIVE-REUSE/.

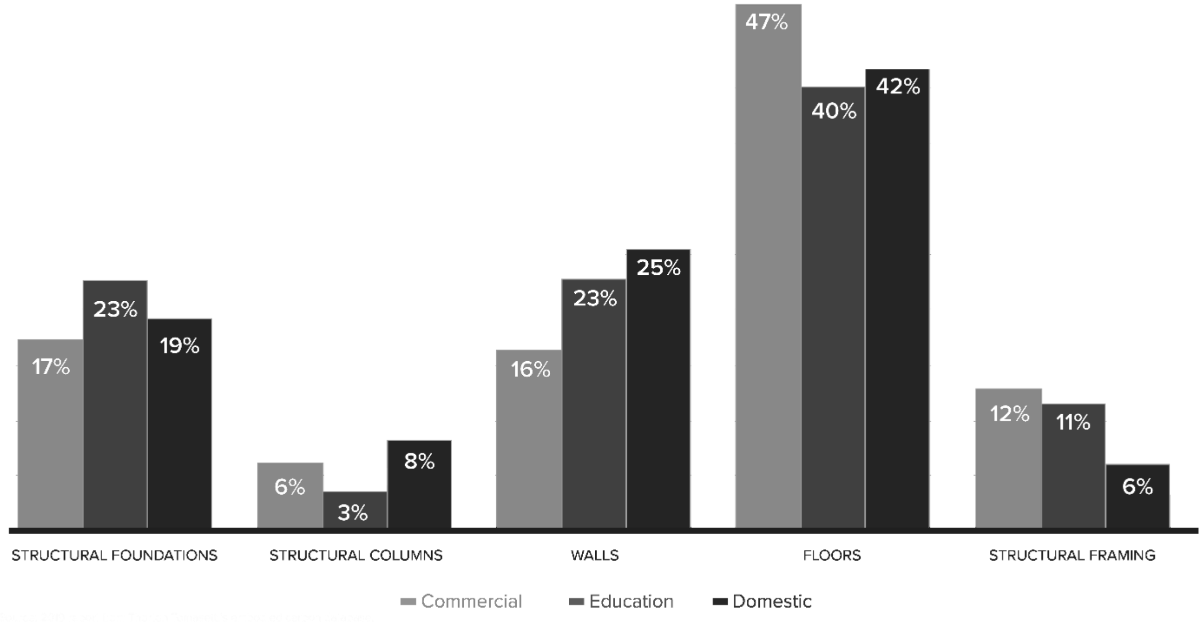

FIGURE 8 - "EMBODIED CARBON" BAR GRAPH SHOWING PROPORTION FOUND BY ASSEMBLY TYPE ACROSS 600 BUILDINGS. "EMBODIED CARBON." THORNTONTOMASETTI.COM, THORNTON TOMASETTI, 1 MAR. 2024, WWW.THORNTONTOMASETTI.COM/CAPABILITY/EMBODIED-CARBON

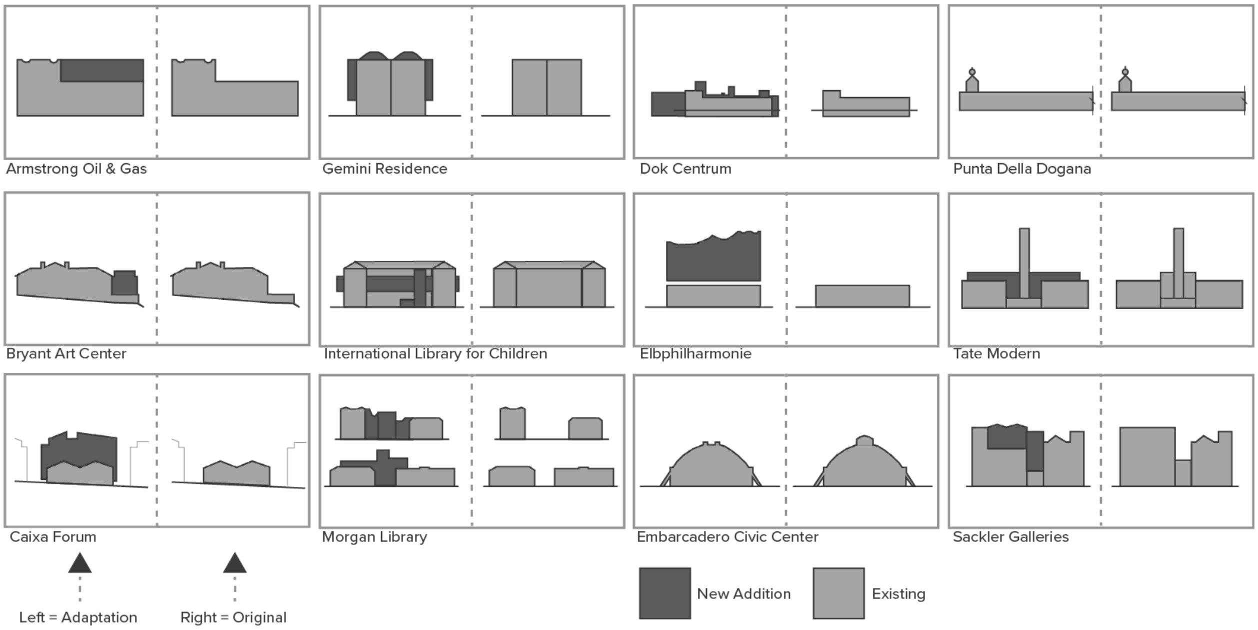

FIGURE 9 - FISHER-GEWIRTZMAN DIAGRAM. FISHER-GEWIRTZMAN, DAFNA. "ADAPTIVE REUSE ARCHITECTURE DOCUMENTATION AND ANALAYSIS." JOURNAL OF ARCHITECTURAL ENGINEERING TECHNOLOGY, VOL. 05, NO. 03, 2017, HTTPS://DOI.ORG/10.4172/2168-9717.1000172.W. COLOR CONTRAST AND KEY BY AUTHER, 2023.

3.2 DOCUMENT & RECIEPT: IMPLEMENTATION & ACCOUNTING PROCESS

To realize and test the conceptual model from the visual framework, I assembled and aligned various reality capture scanning technologies with architectural design and analytical environmental software. The intent of combining reality capture with analytical software was to improve upon existing data quality and efficiency by utilizing an approach of holistic existing building information capture and interpretation. The initial framework of this thesis was designed to investigate and align theory, literature review, and available free survey tools and analytic software. That framework changed when the opportunity to utilize professional survey tools and analytic software was provided by James Harbin, Director of Construction Technology at JTM Construction. This coincided with JTM's support of UW Professor Kathryn Rogers Merlino's Spring 2023 architectural studio, focused on imagining reuse of an existing building, the ASUW Shell House on the University of Washington Campus, in Seattle, WA. Access to contemporary tools and software allowed me to proceed with testing a process of implementation beyond literature review and limitations of free survey tools. The resulting workflow discussed in section 3.2.2 (Fig 15) was to:

1) Carry out a LiDAR scan and point cloud measurement of a building,
2) Produce a 3D segmented model portable to Revit,
3) Identify and assign material and assembly, concluded with
4) A calculation of embodied carbon value using existing carbon calculators such as Tally and the Embodied Carbon in Construction Calculator (EC3).

Overall, the design of this method is to foster rigor in calculation of carbon in existing buildings and contribute to emissions management and reduction across the built environment.

3.2.1: TOOLS AND SOFTWARE: WHAT WAS EMPLOYED IN THE PROJECT

LiDAR: NavVis VLX & IVION

The NavVis brand and VLX model, LiDAR scanning technology, is a new mobile version of LiDAR which utilizes Simultaneous Localization and Mapping or SLAM, "an algorithm that fuses data from a mapping system's onboard sensors to determine its trajectory at the same time as it moves through the environment”. [73] It is wearable, mobile, easily operated and can produce survey quality LiDAR scans “up to ten times faster than terrestrial scanners”, a highly efficient tool for capturing an as-built point cloud of an existing building.[74] Additionally, NavVis provides processing and cloud software, NavVis IVION, featuring capabilities for cross functionality with Revit and other plugin software to utilize the point cloud data. An example of the device (Fig 10) and the typical workflow for using the NavVis VLX (Fig 11) summarizes the scanning workflow.[75,76]

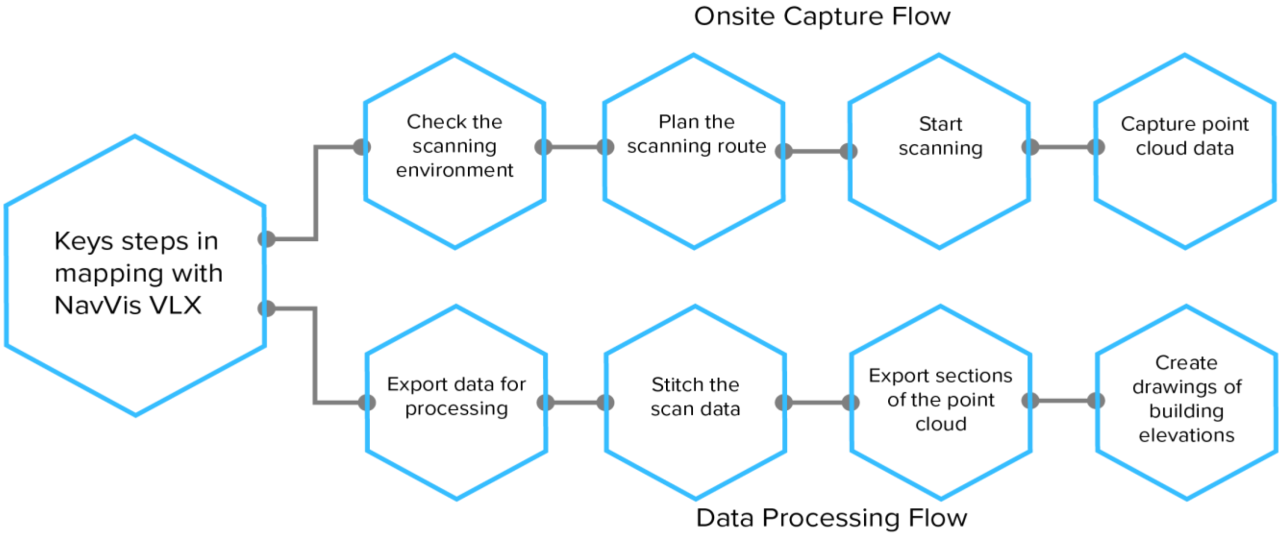

FIGURE 100- NAVVIS VLX TYPICAL WORKFLOW. “NAVVIS VLX.” NAVVIS VLX ACCURACY WHITE PAPER FOR INDOOR AND OUTDOOR USE, NAVVIS, 20 JULY 2021, WWW.NAVVIS.COM/RESOURCES/WHITE-PAPERS/INDOOR-OUTDOOR.

FIGURE 11 - IMAGE OF NAVVIS VLX SLAM LIDAR SCANNER. “NAVVIS VLX.” NAVVIS VLX ACCURACY WHITE PAPER FOR INDOOR AND OUTDOOR USE, NAVVIS, 20 JULY 2021,

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[73] *“NavVis VLX.” NavVis VLX Accuracy White Paper for Indoor and Outdoor Use, NavVis, 20 July 2021, www.navvis.com/resources/white-papers/indoor-outdoor.*

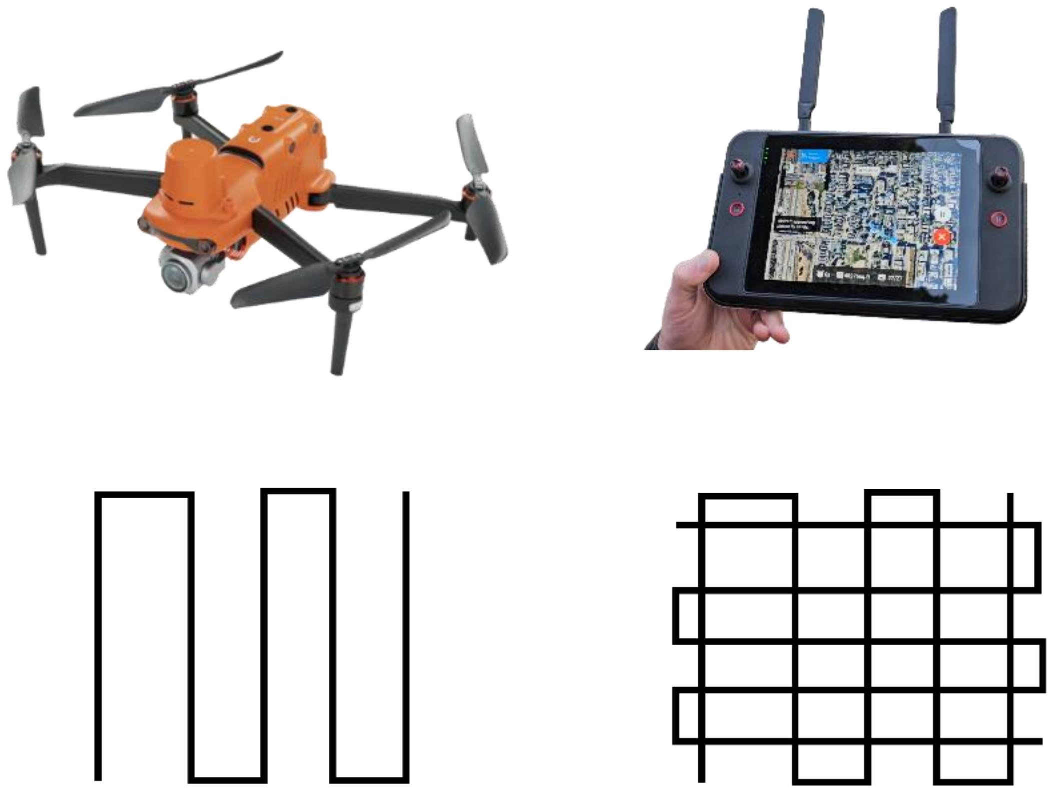
[74] *Ibid*

[75] *Pan, Vivian. “NavVis VLX Powers the Digitization of a Neighborhood in Shijingshan District, Beijing.” Navvis.Com, NavVis GmbH, 2 Apr. 2024, www.navvis.com/blog/navvis-vlx-powers-digitization-of-neighborhood-in-shijingshan.*

[76] *“NavVis VLX.” NavVis VLX Accuracy White Paper for Indoor and Outdoor Use, NavVis, 20 July 2021, www.navvis.com/resources/white-papers/indoor-outdoor.*

PHOTOGRAMMETRY: Autel Robotics, Evo series Quad Copter Drone

The Autel Evo series aerial drone with camera and sensor systems, can perform programmed and remote-controlled flights to collect precise photometric data of terrestrial objects and landscapes. It has secure data connection capabilities to satellite and cell tower and accuracy to the "centimeter".[77] The ability to plan flight paths allows for complete documentation of the object, in this case a building, with grid optimization and overlap of photos (Fig 12).



Create Rectangular or Polygon Programmed Flightpaths

Supports Double Grid Mapping to ensure complete data capture of all angles

FIGURE 11 – UPPER LEFT IMAGE, AUTEL DRONE. UPPER RIGHT IMAGE, AUTEL DRONE REMOTE CONTROLLER WITH MAP OF SITE AND REAL TIME FLIGHT PROGRAM SHOWING ON SCREEN. BOTTOM TWO IMAGES, EXAMPLE OF TYPICAL DRONE FLIGHT COVERAGE OF A PROJECT SITE. "EVO II PRO 6K RTK RUGGED BUNDLE V3." AUTELROBOTICS.COM, AUTEL ROBOTICS, 2024, SHOP.AUTELROBOTICS.COM/PRODUCTS/EVO-II-PRO-6K-RTK-RUGGED-BUNDLE-V3

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[77] *"Evo II Pro 6K RTK Rugged Bundle V3." Autelrobotics.Com, Autel Robotics, 2024, shop.autelrobotics.com/products/evo-ii-pro-6k-rtk-rugged-bundle-v3*

GROUND PENETRATING RADAR: IDS GeoRadar, C-Thrue

The IDS GeoRadar, C-Thrue ground penetrating radar is used to examine sealed assemblies, both in the ground, and on vertical surfaces, such as walls and columns. Typically applied for use on concrete structures to "locate and identify rebars, ducts, cables and other objects", the C-Thrue uses radar wave technology to examine depths of up to forty inches.[78] This tool is easy to transport and operate in building spaces, providing insight on hidden details of building materials.

FIGURE 12 - UPPER LEFT IMAGE, CLOSE UP OF C-THRUE IN USE WITH WAVE FORM READOUT DISPLAY IN VIEW, BOTTOM LEFT, TYPICAL VERTICAL SURFACE SCAN, UPPER RIGHT, C-THRUE GPR SCANNER, RIGHT, DIAGRAM OF C-THRUE HORIZONTAL SURFACE SCAN OPERATION AND WAVE FORM FUNCTION. "C-THRUE." IDSGEORADAR.COM, HEXAGON, IDS GEORADAR, 2024, IDSGEORADAR.COM/PRODUCTS/GROUND-PENETRATING-RADAR/C-THRUE.

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[78] *"C-Thrue." Idsgeoradar.Com, Hexagon, IDS GeoRadar, 2024, idsgeoradar.com/products/ground-penetrating-radar/c-thrue.*

3D MODELING TOOLS

BIMIT

BIMIT is a point cloud to 3D model conversion software produced by Integrated Projects (IPX). This software allows for the conversion of LiDAR scan data into segmented 3D REVIT models.[79] On the company's website, it provides data on the production timeline of scan data to 3D model per square foot which is illustrated below into a stacked line graph showing minimum and maximum time to complete.[80] Currently, IPX is pursuing automation of the scan to BIM process utilizing machine learning which could reduce conversion times.[81]

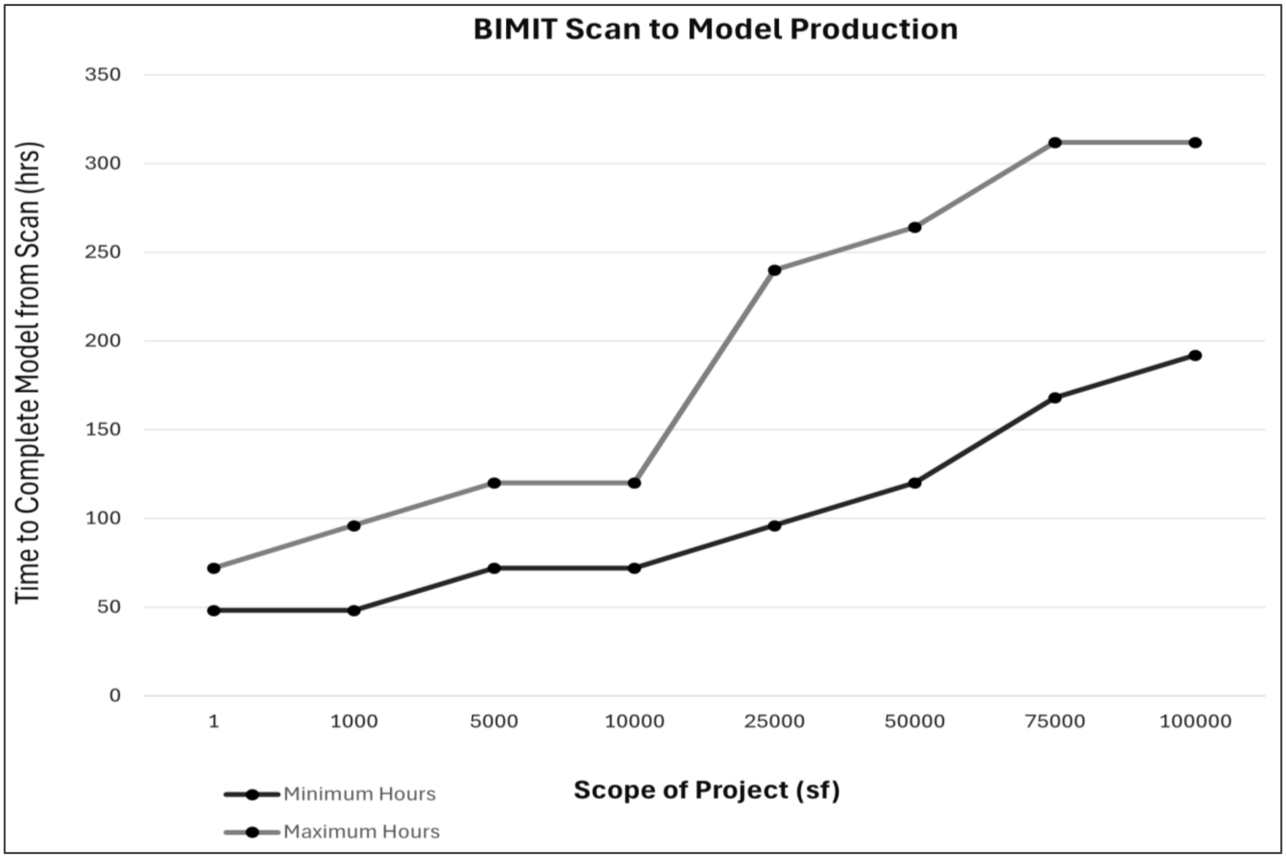

FIGURE 13 - IMAGE OF LIDAR ROUTE MAP (GREEN) AS RECORDED THE UNIVERSITY BRANCH SEATTLE LIBRARY, MAIN FLOOR (PURPLE). SCAN TO MODEL CONVERSION, PRODUCED BY AUTHOR FROM DATA LISTED ON BIMIT WEBSITE.

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[79] *"Bimit - Frequently Asked Questions & Samples." Integrated-Projects.Com, IPX, 2024, www.integrated-projects.com/bimit-specs.*

[80] *Ibid*

[81] *"Thomas Czerniawski, PhD - Applied Machine Learning Scientist - Integrated Projects | Linkedin." Linkedin.Com, Linkedin, 2024, www.linkedin.com/in/thomasczerniawski/.*

REVIT

REVIT is 3D modeling software produced by Autodesk and serves as a host for building shared 3D models within the Architecture, Engineering, and Construction AEC discipline.[82] It has versatile serviceability with many other applications connecting as “plug-ins” or extensions of capabilities for performance and analytics.

REVIZTO

Revizto is cloud BIM software which connects hub software such as REVIT with project and construction management software, allowing for greater depth of uninterrupted coordination and project review.[83]

LCA ANALYSIS SOFTWARE

LCA software tools have found strong integration as plug-ins with existing BIM tools such as REVIT. Information can be extracted from segmented masses and assigned materials with LCA software, then connects and references to existing material EPD data and provide an overall quantification of impacts from a given 3D building model.

TALLY

Tally is a direct plug-in or software extension which can be used within the REVIT 3D modeling software. A 3D building model in REVIT and assigned materials can be quantified for the “embodied environmental impacts to land, air, and water systems”.[84] The CLF describes Tally as enabling “design teams to perform WBLCA [whole building life cycle assessment] within their design model… calculate[ing] impacts [on] a wide range of materials for structural systems, enclosures, and interiors across all life-cycle stages.[85]

EC3

EC3 (Embodied Carbon in Construction Calculator) can be used directly online or in conjunction with Tally through REVIT. Launched in late 2019, it is a contemporary tool in the LCA ‘ecosystem’ of tools with material and product level environmental impact data through voluntary EPD data provided by manufacturers.[86] This tool is useful to explore material selection in environmental impact accounting.

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[82] *“Revit vs. Autocad: What’s the Difference?” Autodesk.Com, Autodesk, 4 Feb. 2024, www.autodesk.com/solutions/revit-vs autocad.*

[83] *Revizto. “2D & 3D BIM Collaboration Platform. Bim Collaboration Software from Revizto.” Revizto.Com, https://revizto.com/en/, 29 Mar. 2024, revizto.com/en/.*

[84] *Tally® LCA App for Autodesk® Revit® Software Development KT InnovationsAwards:2016 Architect R+D Award 2014 AIA Technology in Architectural Practice Building Information Modeling Award. “Tally® LCA APP FOR AUTODESK® Revit®: Kierantimberlake.” Kierantimberlake.Com, Kieran Timberlake, 8 Apr. 2014, kierantimberlake.com/page/tally.*

[85] *CLF, Tools for Measuring Embodied Carbon. “Tools for Measuring Embodied Carbon.” Carbonleadershipforum.Org, Carbon Leadership Forum, 30 Apr. 2024, carbonleadershipforum.org/tools-for-measuring-embodied-carbon/.*

[86] *“EC3 Methodology.” Buildingtransparency.Org, Building Transparency, 26 June 2023, www.buildingtransparency.org/ec3-resources/ec3-docs/.*

CARE

The CARE Tool (Carbon Avoided Retrofit Estimator) is a free online tool used to help guide decision making in building reuse. The design of the tool first focuses on ease of use across user groups to encourage diverse use for "owners, developers, community leaders, and design and planning teams can get answers to nuanced questions about reuse".[87] Fundamentally, this tool serves as a simple input calculator to estimate trade-offs and environmental impacts between building reuse and new construction.

3.2.2 WORKFLOW – ALIGNING TOOLS AND SOFTWARE

To understand the potential carbon value of existing buildings, the following workflow was proposed and tested. Reduced to its simplest parts, the workflow consists of 1) reality capture, 2) build a 3D Model, 3) analysis through LCA (Fig 15). Reality capture begins with LiDAR, photogrammetry, and ground penetrating radar measurements. These data are then uploaded to the cloud or via SD card to NavVis IVION software to be merged into a digital twin or 3D model of the chosen building using control points based on satellite mapping to ensure accuracy of overlays. This combined digital twin is then transferred to IPX BIMIT software for conversion into a 3D segmented mesh model which can be loaded into Autodesk REVIT for review and further analysis. Within REVIT, segmented mesh volumes are assigned materials. Then, through the Tally plugin in REVIT, material EPD assemblies are assigned. Once complete, all data can be ported into EC3 for greater definition of material EPD assemblies and sources. Finally, a comparison can be made of both the Tally report and EC3 report data against the CARE Tool reuse planner to compare results.

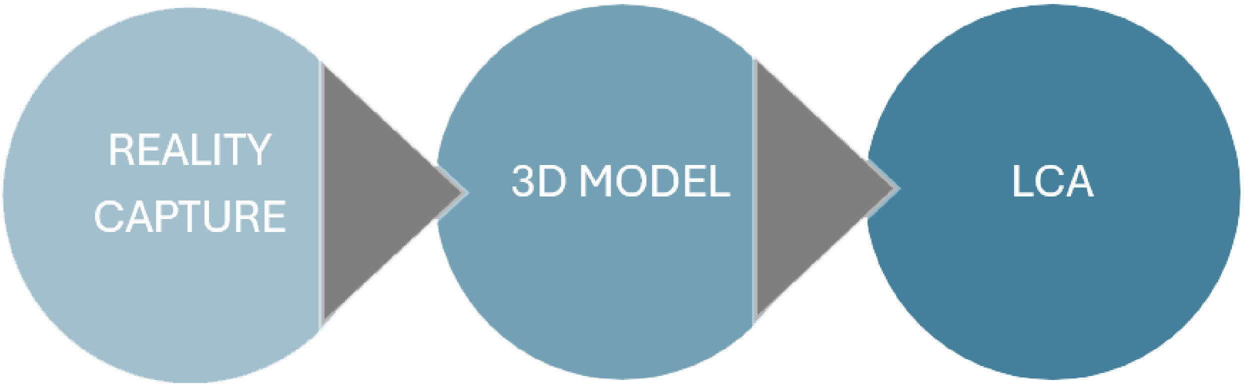

FIGURE 14 - SIMPLIFIED ILLUSTRATION OF PROJECT WORKFLOW

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[87] *"Architecture 2030 Announces the Care Tool, a Valentine for Building Reuse." Architecture2030.Org, Architecture 2030, Feb. 2023, www.architecture2030.org/architecture2030announcesthecaretool/.*

3.2.3 USE CASE APPROACH: WHO AND WHAT IS THIS FOR?

The following outlines the potential benefits to stakeholders, use cases, and outcomes of the proposed workflow:

INTEGRATED BUILDING ASSESSMENT AND LCA MEASUREMENT TOOL

A process that integrates surveying, 3D modeling, and LCA data generation for existing buildings.

PROCESS:

Steps involved:

1. **SCAN:** LiDAR scanning to capture a point cloud for a precise building image (NavVis LiDAR scanner).
2. **MODEL:** Transform data from point cloud into architectural 3D Model (NavVis IVION & Autodesk).
3. **ENHANCE:** 3D model auto-segmentation for analysis (BIMIT).
4. **MEASURE:** Input 3D model in LCA tool for accurate LCA measurement of GHG and embodied carbon potential (Tally, EC3, CARE).

Future integration of machine learning could improve efficiency and scalability.

USE CASE NO 1 – DESIGN

Enables architects and engineers working on retrofit, reuse, and emergency projects to:

- **ACCURATE MEASUREMENT OF EXISTING CONDISTIONS:** Quickly assess existing structural conditions, opportunities, and constraints.
- **REDUCE TIME AND COST:** time spent on field measurements and BIM model reconstruction.
- **QUICKLY ASSESS LCA CONDITIONS:** reduce project timelines and rework resulting from mismeasurement.

USE CASE NO 2 – SUSTAINABILITY

Supports architects, engineers, policymakers, and researchers in:

- **ANALYZE, COMPARE, DECIDE:** Making informed decisions regarding building retrofits and reuse versus new construction.
- **EMISSIONS AND ACCOUNTABILITY:** Improving the accounting of material life cycles and GHG emissions of existing buildings.
- **INTERDISCPLINARY DATA VALUE:** Contributing to public health, equity, land use decisions, and

biodiversity by informing climate adaptation measures for the built environment.

USE CASE NO 3 – PRESERVATION

Aids architects, policymakers, and historic preservationists by:

- **EXTENDING RESEARCH POTENTIAL:** Expanding the preservation potential of existing buildings through increased knowledge.
- **EQUITY IN PRESERVATION:** Valuing buildings holistically, beyond just visual aesthetics, to include environmental, economic, and equity considerations.
- **EXPANDING SCOPE:** Increasing precision and efficiency in the assessment of existing buildings, thereby expanding the overall stock of preserved buildings.

CHAPTER 4: Process & Framework

4.1 FIELDWORK & WORKFLOW - DATA COLLECTION APPROACH

4.1.1 SITE SELECTION

The case studies were selected based on the following criteria:

1) Value as a historic building,

2) Building size and complexity of assembly and structure, from heavy timber construction found in the single-story ASUW Shell House Case Study, to more complex assemblies of unreinforced brick and timber with structural steel additions found in the five story Railspur Case Study.

3) Ease of access to buildings and tools.

    - Access to buildings was provided by the University of Washington and the Seattle Public Library. Reality Capture tools for measurement and LCA data analysis software were provided by JTM Construction, Kieran Timberlake, BuildingTransparency.org, and Architecture2030.org.

4.1.2 IMPLEMENTATION: WORKFLOW IN THE FIELD

Three existing buildings were studied for this project, located in Seattle, WA. The first study was carried out on the ASUW Shell House on the UW campus, the second on the University Branch of the Seattle Public Library, and the final on the Railspur Hotel in Pioneer Square Historic District. Implementation is based on the workflow process established in Chapter 3 Methodology (Fig 15). The first case study at the Shell House tested and refined tool selection for the final process applied across projects, with the Shell House 3D model produced by UW undergraduate architecture students in the Rhinoceros (RHINO) 3D modeling software, not otherwise employed on this project. It should be noted that as a result, LCA tools were only applied on the University Branch and Railspur projects which utilized REVIT 3D modeling, which is compatible with LCA tools utilized in this study (Fig 16).

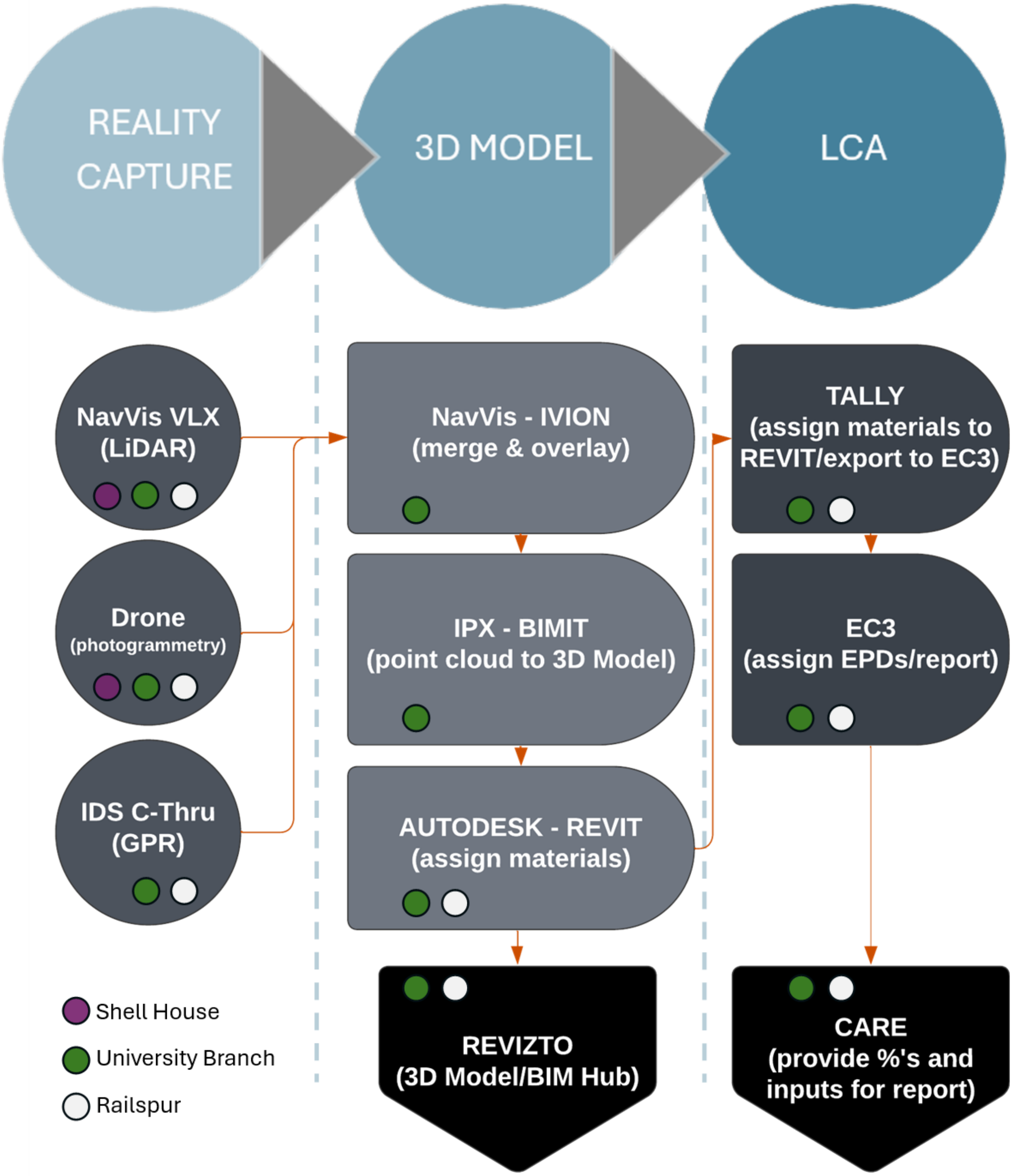

FIGURE 15 - DETAILED WORKFLOW FOR TOOLS EMPLOYED IN PROJECT FIELD WORK PRODUCED FROM CONCEPTUAL PROCESSES AND TOOLS DEFINED IN METHODOLOGY FIGURE 15.

4.2 CASE STUDIES

The following case studies described in 4.1.2 were conducted to test the workflow described in Chapter 3.

4.2.1 ASUW SHELL HOUSE

Location:	University of Washington, Seattle, US
Year Built:	1919
Building Size:	approximately 10,560 sf
No of Stories:	1 (plus mezzanine)
Material Construction:	Heavy timber trusses, wood framing, on concrete slab and piers.[88]

A demonstration of NavVis VLX LiDAR conducted by James Harbin of JTM on the 1919 ASUW Shell House on the UW Campus. The resulting point cloud model was provided for this project was performed with UW architecture students in Professor Merlino's design studio as a reference tool in their adaptive reuse design process. Students learned the LiDAR scanning process and imported the 3D Model point cloud into current UW standard 3D design software and attempted to build a 3D Model from the point cloud. Due to lack of access to requisite software and computing power, only a few students reproduced an accurate model of the Shell House from the point cloud. This demonstrated the possibility of aligning 3D model development with point cloud scans.[89]

This case study and feedback from students served as a baseline for observation and testing of the workflow set forth in Methodology. Results were used to refine scope of workflow for follow on case studies as they informed interoperability, timelines, and challenges with the reality capture technology, 3D modeling, and LCA software throughput (Fig 15).

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[88] *BOLA Architecture and Planning. "Landmark Nomination University of Washington Canoe House ..." facilities.uw.edu, University of Washington, 12 Jan. 2018, facilities.uw.edu/files/media/canoe-house-nomination-submitted-1-12-18.pdf.*

[89] Strand, James M, and Ali Ahmed. "ASUW Shell House - LiDAR Experience Feedback." 19 May 2023.

IMAGES OF NAVVIS VLX LIDAR SCANNER BEING OPERATED BY JAMES STRAND, ACCOMPANIED BY JAMES HARBIN AT ASUW SHELL HOUSE 11 MAY 2023. PHOTOS BY KATHRYN ROGERS MERLINO.

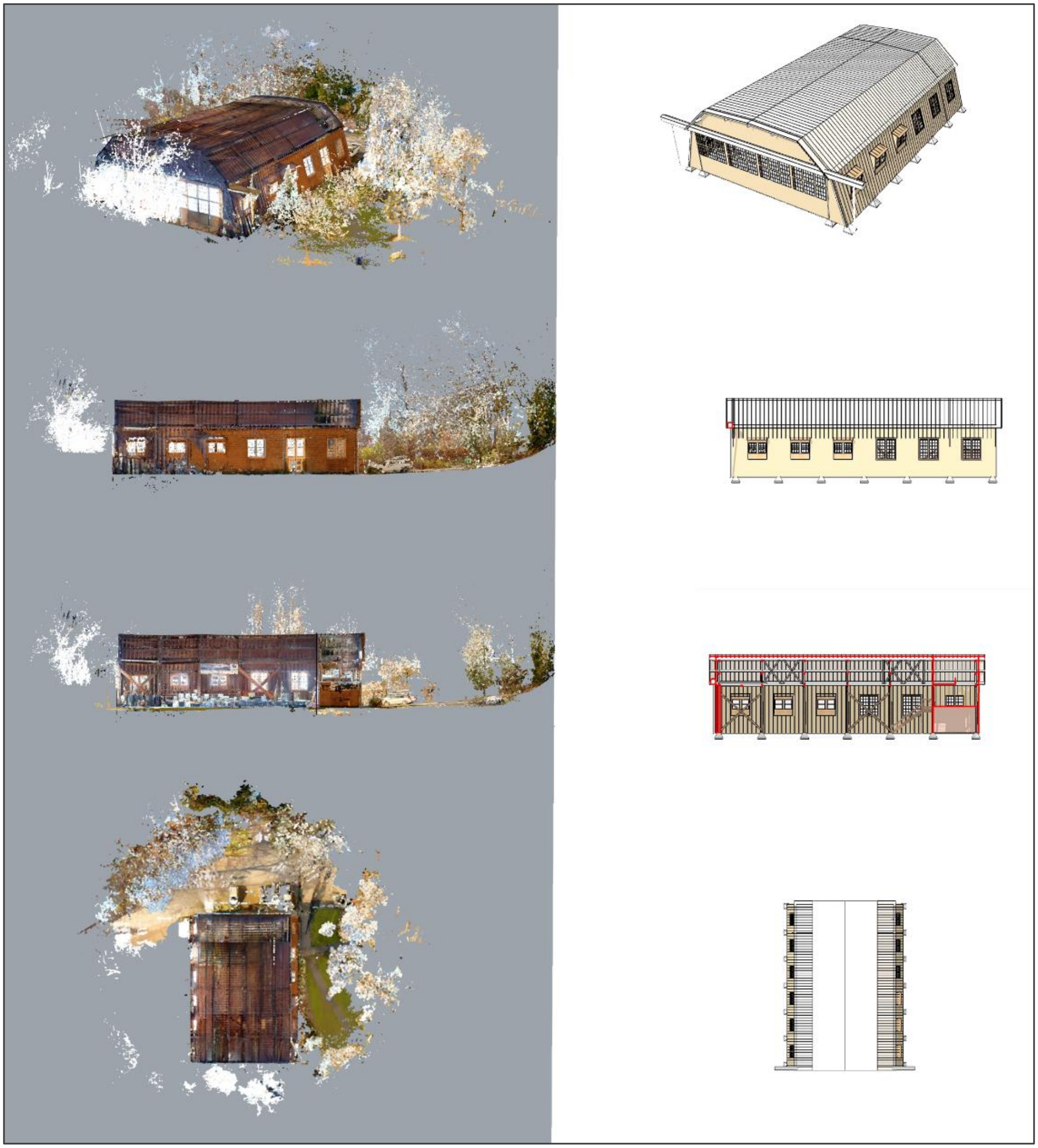

FIGURE 16 - LEFT IMAGES, 3D POINT CLOUD SCAN USING NAVVIS VLX LIDAR. RIGHT IMAGE, 3D ARCHITECTURAL MODEL IMAGES OF SHELL HOUSE, RAW (LEFT) AND RHINO ADAPTATION BY UNIVERSITY OF WASHINGTON ARCHITECTURE UNDERGRADUATE ALI AHMED (RIGHT) MAY 19, 2023.

4.2.2 UNIVERSITY BRANCH SEATTLE PUBLIC LIBRARY

Location:	University District, Seattle, US
Year Built:	1910
Building Size:	appx 6,400 sf
No of Stories:	2
Material Construction:	Reinforced concrete structure with hollow clay tile infill, reinforced concrete slab, and timber roof framing.[90]

This data was uploaded and overlayed NavVis IVION into a single 3D point cloud and subsequently provided to IPX BIMIT for 3D REVIT model development, a hybrid process of manual and machine learning production. Additionally, SHKS provided the original plan set and a 3D REVIT model they produced from the original plans and field and LCA feasibility.

All models were overlayed for alignment with the 3D point cloud as well as visually analyzed, both in analog to the Dafna Fisher-Gewirtzman diagram (Fig 9), contrasting the existing building against proposed addition, and analogous to Brand's Shearing Layer diagram, with materials colored according to life cycle (Fig 7). In REVIT materials were assigned to the segmented volumes available in each model and referenced to the photos taken onsite. Reports were then generated from a model material list following analysis in Tally (Fig 21), EC3 (Fig 22 & 23), and CARE (Fig 44) LCA tools for illustrative purposes and to understand LCA feasibility.

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[90] Gordon, Karen. "University Library Designation." Seattle.Gov, City of Seattle, Department of Neighborhoods and Historic Preservation, 2 Jan. 2002, www.seattle.gov/documents/Departments/Neighborhoods/HistoricPreservation/Landmarks/RelatedDocuments/university-library-designation.pdf.

LIDAR

IMAGES OF LIDAR PERFORMED ON THE UNIVERSITY BRANCH SEATTLE LIBRARY. UPPER LEFT, JAMES HARBIN ON MAIN FLOOR OF LIBRARY SCANNING WITH NAVVIS VLX.

UPPER MIDDLE AND RIGHT, WITH CARE, RAISING NAVVIS VLX INTO ATTIC FOR SCAN.

BOTTOM LEFT, CAROLYN STOVALL SCANNING EXTERIOR AND GROUNDS WITH NAVVIS VLX AND BOTTOM MIDDLE, SCANNING OF ATTIC. PHOTOS BY AUTHOR.

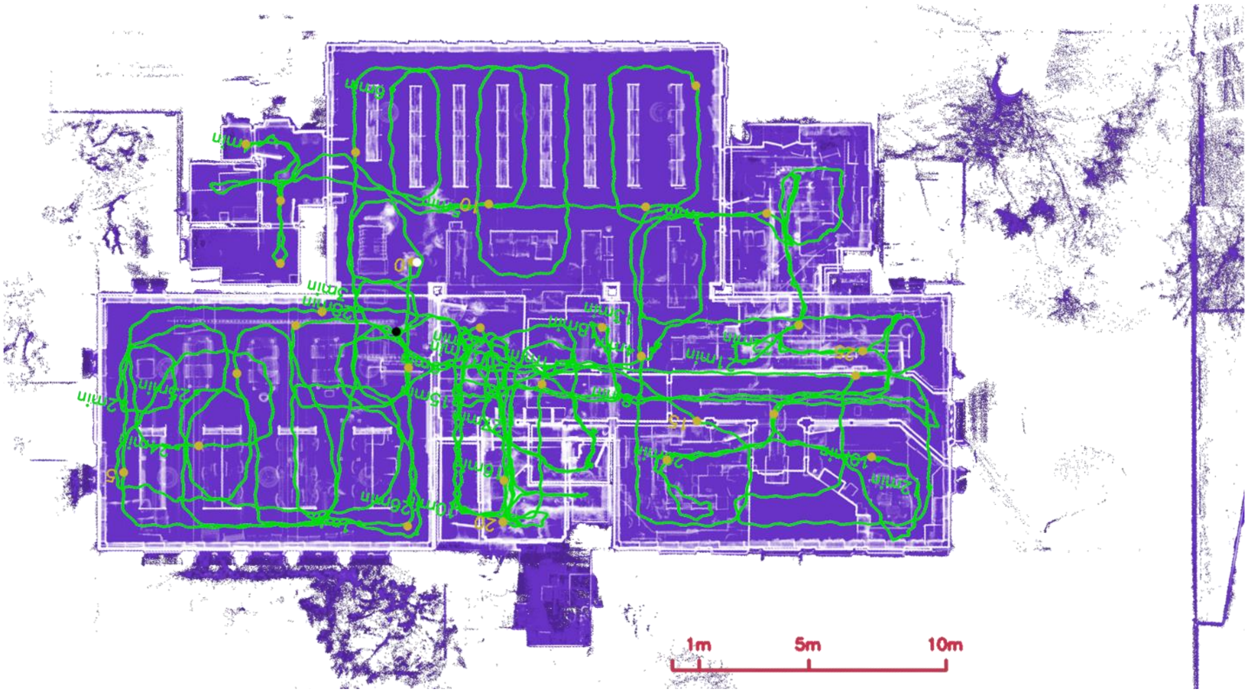
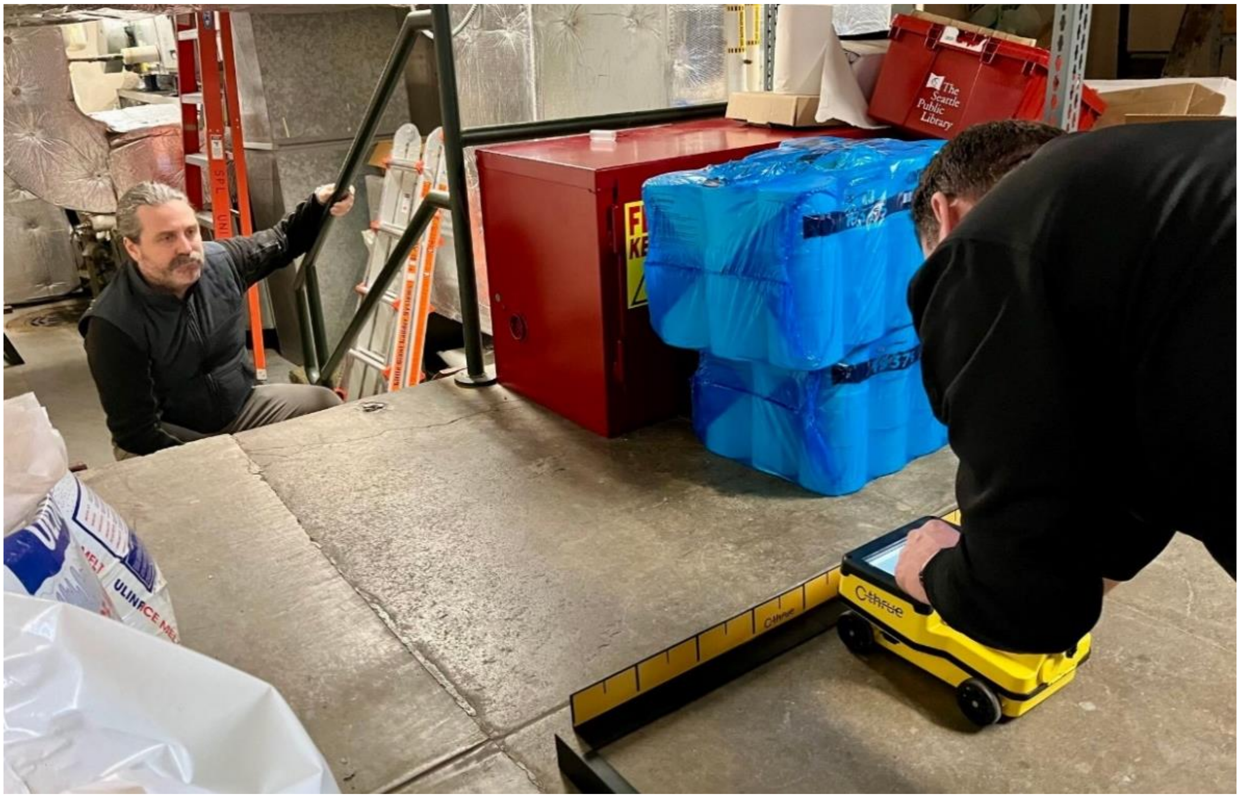


FIGURE 17 - IMAGE OF LIDAR ROUTE MAP (GREEN) AS RECORDED THE UNIVERSITY BRANCH SEATTLE LIBRARY, MAIN FLOOR (PURPLE).

PHOTOGRAMMETRY

TOP IMAGE, IMAGE, AUTEL DRONE IN PRE-FLIGHT, JAMES HARBIN PILOT, AT UNIVERSITY BRANCH, SEATTLE PUBLIC LIBRARY. BOTTOM IMAGE AUTEL DRONE IN FLIGHT COLLECTING DATA OF THE UNIVERSITY BRANCH, SEATTLE PUBLIC LIBRARY. PHOTOS BY AUTHOR.

GROUND PENETRATING RADAR



TOP AND BOTTOM IMAGE, LEFT, JAMES STRAND, RIGHT JAMES HARBIN. OPERATION AND OBSERVATION OF C-THRUE GPR AT THE UNIVERSITY BRANCH SEATTLE PUBLIC LIBRARY. PHOTOS BY CAROLYN STOVALL.

PHOTO

LIDAR

BIMIT 3D MODEL

ALL IMAGES ARE OF THE SAME SOUTHEAST INTERIOR SECTION OF THE MAIN FLOOR IN MAIN FLOOR OF THE UNIVERSITY BRANCH LIBRARY. LEFT, A PHOTO OF JAMES HARBIN OF JTM CONSTRUCTION SCANNING WITH NAVVIS VLX LIDAR. MIDDLE, A SCREEN SHOT OF THE 3D POINT CLOUD MODEL. RIGHT, A SCREEN SHOT OF THE 3D MODEL PRODUCED BY BIMIT. PHOTOS BY AUTHOR

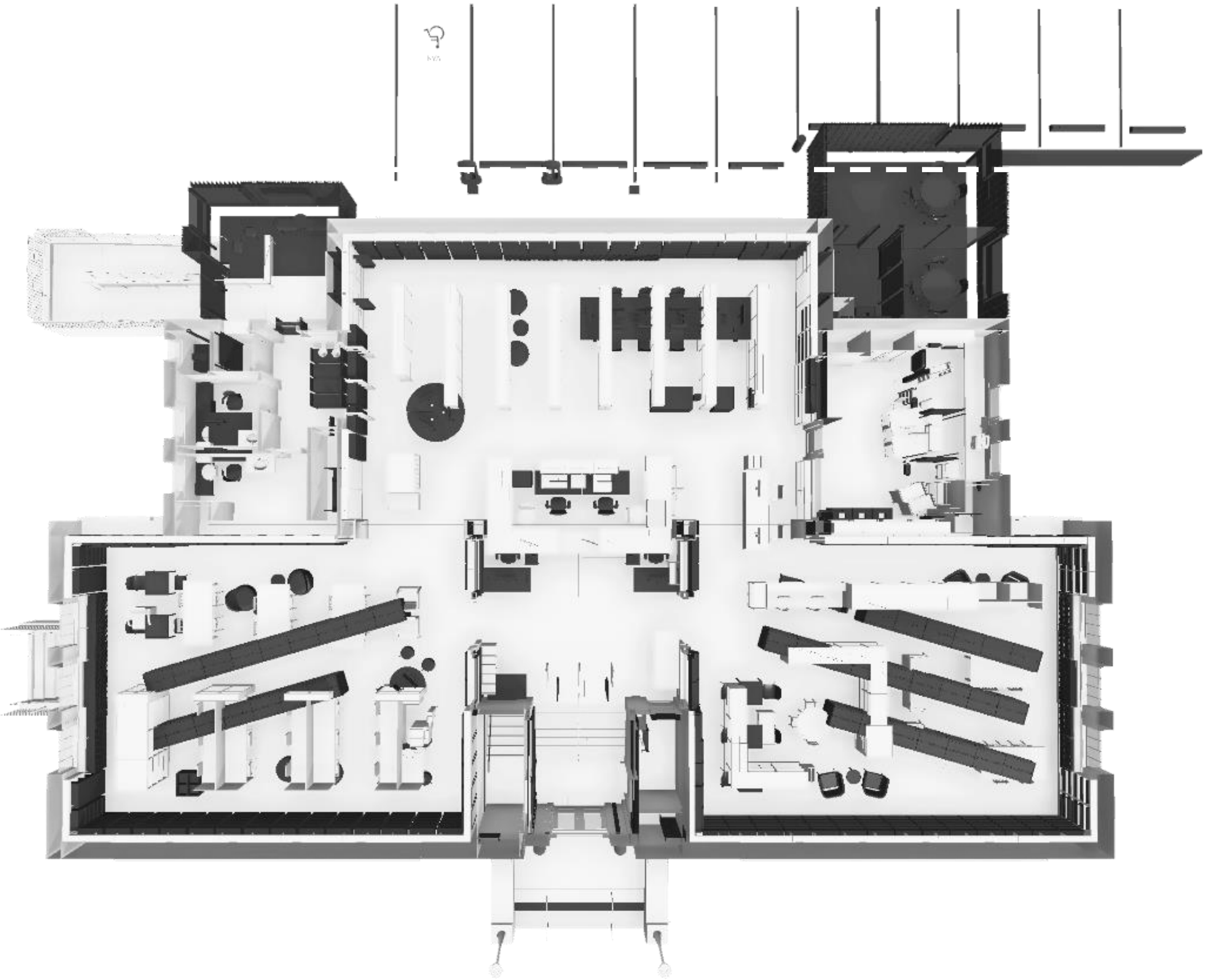


FIGURE 19 – IMAGE OF BIMIT 3D MODEL OF EXISTING BUILDING IN WHITE, OVERLAYED IN REVIZTO WITH SHKS 3D REVIT MODEL IN BLACK SHOWING ADDITIONS, IN ANALOG WITH THE FISHER-GEWIRTZMAN FILTER.

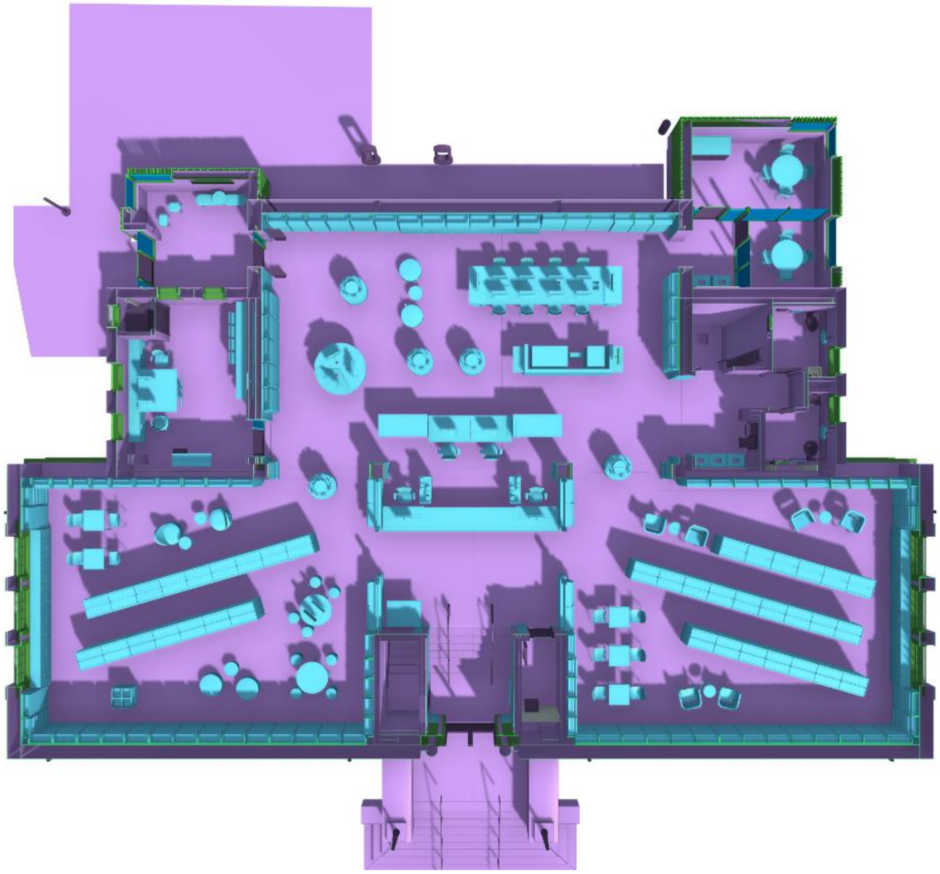


FIGURE 20 - BIMIT 3D MODEL OF SHKS 3D REVIT MODEL WITH GREEN INDICATING ENVELOPE MATERIALS, LIGHT PURPLE INDICATING MATERIALS OF STRUCTURAL VALUE, DARK PURPLE INDICATING SERVICES, AND LIGHT BLUE INDICATING SPACE PLANNING MATERIALS SUCH AS FURNITURE IN ANALOG WITH THE BRAND FILTER.

Tally Report – Material Impact Diagrams – University Branch Library

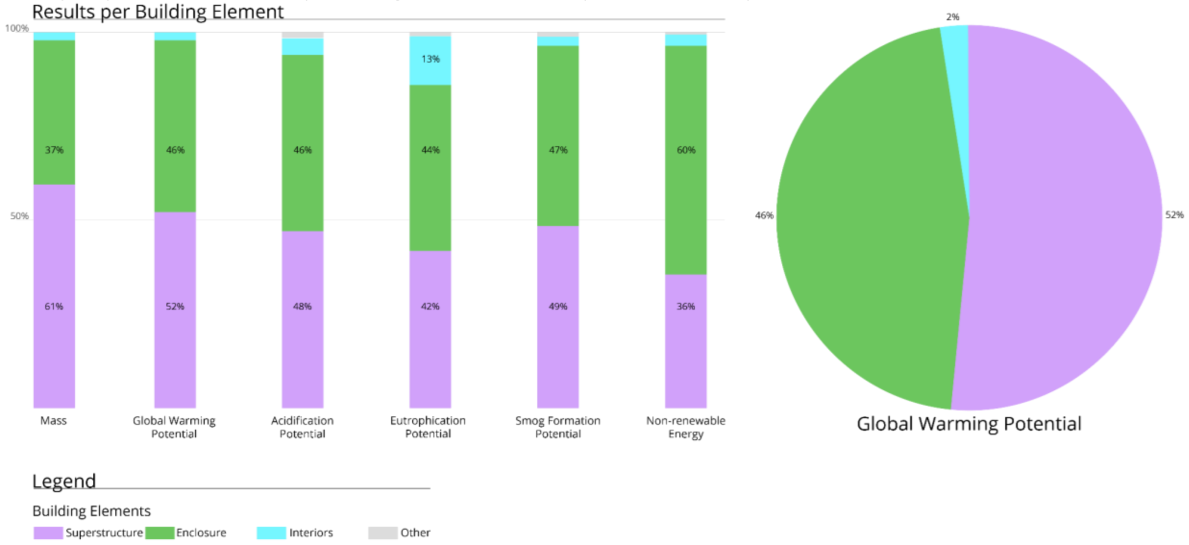


FIGURE 21 - ILLUSTRATIVE TALLY LCA DATA, COLORED TO ALIGN WITH BRAND'S FILTER.

EC3 Report – Sankey Chart – University Branch Library Project

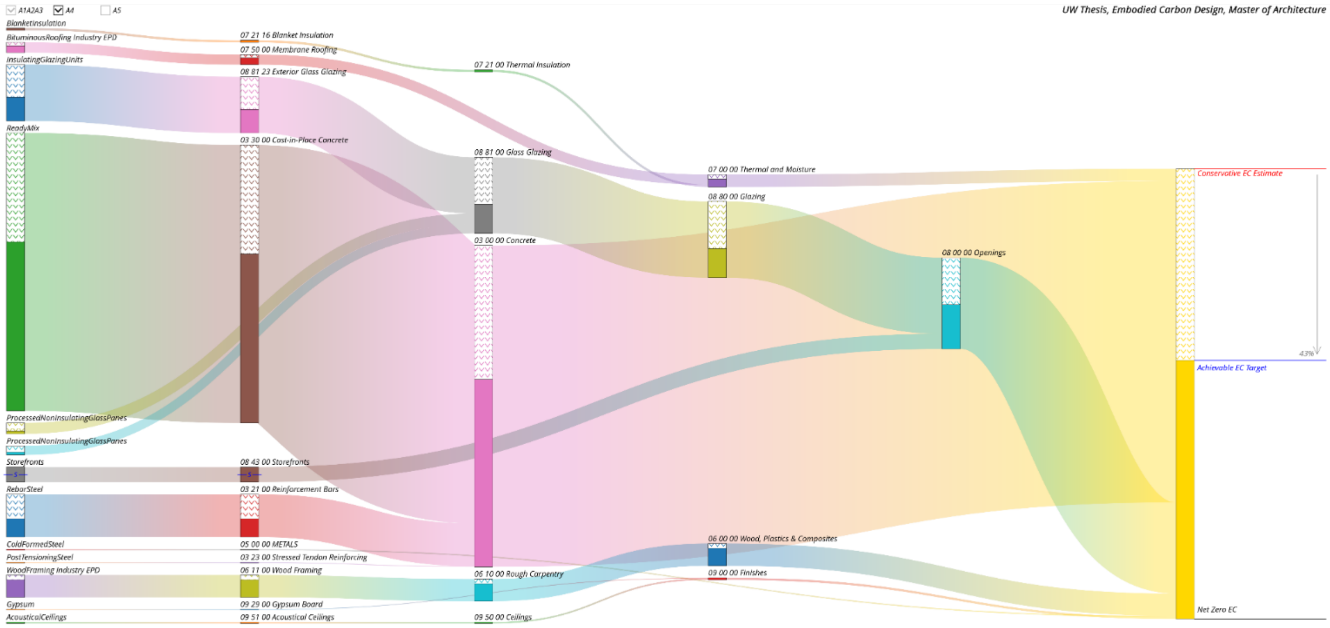
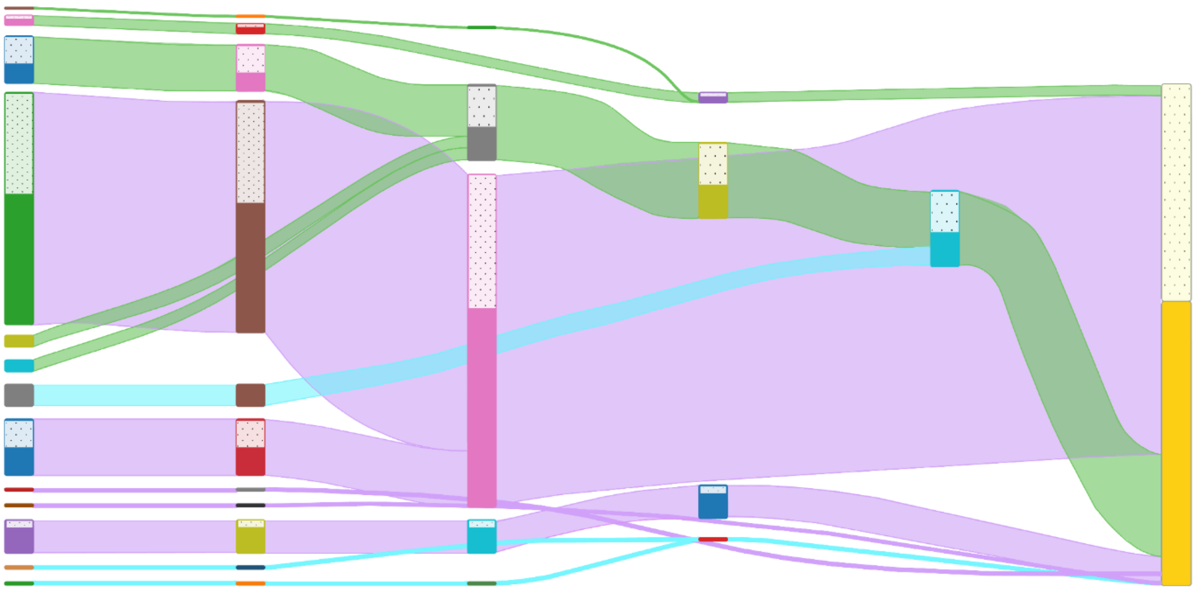


FIGURE 22 - ILLUSTRATIVE EC3 LCA DATA SHOWING THE EC IMPACTS OF PROJECT MATERIALS, BOTH THE CLF CONSERVATIVE AND ACHIEVABLE EC TARGETS.

EC3 Report – Sankey Chart with Brand's Filter – University Branch Library



Legend

Building Elements

🟪 Superstructure 🟩 Enclosure 🟦 Interiors

FIGURE 23 - ILLUSTRATIVE TALLY LCA DATA, COLORED TO ALIGN WITH BRAND'S FILTER.

CARE Report

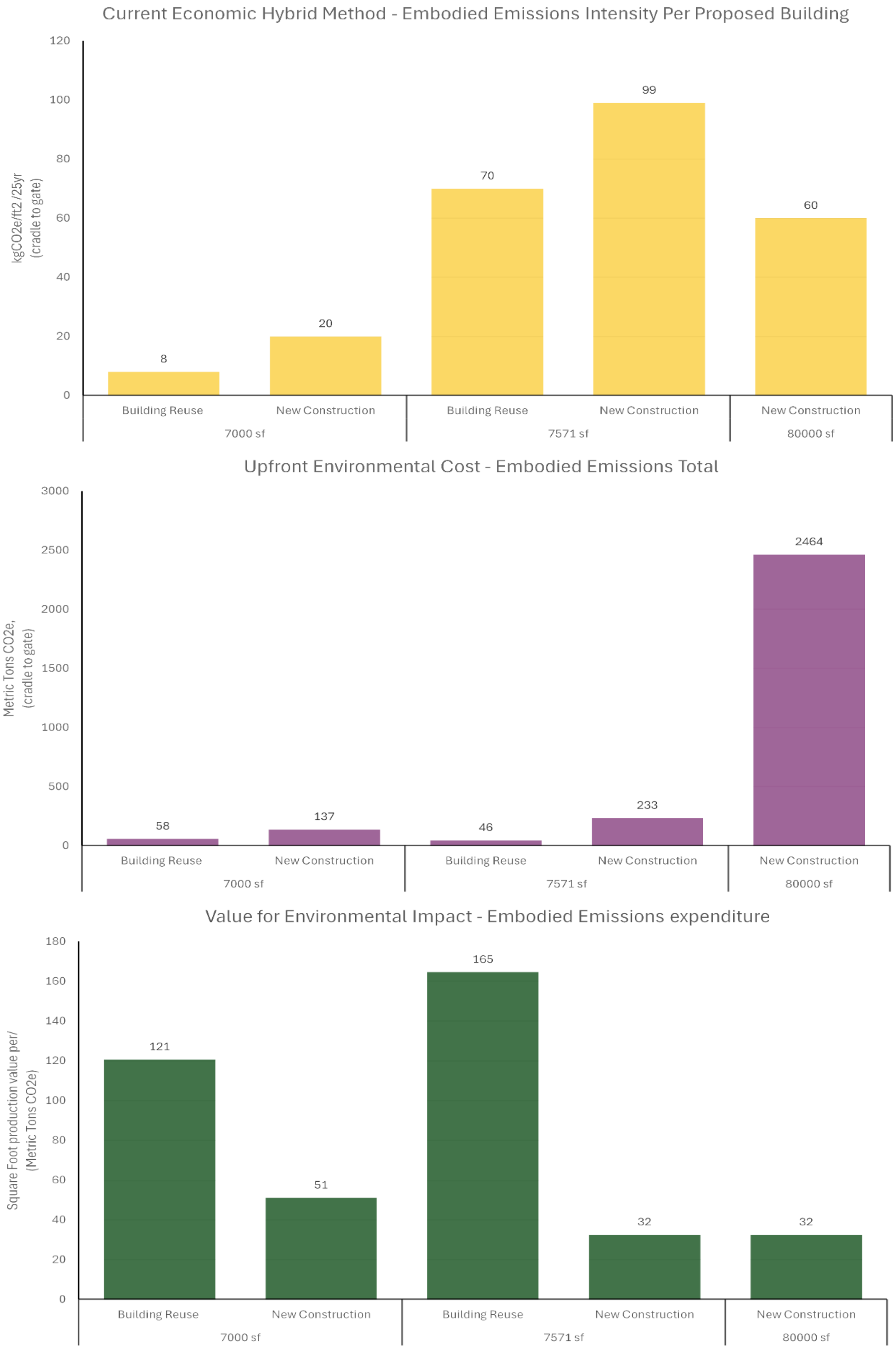


FIGURE 2418 - ILLUSTRATIVE BAR GRAPH DATA OF CARE OUTPUT, CONSOLIDATED FROM BUILDING REUSE AND NEW CONSTRUCTION SCENARIOS FOR THE UNIVERSITY BRANCH LIBRARY.

4.2.3 RAILSPUR HOTEL

Location:	Pioneer Square Historic District, Seattle, US
Year Built:	1904
Building Size:	appx 66,940 sf
No of Stories:	6
Material Construction:	Heavy timber post and beam with brick cladding, structural steel added in current adaptive reuse project.[91]

Analysis performed on the Railspur Hotel Project was performed retroactively on project progress, through analysis on the iterations of point cloud scanning and 3D model data provided by JTM construction and Miller Hull architects. The site is the most complex and densest development of the three projects, an adaptive reuse located in the Pioneer Square Historic District in Downtown Seattle, Washington. JTM construction performed surveys of the building throughout demolition of interior through all building phases. Project progress, the as-built surveys and 3D model data, were assessed at different points following the method explored in the University Branch Project, both in analog to the Fisher-Gewirtzman diagram, contrasting the existing building against proposed addition (Fig 9), and analogous to Brand's Shearing Layer diagram, with materials colored according to life cycle (Fig 7). Materials were assigned in Revit to 3D model data of segmented volumes available in each model, though without site photos for reference in this case. While data on MEP systems was abundant, these data were excluded from the bill of materials for the illustrative LCA feasibility reports generated in Tally (Fig 31), EC3 (Fig 32 & 33), and CARE (Fig 34).

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[91] *Oorley, Margaret A. "NATIONAL REGISTER OF HISTORIC PLACES INVENTORY - NOMINATION FORM - Pioneer Square - Skid Road District." npgallery.nps.gov, National Parks Service, 7 Jan. 2012, npgallery.nps.gov/pdfhost/docs/NRHP/Text/70000086.pdf.*

FIGURE 25 - IMAGES ILLUSTRATE POINT CLOUD SCAN AND 3D MODEL DATA ANALYZED. TOP IMAGE, A POINT CLOUD SCAN OF THE RAILSPUR HOTEL DURING INTERIOR DEMOLITION OF EXISTING BUILDING. MIDDLE, A 3D MODEL OF THE EXISTING BUILDING STRUCTURAL SYSTEMS OVERLAYED WITH THE LIDAR SCAN AT 25% TRANSPARENCY. BOTTOM IMAGE, 3D ARCHITECTURAL DESIGN MODEL OF FINISHED BUILDING AT 75% TRANSPARENCY.

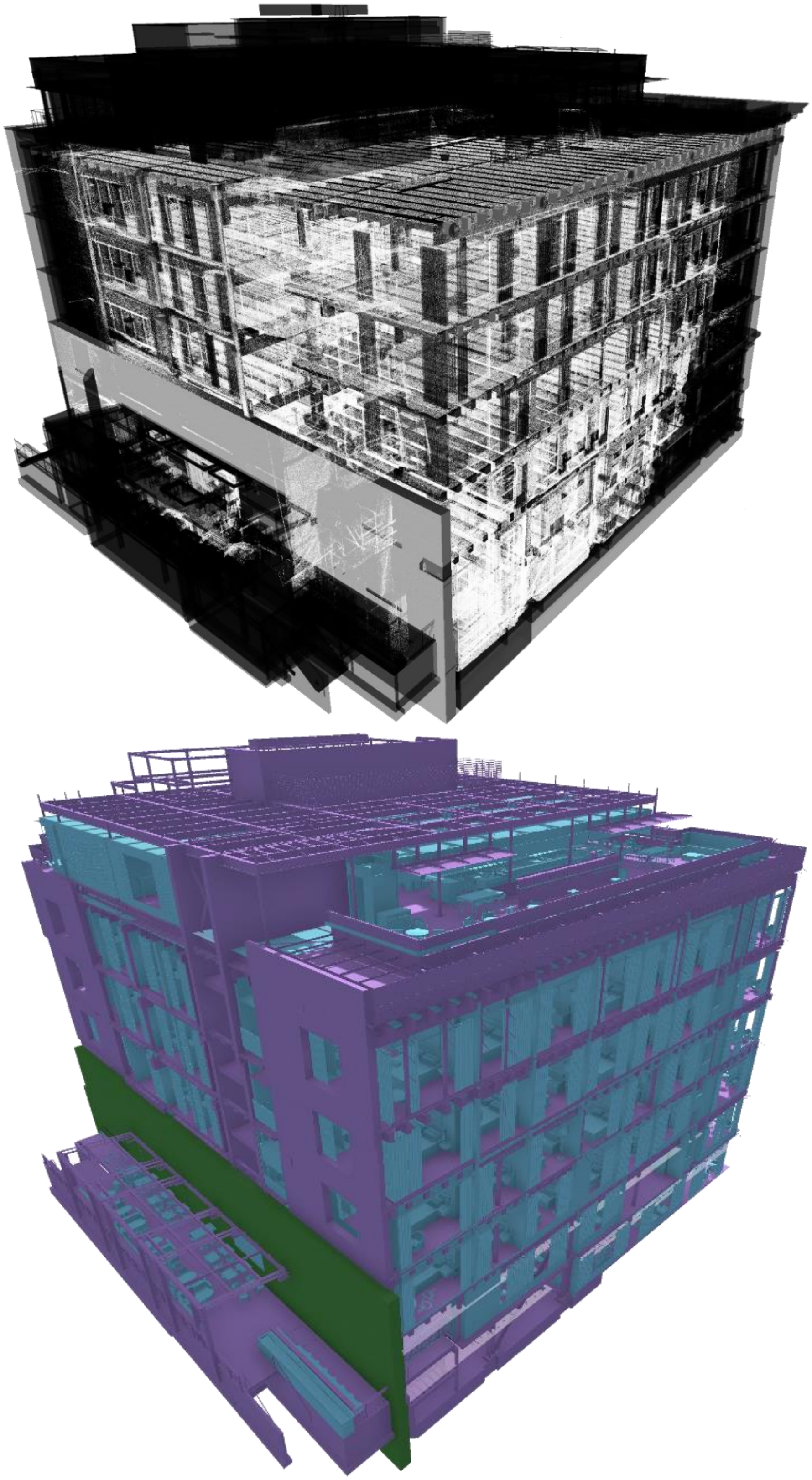


FIGURE 676 – TOP IMAGE OF BUILDING AXON AT 50% TRANSPARENCY WITH FISHER-GEWIRTZMAN FILTER. BOTTOM IMAGE OF BUILDING AXON WITH BRAND FILTER.

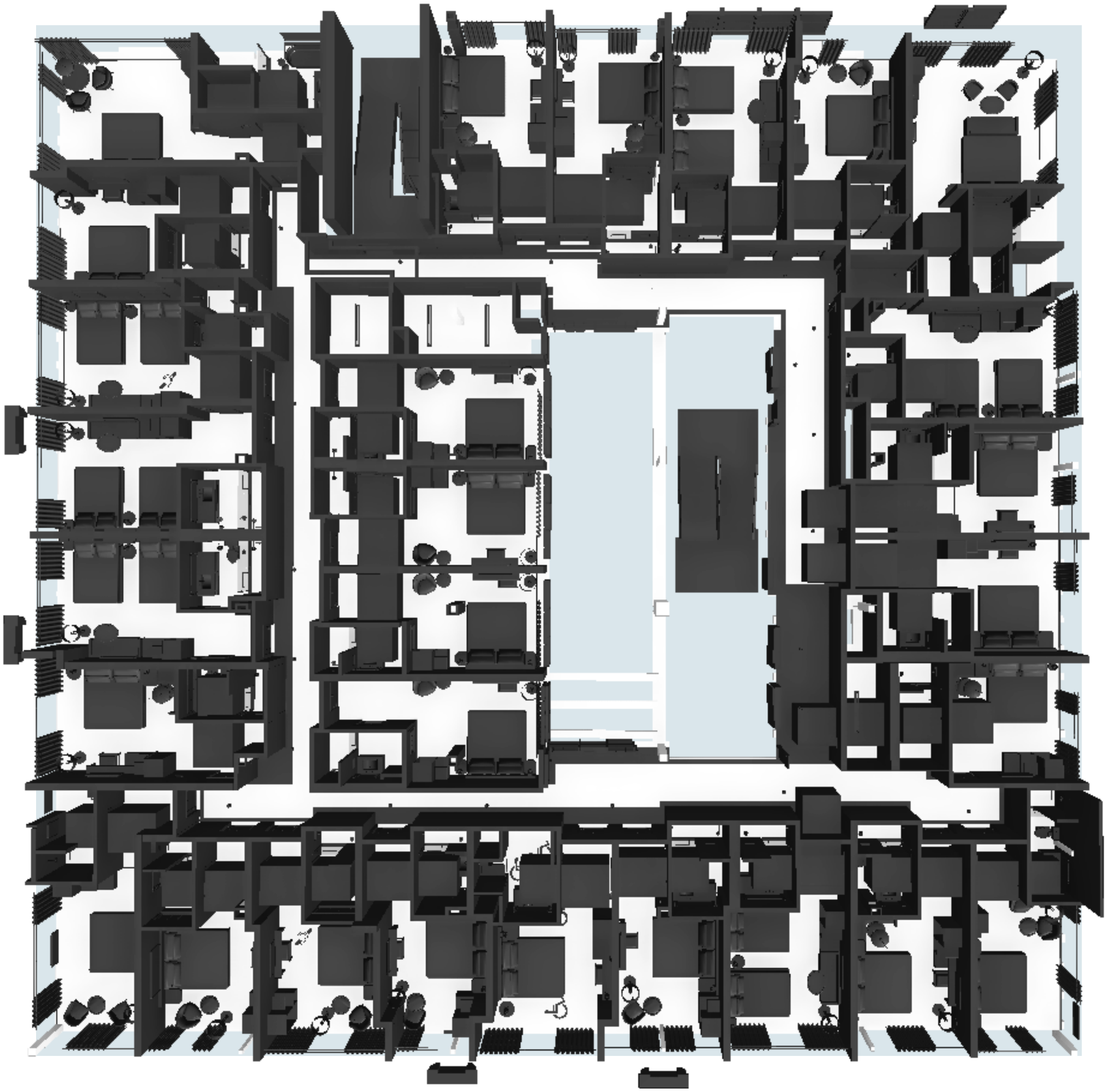
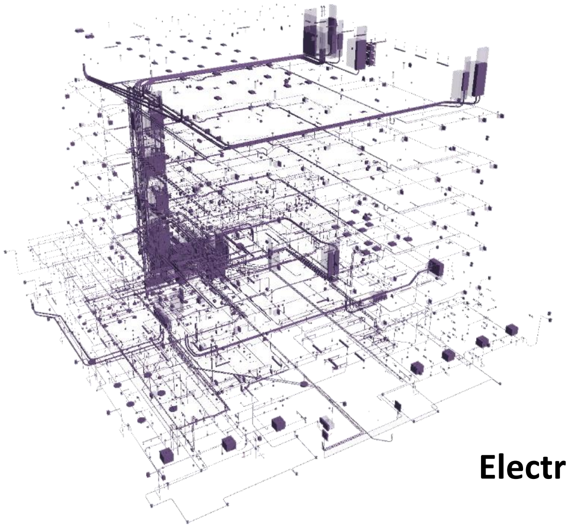
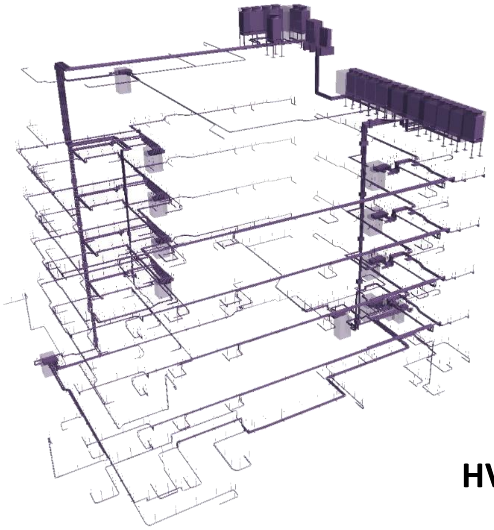


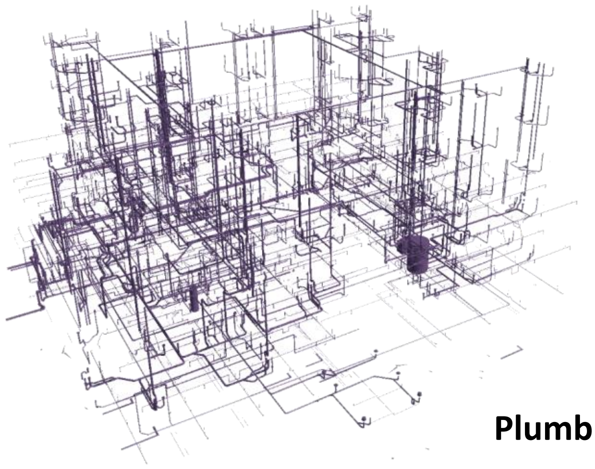
FIGURE 2768 – IMAGE OF 5TH FLOOR IN PLAN VIEW WITH FISHER-GEWIRTZMAN FILTER.



Electrical



HVAC



Plumbing

FIGURE 28 – IMAGES OF BUILDING SERVICES IN 3D MODEL IN BRAND'S FILTER NOT ACCOUNTED FOR IN TALLY OR EC3 REPORTS.

Tally Report – Material Impact Diagrams – Railspur Hotel Project

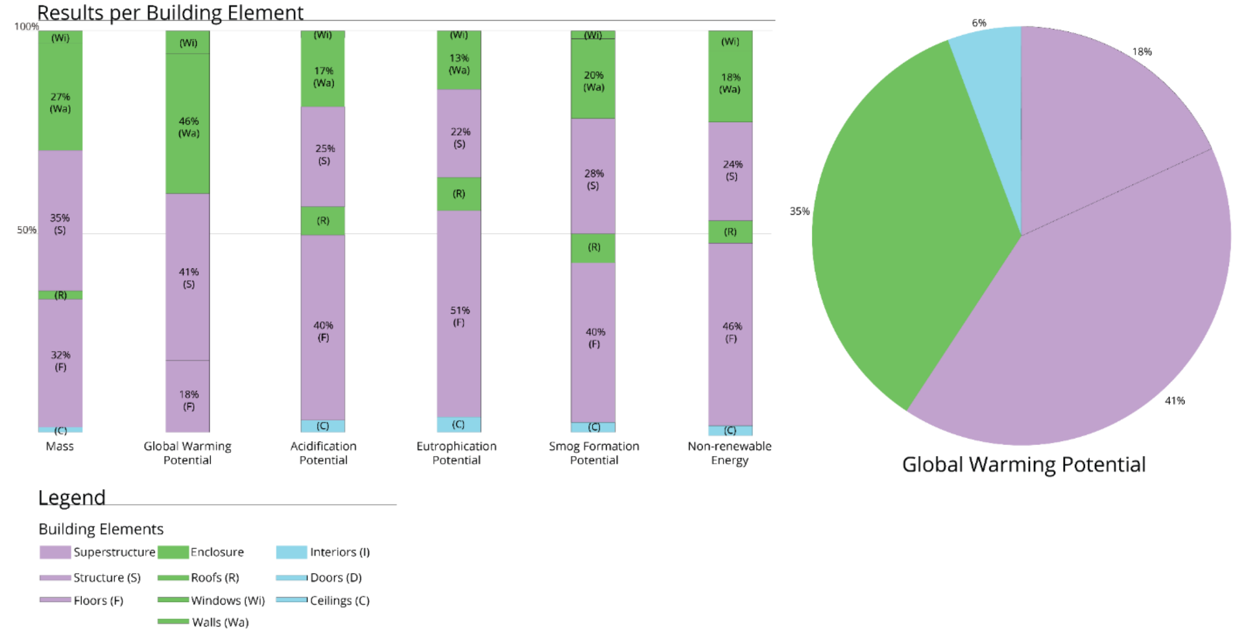


FIGURE 29 - ILLUSTRATIVE TALLY LCA DATA, COLORED TO ALIGN WITH BRAND'S FILTER.

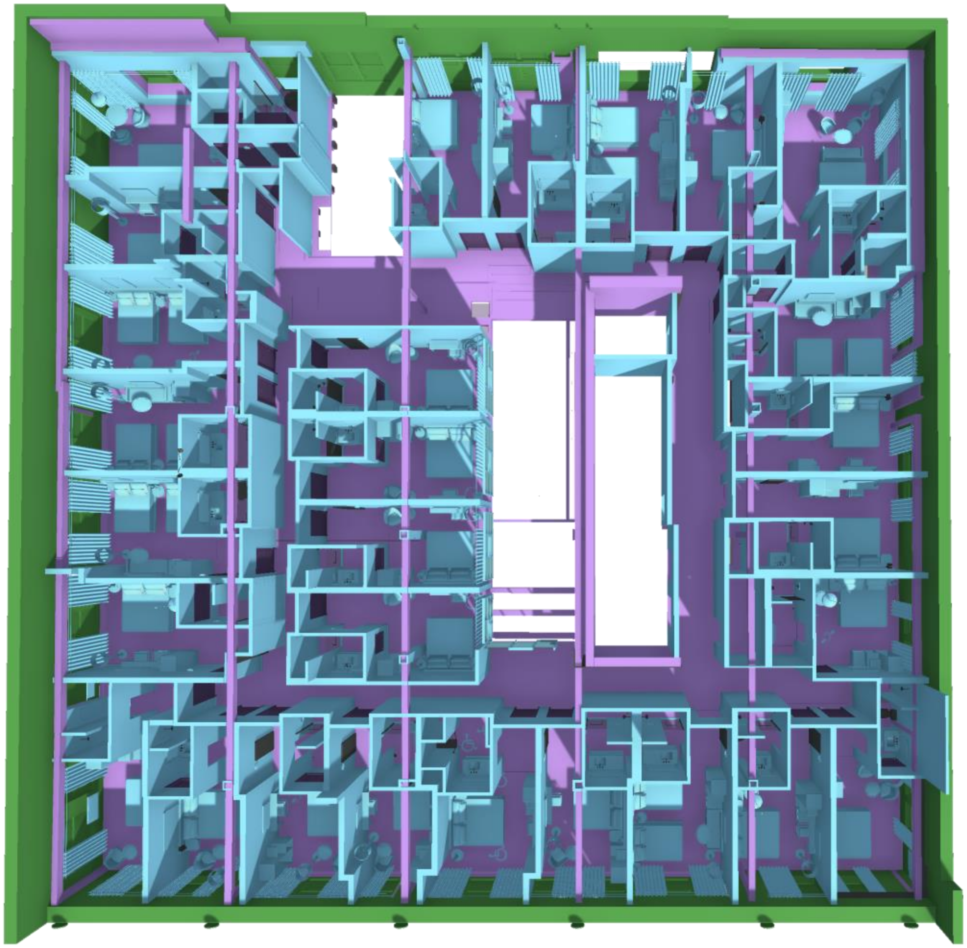


FIGURE 30 – IMAGE OF 5TH FLOOR WITH BRAND FILTER.

EC3 Report – Sankey Chart - Railspur Hotel Project

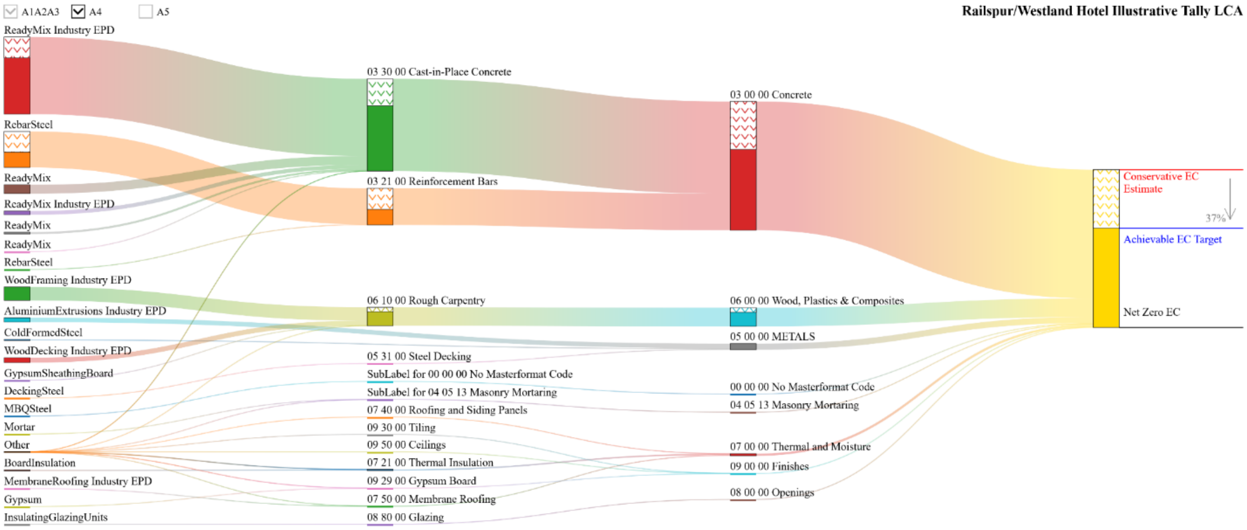


FIGURE 31 - ILLUSTRATIVE EC3 LCA DATA IN SANKEY DIAGRAM SHOWING THE EC IMPACTS OF PROJECT MATERIALS, BOTH THE CLF CONSERVATIVE AND ACHIEVABLE EC TARGETS.

EC3 Report – Sankey Chart with Brand's Material Life Cycle Overlay – Railspur Hotel Project

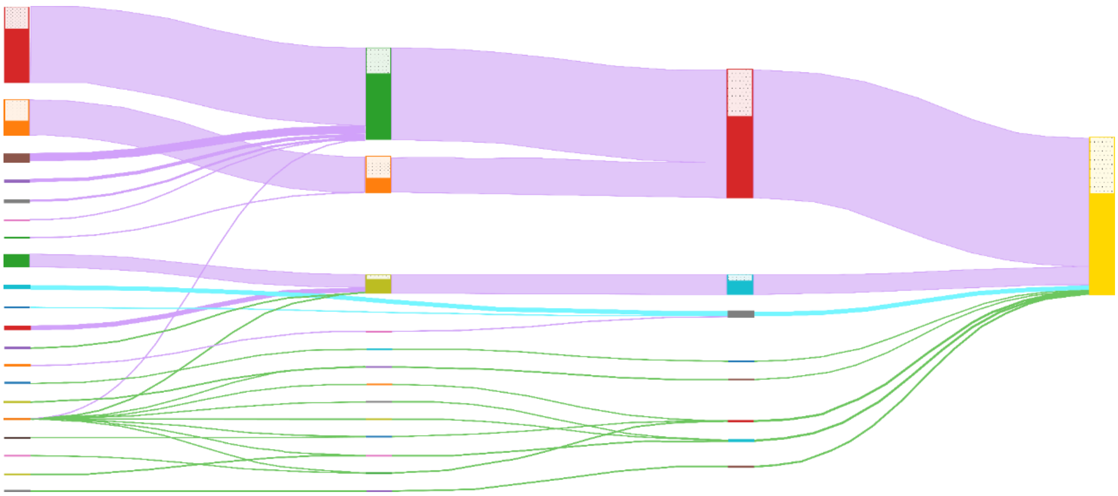


FIGURE 32 - ILLUSTRATIVE TALLY LCA DATA, COLORED TO ALIGN WITH BRAND'S FILTER.

CARE Report

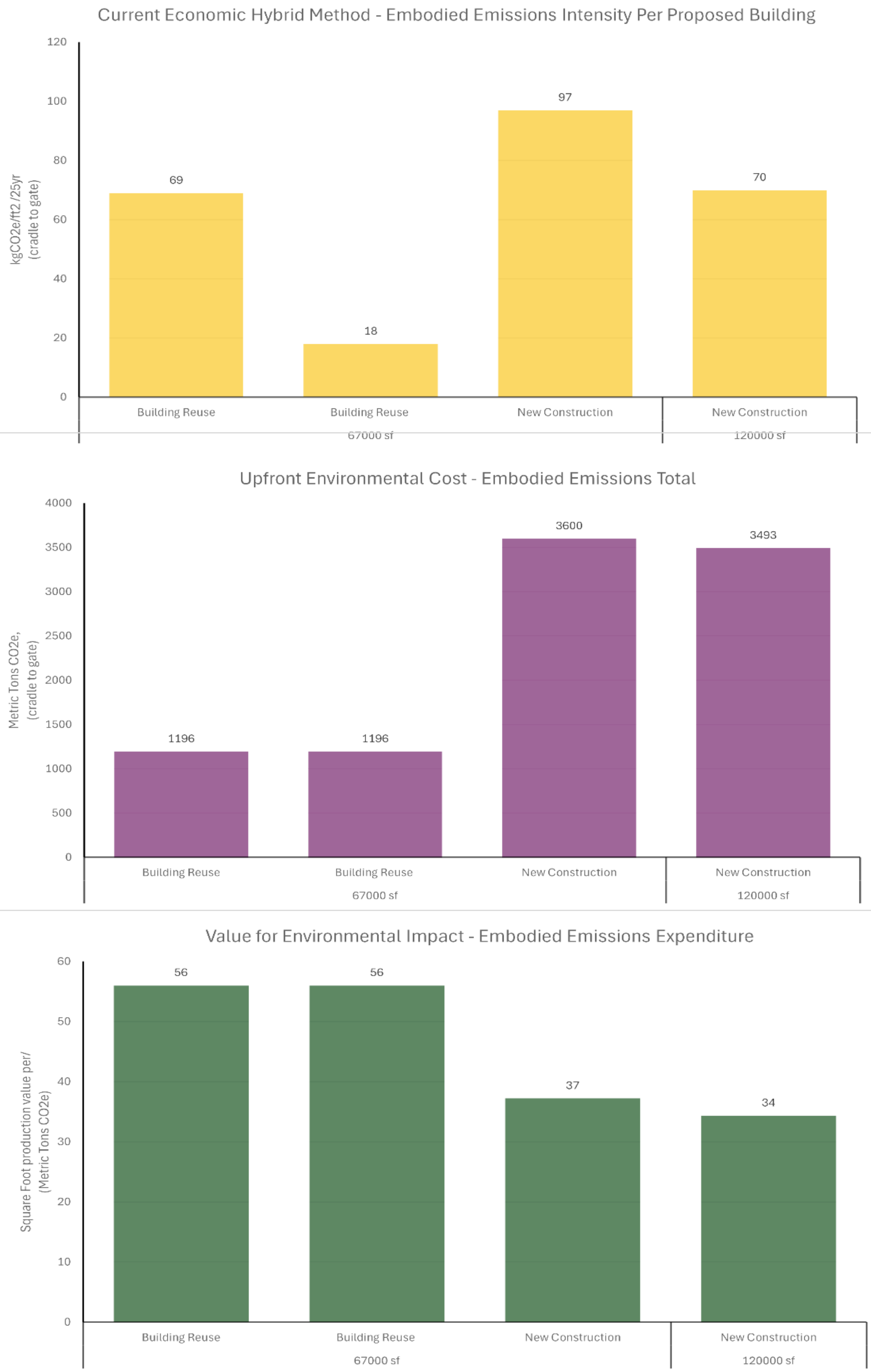


FIGURE 33 - ILLUSTRATIVE BAR GRAPH CARE DATA, CONSOLIDATED FROM BUILDING REUSE AND NEW CONSTRUCTION SCENARIOS.

CHAPTER 5: Findings

5.1 CASE STUDIES

The following section assesses the performance of the workflow and data produced from the case studies in Chapter 4.

5.1.2 ASUW SHELL HOUSE

REALITY CAPTURE

The Shell House case study, supplemented with research into LiDAR and photogrammetry, helped refine the workflow and project scope feasibility. This contributed to the selection of the other case studies. The Shell House revealed the limitations in communication between software, demonstrating that RHINO is not efficient for developing a 3D model from a point cloud scan. Additionally, it showed the need for software with robust material analysis and quantification capabilities, leading to the later use of Revizto and BIMIT in subsequent case studies.

3D MODELING

Observations of student work on the Shell House and discussions with students helped confirmed operability issues with RHINO as the primary 3D modeling software for this project workflow. The first critique was that the raw appearance of the 3D point cloud in RHINO, consisting of millions of point measurements, placed a high burden on graphic processing. Most participating students were unable to overcome this burden using laptop computers in the studio. Both their personal computers and the common access UW desktops struggled with the 3D point cloud files in RHINO. Even with stronger computing power, students found the additional work required to make the 3D model useful for design exploration of questionable value. However, student Ali Ahmed successfully drew over the raw 3D model point cloud in RHINO, utilizing the precision measurements to develop an accurate full-scale model of the building and each structural member

5.1.3 UNIVERSITY BRANCH SEATTLE PUBLIC LIBRARY

REALITY CAPTURE

The first visit was conducted before public access hours, which helped conduct the scan slightly faster by avoiding public intrigue and obstruction of scanning paths. Obstructions did affect the ability to seamlessly traverse all spaces; however, the mobility and scanning capability of the NavVis VLX proved successful navigating difficult spaces, such as the boiler room on the lower floor. Access to the attic and roof was limited to a ladder and a series of small access portal doors. A return visit was necessary, employing safety measures using rope and clips to lift the NavVis VLX into the attic. Despite these challenges, the total LiDAR scanning time across both visits was less than 30 minutes, though limitations of risk due to high cost of the device was also a consideration.

Ground penetrating radar (GPR) scans of the floors, foundation, and walls, identified material depths and confirmed presence of rebar and spacing in concrete (Fig 13). Access to the GPR itself limited and dictated the scanning schedule. Data collected from the GPR was not integrated into the 3D model, but informed inputs into the Tally materials specifications, when options in Tally permitted.

The photogrammetry capture by drone was conducted in less than ten minutes under optimal conditions, including fair weather with low winds and no rain. A clearance area for drone takeoff and landing necessary in the parking lot was optimal for operations and was accessible at the site. There was some public interest which did not interrupt the flight as James Harbin acted as pilot and the author, as observer, was able to answer the questions of curious members of the public. The data was easily transferable via sim card for overlay with other scanning data, providing good detail of the roof, site, and adjacent structures.

Once uploaded, alignment of different data, the LiDAR scan from both visits and photogrammetry from the drone, were combined in NavVis IVION cloud software. The initial time to upload and process the point cloud data took approximately four hours, a respectively short amount of time benefited by high computing power of 256GB of RAM and an Intel i9 processor. The resulting combined model data was transferred online to Integrated Products for REVIT 3D model production in their BIMIT scan to 3D model software and compared to the manually produced 3D REVIT model produced by SHKS for the University Branch renovation.

3D MODEL

The BIMIT model aligned to the point cloud model with no substantial variation. There was one aspect that was out of scale with actual onsite building dimensions, an additional stem wall running the full length of the main floor's Western façade to a depth equivalent to the lower floor foundation. This stem wall does not appear in any historic plans and was not verified by scans of this project or in the SHKS REVIT model. With this observation, this volume was removed from input into the final Tally material data prior to report generation.

The SHKS model was not used for materials input into Tally as it was not produced using the LiDAR point cloud survey. The model was referenced for measurement to the point cloud and for material assembly inquiry during the Tally material data assignment. No substantial material information was assigned from the SHKS model, beyond the determination of the stem wall removal, to the BIMIT model assessment which was the primary model used in the Tally LCA assessment.

Assignment of materials to segmented masses in Tally was carried out on the BIMIT 3D model based in REVIT. A major observation was that both the BIMIT model and the SHKS model substantially lacked material assembly assignments to the segmented masses they are composed of. Perhaps as a utility of the 3D design process, existing segmented masses were more often defined as single blocks, with detailed segmentations mostly being applied to objects such as mullions or definable visible exterior features. This led to a great deal of additional work to create assemblies for interior masses in REVIT and Tally for material assignment of the model. In parallel, it was observed that no pre-loaded assemblies were available for material selection in Tally, leaving all input to be carried out manually.

LCA - TALLY

The time to complete material assignment in Tally was approximately 10 hours. Materials were assigned based on in-person inspection, photo, and shape segmentation quality. A level of speculation was required for assemblies of interior walls and floors, assigned as accurately as possible to the dimensions of segmented objects. Notably, there were no available historic materials or a contemporary equivalent of environmental impact value. This left the decision up to the user to select only contemporary materials and to make best judgement in their selection to determine environmental impact value.

With all assemblies created and materials assigned, the final Tally results were generated in seconds as a report through an internal request function in Tally. The report itself was downloaded as a twenty-six-page pdf, complete with title page, table of contents, colored graphs, LCA methodology, and LCI data for the materials. By default, the report claims in the appendix section, “Calculation Methodology – Life Cycle Stage”, that all LCA stages are covered from cradle to grave, notably stating that “[f]or products listed in Tally as Environmental Product Declarations (EPD), the full life cycle impacts are included, even if the published EPD only includes the Product stage [A1-A3]”.[92] This and the observation made during material assignment that neither historic materials nor option to assess what their respective contemporary equivalent could be, undermines confidence in the completeness of the LCA

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[92] *Strand, James. “University Branch Library Illustrative Tally LCA.” James Strand via Tally Software, 16 May 2024.*

results. The results of the Tally report is labeled as "Illustrative", showing that the process proposed (Fig 21) is viable as an efficient throughput in producing cogent LCA results, but that those LCA results require additional considerations mentioned, as well as typical 3rd party verification.

Brand's Shearing Layer filter applied to a graph from the Tally report (Fig 21), shows both the percentages of emissions impacts by assembly as reported by Tally, but also reveals a concept of life performance expectation of those assemblies. This could be useful in future applications to assess lifespan performance and adjust embodied carbon value of material assemblies. The color spectrum applied could also be expanded to include more specificity of material, assembly, age, and location in the building for additional performance assessment, such as has been illustrated in the 3D model application of the Brand Filter (Fig 20). The Fisher-Gewirtzman filter applied to the 3D model visually contrasts the new and retained building elements. This was an effective tool to visualize mass, intensity, and when compared with the Brand filter, a means to consider overlap of embodied carbon utilization and balancing design choices.

LCA - EC3

The final Tally data was transferred into the EC3 Tool for additional data analysis and report generation. Conservative material EPD results were accepted in the generation of reports for this project, including the Sankey Diagram (Fig 22). Brand's filter was also applied as an overlay of analysis to material results of the Sankey Diagram (Fig 23). The Brand overlay was informative in showing the relationship between assembly life cycle and their share of GHG impacts. Additionally, the absence of material colors, such as Brand's "stuff" or interior elements and "services" or MEP, revealed a substantial gap in material accounting and LCA analysis.[93] The time to produce reports from EC3, without additional material specification and including the upfront time to input basic project information, was approximately 20 minutes.

LCA – CARE

The CARE tool is a single online page with a book of project data tabs, from right to left, were general information, existing building, building reuse, and new building. After inputting general information, I was able to test out three different scenarios for the University Branch (Fig 24). The first scenario copies the data of the existing building for

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[93] *Brand, Stewart. "Shearing Layers." How Buildings Learn: And Fail to Learn, Viking, New York, NY, 1994.*

building reuse and the new building, assuming no changes. The second scenario shows an increase reflective of the changes proposed in the SHKS renovation for building reuse and data entered for the new construction. The third scenario contrasts the SHKS renovation against the new construction of a multi-family mixed use tower replacing the University Branch. The results for all three were an informative way to compare possibilities of embodied carbon impacts of different building scenarios. Of particular interest were the sliders for assessing building reuse embodied carbon which allow the user to adjust a movable slider, on a 0-100 scale, to show how much of the existing building was preserved in categories of structural, envelope, interior, and mechanical-electrical-plumbing (MEP) systems. It was useful to interrogate the 3D models for this data. However, determining percentages was difficult and lacked instruction for users to follow to assess their project for those data points. Clarity of user interface and data inputs made the CARE tool easy and time efficient to use, only taking less than 10 minutes per scenario, providing a useful report of data inputs for comparison in graph and list form. Side by side comparison of this data across scenarios was not possible without input into an Excel spreadsheet. Results comparing the scenarios in this project show how dramatic differences can be in environmental impacts when changing criteria in project scenarios (Fig 24). While not carried out in this study, it would be beneficial for further analysis into the supporting algorithms of the CARE tool would be beneficial to understand how data supports calculations for report outcomes.

5.1.3 – RAILSPUR HOTEL

REALITY CAPTURE

The Railspur Hotel case study uses the same process as the University Branch Library, deviating only in that scan and model data were collected following their completion without direct observation of the scan and model development process. This was a useful means to isolate and test the workflow process for remote analysis, something which could be useful for 3rd party analysis and verification in the future.

3D MODELING

JTM construction provided several 3D models of the Railspur via the cloud for downloading and for viewing and analysis in the Revizto design and coordination software online. The data included as-built scanning data of the project following interior demolition, a 3D REVIT model of existing building structural members retained for the project, REVIT MEP models, and Miller Hull architectural design models (Fig 25). Downloading copies of the model for review and analysis in REVIT was essential for Tally and EC3 review as well as general building dimensional reference. The Revizto online platform provided an excellent means of consolidating all 3D model data into one program for visualization, comparison, and analysis. Within Revizto, 3D model data was overlayed, isolated, recolored, and analyzed for this thesis. Use of Revizto was essential in developing the Brand and Fisher-Gewirtzman filter for use with the 3D model data. It is important to note that definition, clarity, and time to generate images produced in Revizto was greatly dependent on the specificity of the segmentation and labeling structure in the 3D models. A notable weakness of using Revizto was a lack of orthogonal view options of the 3D models, meaning that viewpoint scalability was not possible, leaving views to be useful for visual analysis but less so for scale comparison of printed documentation outside of the program. The Brand and Fisher-Gewirtzman results show how effective that visualization is, in this case showing the intensity of the building reuse employed in Railspur, which corresponds with results from LCA analysis.

LCA - TALLY

The processing of Tally results was made easier for the Railspur project than the University Branch as more than half of the task of material had been completed by JTM and Miller Hull. However, the same issue of not having access to material assembly selection for segmented 3D volumes led to lengthy manual inputs, on a project of much greater intensity than the University Branch. Despite this, the time to input this data was about the same as the University Branch at approximately 10 hours. Tally LCA data quality mirrored conditions found in the University Branch with EPD scope, absence of historical material equivalents, lack of assembly option selection. Similarly, without 3rd party verification, the LCA assessment of the Railspur results is listed as “Illustrative”. Another important similarity with the LCA assessment was the absence of estimates for the interior furnishings and MEP system change which, for the aspect of reuse for the Railspur Project, was particularly intensive as evidenced in the Brand filter results in axon (Fig 29) and of MEP “services” (Fig 30). This illustrates another opportunity for future consideration of overall precision improvement in targeting the full scope of embodied emissions.

LCA – EC3

The same process for University Branch was applied to the Railspur project for the transfer of Tally LCA data to EC3 and in report generation of default material EPDs without further specification. The most notable difference in the data results was that the greater intensity and scale of the Railspur Project contributed to a list of a great deal more source materials, especially for the envelope of the building, shown in the Brand filter over the Sankey Diagram (Fig 33). The time to transfer data from Tally to EC3 and produce reports was in parity with the University Branch project at approximately 20 minutes.

LCA – CARE

The process for assessing Railspur mirrored that of the University Branch, with deviation only in scenario three to increase the size of the proposed new building in the context of new construction averages in the Pioneer District Neighborhood where Railspur is located. The same observations of positive performance as well as opportunities to improve precision with data from this thesis process, were made in the process of generating the reports and analyzing results in the CARE tool.

CHAPTER 6: Discussion & Conclusion

The implementation of advanced tools and software can significantly improve the accuracy and efficiency of capturing and analyzing building data. The methodology fostered a rigorous calculation of embodied carbon and aimed to contribute to emission management and reduction within the built environment. The integration of these technologies demonstrates a promising approach to sustainable architectural practices and efficient building information management.

SUMMARY OF CASE STUDIES ON HISTORIC BUILDING REUSE

Three historic buildings in Seattle, WA, were studied to test a workflow for building reuse. The chosen buildings varied in construction complexity and accessibility, offering valuable insights for the study.

ASUW SHELL HOUSE

- **Construction**: Heavy timber trusses, wood framing on concrete slab and piers.
- **Process**: The study involved using NavVis VLX LiDAR to create a point cloud model, further developed into a 3D model by UW architecture students using Rhinoceros (RHINO) software.
- **Outcomes**: The feedback from students suggested that integrating point cloud scans with 3D modeling increases efficiency and accuracy. This study also refined the workflow for subsequent projects.

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- **Construction**: Reinforced concrete structure with hollow clay tile infill, concrete slab, and timber roof framing.
- **Process**: Data was overlaid into a 3D point cloud and used to develop a 3D REVIT model through manual and machine learning techniques. Models were visually analyzed, and materials were assigned for LCA feasibility.

- **Outcomes**: The study used models in Tally, EC3, and CARE LCA tools to understand life cycle assessment feasibility and generate illustrative reports.

RAILSPUR HOTEL

- **Construction**: Heavy timber post and beam, brick cladding, structural steel added during adaptive reuse.
- **Process**: The study retroactively analyzed project progress through point cloud scanning and 3D model data, following methods explored in the University Branch Project. Materials were assigned in Revit for LCA.
- **Outcomes**: The project tested the workflow on a more complex and dense development, providing further insights into the practical applications of reality capture technology, 3D modeling, and LCA tools in building reuse.

These case studies highlight the value of using advanced technologies like LiDAR, 3D modeling, and LCA as one workflow in pursuit of a standard method of data collection and emissions analysis of existing buildings.

The development of means and measurement, the iteration and refinement of measurement tools and methods, should be continuous. While a rigorous and replicable means of data collection and analysis, the workflow of this thesis requires additional testing and development for LCA accuracy, especially in comparison to existing processes of LCA assessment to understand its full value.

Method Strengths

- Accuracy of data collected using photogrammetry and LiDAR used to inform 3D model.
- Speed of data collection using photogrammetry and LiDAR.
- Accuracy of 3D model used in emissions analysis.
- Ease of accuracy verification of 3D model to 3D point cloud.
- Speed of production of 3D model used in emissions analysis.

- Speed of visual analysis using Fisher-Gewirtzman and Brand filters.
- Ease of visual analysis using Fisher-Gewirtzman and Brand filters.
- Ease of emissions analysis through Revit, Tally, EC3, and CARE.

Method Challenges

- Access to tools and software.
- Interoperability of tools and software.
- Multiple proprietary tools and software.
- Site and building accessibility.
- Computation power performance in data analysis.
- Heterogeneity of LCA data collection methods, tools, and standards.
- Absence of historical material and assembly reference or equivalent in LCA tools.

Method Opportunities and Future Research

- Test replicability of the workflow for 3rd part assessment and verification.
- Develop additional case studies for comparison of results for speed and accuracy to traditional methods.
- Scalability resulting from speed and accuracy of workflow to existing building portfolio analysis.
- Consolidate workflow technologies into a single assessment tool.
- Automation of workflow to further speed, scale, and assessment of data.
- Data to inform emissions management and LCA material and building reuse strategies, prioritization frameworks, and standards.
- Real time visual information design development and decision making.
- Further definition of building age, assembly, and material performance.

Assessment of the workflow strength indicates ease of replicability and speed of data collection. Replicability could assist in providing greater clarity and comparability of data. Efficiency of the workflow could allow for data collection during progression of project construction as well as could improve feasibility of assessing multiple buildings. Data on building typologies, at a greater granularity of detail, could improve performance of embodied carbon decision making at a greater scale. Scaled assessment of existing buildings and emissions potential could inform policy and decision making across the built environment, including Historic Preservation Policy. Data from scaled studies of buildings could contribute to improvements in accuracy of MACC curves (Fig 35) to refine embodied carbon reduction investments and incentives to improve speed of embodied carbon reduction (Fig 36).[94]

While consensus on a single standard and methodology in building LCA may not yet exist, the tools and literature of LCA have matured, with interest in understanding the value building reuse continuing to trend. Understanding the context of that trend may help to inform consensus on the development of standards and methodology.

KEY TAKEAWAYS FOR STAKEHOLDERS

- **Architects** can leverage advanced LCA tools like Tally and EC3 to make more informed decisions regarding material selection and design.
- **Researchers** can build upon the evolving databases and methodologies to further refine LCA practices.
- **Building Conservationists** can advocate for the reuse of existing structures backed by robust LCA data.
- **Policy Makers** can use standardized LCA methods to shape regulations that promote sustainability.
- **Environmental Scientists** can contribute to the development of more accurate LCA models and databases.

By staying informed and utilizing these advanced tools, stakeholders can play a crucial role in the development of standards and promoting sustainable building practices to reduce carbon emissions. Opportunities exist for machine learning tools to be employed in various aspects of the workflow. It may be possible to consolidate the workflow into one application and incorporate additional tools of building analysis, such as providing input data

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[94] *Du Plessis, D. "Marginal Abatement Cost Curves for the Built Environment." Cloudfront.net, Branz, 2022, d39d3mj7qio96p.cloudfront.net/media/documents/sr470_marginal_abatement_cost_curves_for_the_ built_environment_-_developing_a kkwsx2n.pdf*

requested by the CARE tool. Data points on embodied carbon requested by the CARE tool could improve precision in decision making on trade-offs between building reuse and new constriction.

Accounting for embodied carbon in existing buildings, in building reuse design, and for decision making in new construction can benefit from greater standardization to improve time efficiency, precision, and lower data collection costs. Much like the adoption of the kilogram and meter, we must ensure continuity of measurement methodology to achieve reliable results. Development of decision-making tools and workflows, such as the workflow proposed in this study, which quickly and accurately assess carbon emission trade-offs, can benefit the balancing of humanity's carbon emissions accounting of the built environment and serve as a reasonable action in response to the observations made in the *Time Value of Carbon.*[95]

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[95] *Strain, Larry. "CLF Time Value of Carbon." Carbon Leadership Forum, 30 May 2017, carbonleadershipforum.org/wp content/uploads/2017/06/CLF-Time-Value-of-Carbon.pdf.*

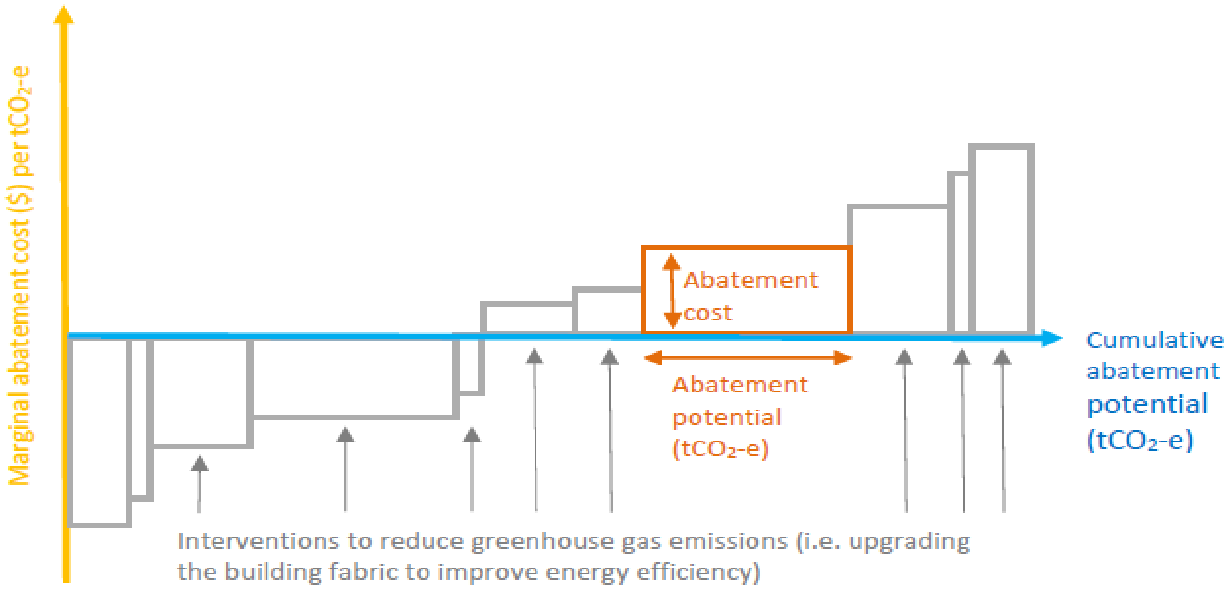

FIGURE 34 - THEORETICAL FRAMEWORK FOR MACC BAR CHART.

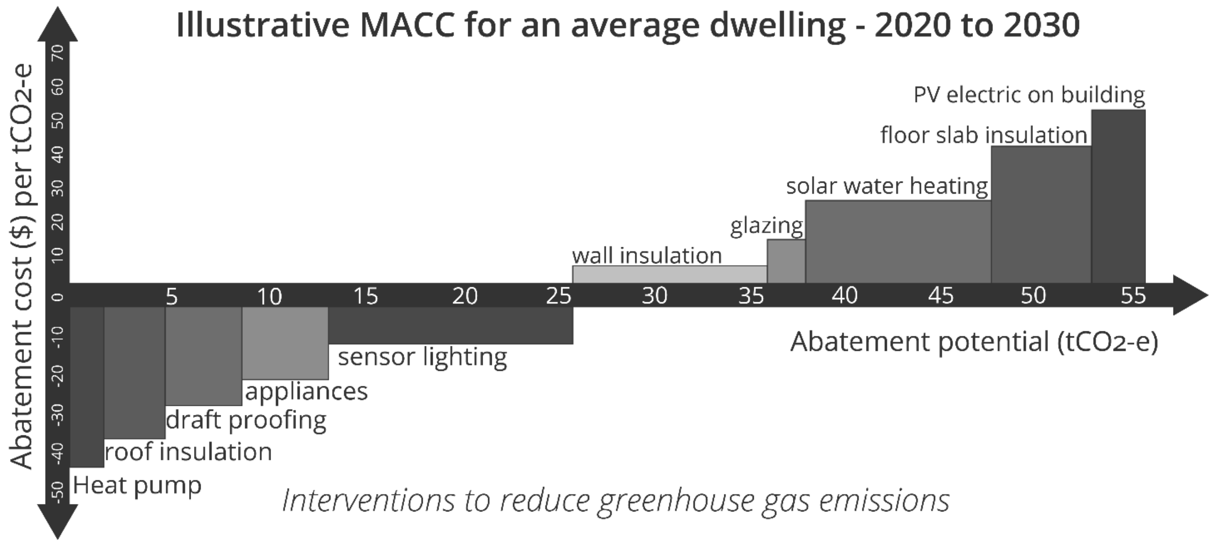

FIGURE 35 - EXAMPLE OF MACC BAR CHART APPLIED TO THE BUILT ENVIRONMENT WITH EDITS BY AUTHOR.

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