University of British Columbia

Social Ecological Economic Development Studies (SEEDS) Sustainability Program

Student Research Report

Understanding the Embodied Carbon in BCR 6 Mechanical, Electrical, and Plumbing Systems

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EXECUTIVE SUMMARY

This study explores the embodied carbon contributions of Mechanical, Electrical, and Plumbing (MEP) systems in Building C of the BCR-6 project at UBC, focusing on improving whole building life cycle assessment (WBLCA) practices. With growing attention on embodied carbon, particularly in buildings, this research aims to provide a comprehensive perspective on MEP system impacts and guide the future UBC guideline update to better incorporate the MEP system into WBLCA to further support building decarbonization.

The project was conducted in two phases. The first phase reviewed current methodologies and tools for MEP embodied carbon assessment, comparing their applicability, limitations, and select the best suitable method and tool for next phase research. Three distinct methodologies - TM65, LCA database and EPD-based, and BIM-based WBLCA—were analysed, leading to the selection of the database and EPD-based WBLCA methodology for its balanced feasibility, accuracy, and data availability. One-Click LCA was chosen as the tool for experimental calculations due to its comprehensive MEP-related database and compatibility with the existing structure and envelope assessment.

The second phase involved experimental WBLCA calculations for the plumbing system, supplemented by literature-based estimations for the mechanical and electrical systems. Results showed that the GWP of the plumbing system accounts for roughly 1/10th of the embodied carbon in the structure and envelope. Notably, acrylic shower tubs emerged as a major emissions contributor, indicating a clear opportunity for decarbonization. Through an extensive literature review on MEP system emissions - considering factors like building size, type, refrigerant leakage, and component replacements over the building's lifespan - we estimate that MEP systems collectively contribute approximately 36% of the building's total embodied carbon. This underscores the significant impact of MEP systems, particularly mechanical components, on the overall carbon footprint.

The analysis of plumbing and MEP systems faced several key limitations. For plumbing, three levels of uncertainty arose from raw data gaps, inconsistent database matching, and EPD variability during emissions estimation. For MEP systems, challenges included data availability and benchmarking difficulties, such as supplier engagement issues, gaps in electrical data, absence of BIM models, and limited WBLCA tool compatibility. Benchmarking was further complicated by the lack of standardized MEP methodologies, incomplete equipment listings, and the absence of MEP-specific benchmarks and residential building data. These issues highlight the need for further case studies to inform future guideline development.

Based on our findings, we recommend building a solid data foundation in the short term through proactive stakeholder engagement, systematic record-keeping, and close supplier collaboration. For the mid to long term, we emphasize the importance of partnerships and broader industry collaboration, such as through initiatives like the MEP 2040 Challenge, to enhance both data quality and methodological rigor. Future research should prioritize developing comprehensive MEP embodied carbon guidelines, validating methods through comparative studies, and establishing clear benchmarks for industry standards. Additionally, exploring decarbonization strategies—including the use of low-GWP materials and retrofitting system designs—is essential to achieve long-term sustainability and decarbonization goals.

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LIST OF ABBREVIATIONS

MEP	Mechanical, Electrical, and Plumbing
WBLCA	Bhole Building Life Cycle Assessment
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
CAP 2030	UBC's Climate Action Plan 2030
GHG	Greenhouse Gas
EPDs	Environmental Product Declarations
DQ	data quality
CIBSE	The Chartered Institution of Building Services Engineers
ISO	International Organization for Standardization
BIM	Integrating Building Information Modelling
EC3	Embodied Carbon in Construction Calculator
GWP	global warming potential
VRF	variable refrigerant flow

1. INTRODUCTION

1.1 RESEARCH TOPIC

This project aims to evaluate the embodied carbon of mechanical, electrical, and plumbing (MEP) systems within Building C of the BCR-6 project, located on UBC's Westbrook Mall. The primary focus is to assess the significance of MEP systems' embodied carbon contributions, an aspect that is often overlooked in current assessments. According to the existing UBC Guidelines, the whole building life cycle assessment (WBLCA) scope is limited to a building's structure and envelope. While MEP systems can be optionally included, their potential contribution to embodied carbon is substantial, yet methodologies for accurate quantification remain underdeveloped and existing data is limited.

This presents an opportunity to advance the understanding of MEP systems' embodied carbon within WBLCA by exploring and quantifying their impact. The findings will be compared with the current WBLCA practices under UBC Guidelines, with the aim of proposing more comprehensive methods for incorporating MEP systems into future assessments.

1.2 RESEARCH RELEVANCE

How UBC's buildings are designed, constructed and operated will significantly impact UBC's ability to meet its climate and sustainability commitments. Therefore, it is important to target a building's total carbon emissions throughout its life cycle from materials production, construction, and operation to disassembly at the end of life. This work aligns with UBC's Climate Action Plan 2030 (CAP 2030) targets(*Climate Action Plan*, 2019) and provides a foundation for updating the university's embodied carbon guidelines.

- Broader Societal Impact:
  Expanding the understanding of embodied carbon in MEP systems supports global efforts to reduce emissions by filling critical data and methodology gaps. This research promotes more informed and sustainable design choices within the construction and engineering sectors, driving the adoption of lower-carbon solutions.
- Advancing Campus Sustainability:
  By enhancing methodologies to better account for MEP system contributions, this project strengthens UBC's approach to achieving CAP 2030 targets. More accurate assessments will enhance campus policies and practices, establishing UBC as a leader in sustainable building design.
- Community Benefits:
  This research supports the broader community by providing a framework for reducing embodied carbon in construction, leading to more sustainable buildings and healthier environments for users and occupants.

1.3 PROJECT CONTEXT

The development at Lot BCR 5-6, located at the intersection of Wesbrook Mall and Binning Road, encompasses a 37,480 sq. m market and faculty/staff rental housing project. This complex includes an 18-storey market rental high-rise and two six-story mid-rise apartment buildings designated for faculty and staff rental, providing a total of 515 residential units. This research focuses on Phase 1: Building C, one of the six-story faculty/staff rental mid-rise apartments.

Building C has already undergone a whole building life cycle assessment (WBLCA), providing existing data that can serve as a benchmark for evaluating the embodied carbon contributions of its MEP systems. Unlike typical studies limited to design-phase estimates, this project benefits from analyzing the actual installed MEP system, offering greater accuracy and real-world insights. Additionally, since the building has been constructed, all contacts and documentation from design through construction phases are well-established, enabling comprehensive data access and collaboration.

Figure 1 UBC BCR 6 – building C, 3638 WESTBROOK MALL, VANCOUVER BC

This project was identified as a critical need due to the current limitations in WBLCA guidelines, which primarily focus on the building's structural and envelope components. By exploring the methodologies for quantifying MEP system embodied carbon, this work aims to fill an existing data gap and improve future lifecycle assessments and building decarbonization, aligning with UBC's sustainability and climate action goals.

1.4 PROJECT PURPOSE, GOALS AND OBJECTIVES

- Conduct a Literature Review on Methodologies and Tools for Embodied Carbon Assessment of MEP System
  Explore existing literature to gain a comprehensive understanding of the methodologies, tools, and industry best practices for assessing the embodied carbon of MEP systems.
- Identify and Develop Feasible Research Methods for MEP System Embodied Carbon Accounting
  Develop practical and applicable research methods tailored to the unique challenges and requirements of accurately accounting for the embodied carbon of MEP systems within building projects.

- Perform LCA and Undertake Preliminary Data Collection and Experimental Calculations
  Conduct a WBLCA focused on MEP systems, gathering primary data and performing initial calculations to test and validate the chosen methodologies.
- Compile a Report with Actionable Recommendations and Future Research Suggestions
  Develop a comprehensive report detailing the findings and providing recommendations on methodologies for MEP system LCA. This includes guidance on incorporating MEP systems into UBC's WBLCA, addressing informational needs, necessary assumptions, and any identified limitations for future research and practical applications.

2. METHODOLOGY AND METHODS

2.1 RESEARCH METHODOLOGY

- Collaboration with Project Partners and Stakeholders
  The research was conducted in partnership with UBC's Campus + Community Planning department, working alongside the project partners responsible for generating the WBLCA. This collaboration ensures that the research outcomes align with institutional sustainability goals and directly contribute to campus planning initiatives.
- Comprehensive, Participatory Data Collection
  Data was gathered in partnership with a broad network of industry partners across various sections of the project, including design firms, construction teams, trade partners, and suppliers. This approach allowed for the collection of diverse and relevant data at different project stages. Additionally, the research incorporates insights and experiences from the WBLCA process, as well as my own expertise in LCA studies, ensuring a well-rounded and informed analysis.
- Transparency and Ethical Conduct
  The project prioritized transparency and ethical standards by openly sharing methodologies and maintaining clear communication with all stakeholders. This approach fosters trust, accountability, and mutual respect throughout the research process.
- Societal and Environmental Impact
  By advancing embodied carbon assessment practices, this research supports UBC's sustainability initiatives and contributes to broader carbon reduction goals. The data and methodologies developed provide valuable insights for improving future policies and sustainability practices on campus and beyond.

2.2 RESEARCH METHODS

This project comprises two main components: an exploration of methodologies for embodied carbon accounting in MEP systems and a practical experiment in applying these methodologies. Due to the evolving nature of available information and uncertainties, the project scope has remained flexible, adapting as new insights, data, and tools became available.

The first phase focused on secondary research to investigate existing policies, standards, guidelines, and industry practices for accounting embodied carbon. This included a critical review of available tools, their strengths, and limitations. To complement this, interviews, webinars, and learning sessions were conducted with industry professionals and scholars to gain diverse perspectives and insights on current practices and emerging methodologies.

The second phase involved the collection and calculation of embodied carbon emissions for the MEP systems. Data was primarily gathered from project team sources, supplemented by necessary estimations where specific details were lacking. This phase also involved adapting assumptions and methodologies within WBLCA tools to find practical ways to implement the methodology and explore potential solutions and results through this experiment.

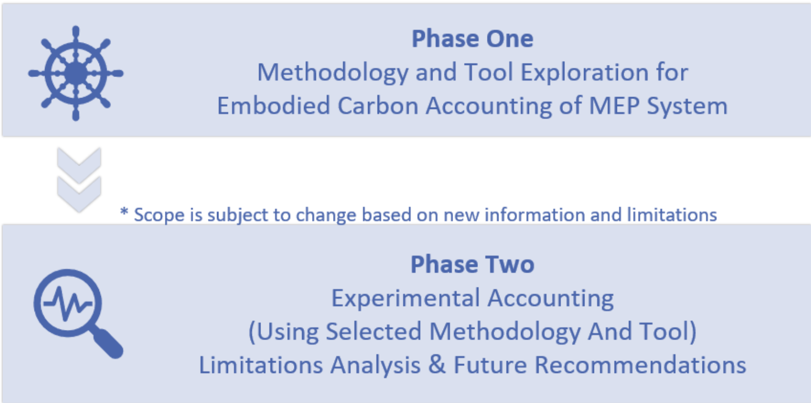


Figure 2 Research methods overview

2.2.1 RESEARCH METHODS FOR PHASE ONE

This section focuses on the methods used for literature review, industry dialogues, and knowledge gathering to explore methodologies and tools for embodied carbon accounting in MEP systems.

he initial phase of understanding began with industry-recognized courses offered by BCIT, specifically “Introduction to Embodied Carbon and Whole-Building Life Cycle Assessment”(BCIT, 2022). This provided foundational knowledge of key LCA concepts, how the methodology has been adapted to Whole-Building Life Cycle Assessments, and an overview of international and national standards and guidelines relevant to WBLCA.

To build on this foundational understanding, practices and case studies from industry leaders, such as Introba(Introba, 2024), professional associations like the Carbon Leadership Forum(Ghina, 2024a), and peer-reviewed literature were reviewed. The purpose was to understand real-world applications, challenges, and opportunities in accounting for embodied carbon, particularly within MEP systems.

The criteria for selecting and comparing resources centered on relevance to MEP systems, industry recognition, and recommendations from trusted professionals. Resources were chosen based on:

- Industry Recognition: Content from leading companies and respected associations.
- Professional Recommendations: Insights shared during webinars and through professional networks.
- Relevance to MEP Systems: Emphasis was placed on identifying practices specifically applicable to MEP systems, while also considering residential building contexts in this project.

As methodologies and tools were explored, findings were discussed with the project team. Input was sought from individuals with experience conducting WBLCA for this building, as well as those with broader industry expertise. This collaborative approach allowed for evaluating different methodologies, identifying limitations, and testing practical ways to implement embodied carbon accounting within the specific context of MEP systems.

2.2.2 RESEARCH METHODS FOR PHASE TWO

WBLCA originates from the broader LCA framework outlined in ISO 14040 and ISO 14044 standards(Finkbeiner et al., 2006), which establish key principles and guidelines for conducting LCA studies. The LCA process typically consists of four main steps: goal and scope definition, inventory analysis, impact assessment, and interpretation. When incorporated into WBLCA, these steps are adapted to evaluate the environmental impacts of building systems across their entire life cycle.

2.2.2.1 Goal and scope definition

The goal and scope definition phase are a critical component of any LCA study, as it establishes the foundation for all subsequent phases. This phase guides key decisions, such as what to include in the assessment, the level of uncertainty that is acceptable, and the desired data quality. Clearly defining the study's purpose ensures that the methodology aligns with the intended objectives and helps maintain focus throughout the analysis.

In this case study, the primary goal is to explore and validate feasible methodologies for accounting for embodied carbon in MEP systems. Given this exploratory nature, the scope is designed to remain flexible, evolving as new information and limitations are observed. Data quality requirements are adjusted accordingly, prioritizing practicality and the ability to generate preliminary results overachieving absolute precision.

After exploring various methodological options and considering the project’s stringent timeline, the study's final scope was narrowed to focus on calculating the embodied carbon of the plumbing system. This focus was selected due to its relative simplicity and practicality for completion within a limited timeframe. The mechanical and electrical systems, by contrast, are assessed using average estimations derived from industry reports and peer-reviewed literatures.

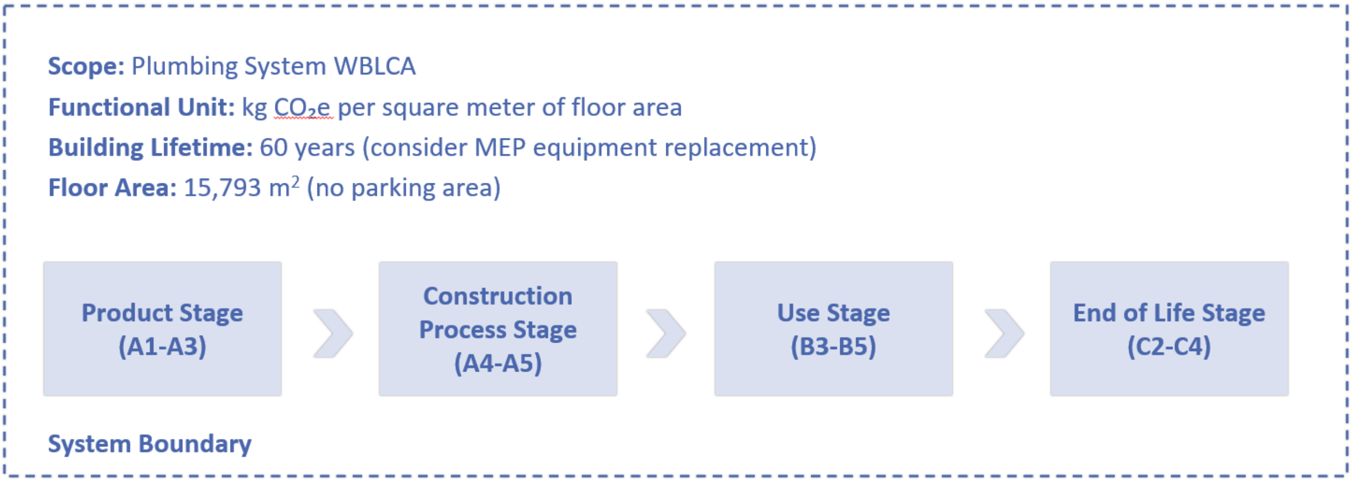


Figure 3 Goal and scope definition for phase two study

The study boundaries align with the WBLCA framework (Appendix A)(Government of Canada, 2024), encompassing life cycle stages A1 to A5 (product, transport, construction), as well as B3-B4 (repair and replacement) and C2 to C4 (end-of-life stages). Stage D (benefits and loads beyond the system boundary) is excluded in accordance with the boundary definitions established by WBLCA standards. Due to the shorter lifespan of MEP systems compared to the overall building lifecycle, replacement of these systems will be necessary. If a single replacement occurs within the building's 60-year lifespan, the associated carbon emissions will effectively double.

The functional unit of this study mirrors that of WBLCA, focusing on greenhouse gas (GHG) emissions measured in kg CO_2e per square meter of floor area, floor area definition aligned with WBLCA for structure and envelope which exclude the parking area. This consistent functional unit ensures comparability of results and provides a standardized metric for assessing the environmental impact of MEP system components.

2.2.2.2 Inventory analysis

Life Cycle Inventory (LCI) analysis in WBLCA involves systematically identifying and quantifying all input materials and energy used throughout the life cycle of a building's components. This stage collects detailed data on the materials and energy flows associated with each component to evaluate its environmental impact accurately. For MEP systems, this means tracking inputs from production through transportation, construction, maintenance, and end-of-life processes.

In pursuit of this objective, we explored various channels within the building project to obtain relevant data. As illustrated in Figure 4, our data collection approach spanned the entire value chain, starting from service providers at the end of the chain to upstream project stakeholders responsible for specifying and sourcing materials and equipment for the building's components.

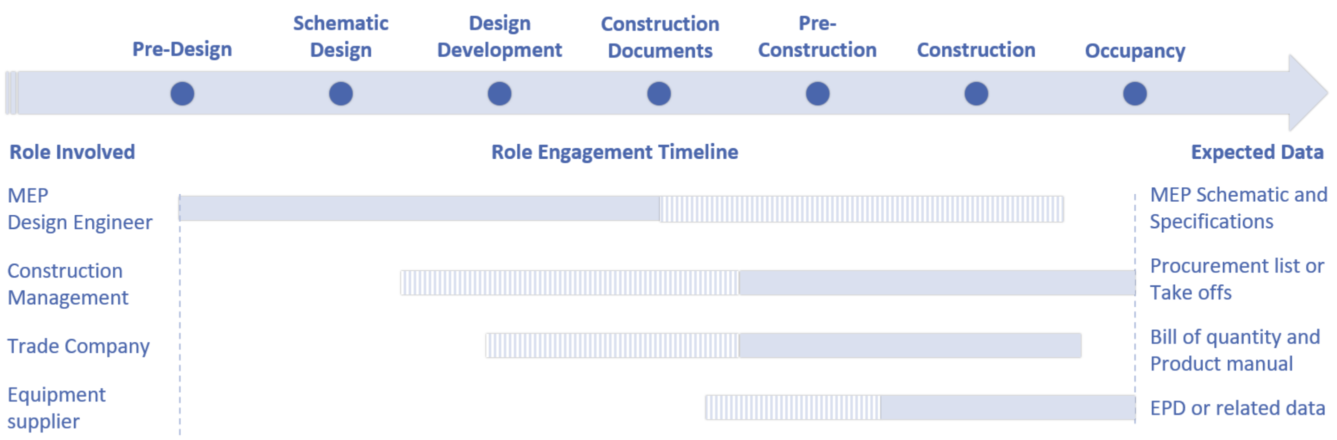


Figure 4 Role Engagement Across Building Stages and Corresponding Data Collection

The primary methods for data collection included emails, phone calls, and online meetings, which allowed for timely communication and accelerated data gathering. We engaged with project stakeholders by explaining the purpose and goals of this pilot project and inviting them to collaborate on the embodied carbon accounting experiment by sharing data and related information. In total, 14 contacts were reached, each with direct involvement in the building's design and construction phases. These contacts were expected to have the most comprehensive information needed for the study, as depicted in Figure 4.

If only drawing available, there will be another estimation process especially for the system like plumbing. In this condition, all the material types come from the specifications of design and the related information in trade level for real construction and installation. And quantity will be approximately estimated based on the size and material type of each pipe and equipment.

2.2.2.3 Impact assessment

The impact assessment phase in WBLCA links the inventory data gathered during earlier stages to environmental impacts, such as GHG emissions. This step involves selecting and applying specific emission factors to quantify the GHG emissions associated with each material's life cycle processes and the energy used, including electricity and other primary or secondary energy sources.

Given the extensive range of life cycle stages and the large number of components within the MEP system – even the narrow-downed scope of plumbing system - this task can be labor-intensive. To manage this complexity, LCA professionals often rely on established building industry databases and recognized LCA impact assessment tools. Databases(Martínez-Rocamora et al., 2016a) such as GaBi and Ecoinvent provide comprehensive and standardized data for linking material and energy inputs to environmental impacts. These resources, along with common standards and guidelines, offer valuable frameworks for ensuring consistent and reliable impact assessment.

An additional perspective is provided by Environmental Product Declarations (EPDs), which are standardized according to ISO requirements, including EN 15804(U.S. Green Building Council, 2011) and ISO 21930(ISO, 2017a) for construction materials. EPDs offer detailed LCA results for individual products from a supplier's perspective, aligning with the WBLCA system boundary framework. However, integrating EPD data into broader assessments can be challenging due to variations in assumptions, data sources, and scopes between different equipment and components.

Based on these considerations, we prioritized the use of impact assessment databases according to different levels of data quality (DQ), listed from highest to lowest priority:

- DQ-1: Exact EPD Data from Each Equipment Supplier
  This level utilizes specific EPDs provided by the equipment suppliers, offering detailed data tailored to individual components. While these EPDs are highly accurate, adjustments may be needed to ensure comparability between different components, as suppliers may use varying scopes and databases when developing their EPDs.
- DQ-2: Similar EPD Data from Canada in WBLCA Software
  This data level involves using comparable EPDs available in WBLCA software for products manufactured or distributed in Canada. Although these EPDs may not match the exact specifications of the project's components, they provide consistency for comparisons. Some adjustments may be necessary to account for differences in size or unit equivalence.
- DQ-3: Similar EPD Data from Other Regions in WBLCA Software

When localized Canadian data is unavailable, similar EPDs from other regions may be used. However, related energy and material impacts may not fully align with Canadian conditions due to software limitations. To maintain consistency, these data sets are kept in their original regional contexts for the calculations.

- DQ-4: No EPD Available – Use of Average Material Data in WBLCA Software
  In cases where no specific EPD data is available, average material data from recognized databases, such as Canadian government sources for electricity impact factors or other material-level averages, are utilized. This approach ensures that calculations remain consistent with available resources and industry standards.

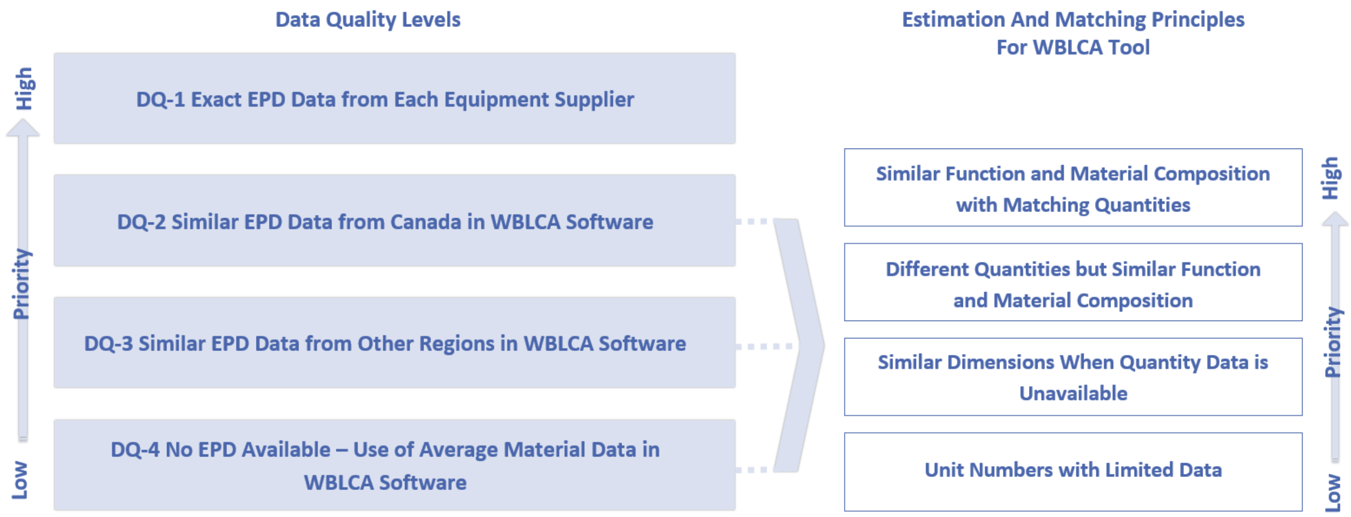


Figure 5 Data Quality Levels and Estimation-Matching Principles for WBLCA Tool

For DQ-2 and DQ-4, this process involves estimating and matching project-specific equipment or materials to the data available in WBLCA tools. The following principles guide the estimation and matching methodology for different products, prioritized from the highest to lowest level of data accuracy:

- Similar Function and Material Composition with Matching Quantities
  Priority is given to identifying products with similar functions, material compositions, and quantities to those used in the project, ensuring the closest match possible.
- Different Quantities but Similar Function and Material Composition
  When products have the same function and material composition but differ in quantity, adjustments are made by applying multiplication factors to align the database quantities with those used in the project.
- Similar Dimensions When Quantity Data is Unavailable
  If specific quantity data is not available from the project's specifications or supplier information, similar dimensions are prioritized to find a comparable match within the WBLCA database.
- Unit Numbers with Limited Data
  When only unit numbers (e.g., number of equipment pieces or meters of material) are known, and detailed quantity or dimension data is lacking, similar products based on function or material type are used, with inputs made according to the number of units.

2.2.2.4 Interpretation

The interpretation of data in the embodied carbon assessment follows a structured approach to ensure that the analysis is robust, meaningful, and adaptable for future improvements. The key principles guiding data interpretation are:

- Evaluating Data Quality and Quantity Uncertainties
  A critical aspect of data interpretation begins with assessing the raw data for materials and energy inputs collected during the LCI stage. This involves examining the quality of available data, including data sourced from EPDs and industry databases, and recognizing uncertainties introduced through estimation and matching processes. Special attention is given to the consistency, reliability, and potential variability of the data used for each MEP component, acknowledging areas where estimation was necessary due to gaps or limitations.
- Linking Input Data to Environmental Impacts
  Interpreting how raw material and energy data translate into environmental impacts requires a careful selection of emission factors and impact assessment models. The comparability of EPDs across different suppliers, regions, and product categories is evaluated to ensure that data can be meaningfully linked to the project's embodied carbon results. Considerations include whether variations in scope, data sources, and methodologies between different EPDs can be harmonized to provide a coherent assessment. This principle emphasizes maintaining consistency and comparability while identifying potential discrepancies in regional and supplier-based data.
- Comparison with Industry Case Studies and Peer-Reviewed Publications
  To contextualize and validate the findings, impact data is compared with other relevant industry case studies and peer-reviewed literature. This comparison helps identify trends, highlight deviations, and assess whether the observed results align with broader industry practices and findings. Such benchmarking provides a valuable reference point for evaluating the effectiveness of methodologies and offers insights into potential areas for improvement or refinement in embodied carbon accounting.
- Reflecting on Limitations, Uncertainties, and Practical Implications
  The final principle involves synthesizing identified limitations, uncertainties, and practical considerations to provide insights for future studies. This includes summarizing data gaps, addressing inherent uncertainties in the current methodologies, and reflecting on how practical approaches can be adapted or refined to enhance future embodied carbon assessments. By highlighting areas for improvement and methodological challenges, this principle aims to guide the development of more consistent, reliable, and scalable practices for the industry.

2.2.2.5 Industry readiness poll

Given the anticipated challenges stemming from the limited availability of comprehensive Environmental Product Declarations (EPDs) for each piece of equipment, the project team sought to assess the industry's readiness for embodied carbon accounting in MEP systems. This assessment aimed to gather insights from various points along the value chain, spanning downstream suppliers to upstream design engineers.

To explore industry readiness, a range of tools were employed, including email surveys, telephone surveys, and interviews. The objective was to understand the current demand for embodied carbon accounting within their products or services, their ongoing efforts to collect and prepare related data, and the obstacles they face in this endeavour. In cases where more in-depth interviews were possible, discussions extended to the expected timeframes and resources needed for further data exploration and storage. The detailed questions can be found in Appendix B.

This readiness poll aimed to capture the motivations and drivers influencing different stakeholders across the value chain regarding embodied carbon accounting. The findings are expected to provide valuable insights for future projects, highlighting effective strategies and areas of focus for conducting similar studies.

2.2.3 METHODS OF ADMINISTRATION

- Administration and Recruitment Process
  The administration and recruitment process for gathering data on industry readiness and embodied carbon accounting practices in MEP systems involved a multi-pronged approach. Potential participants, including design engineers, downstream suppliers, and key stakeholders in the value chain, were approached directly through targeted email communications, telephone calls, and online meetings. Initial contact focused on providing an overview of the project goals and inviting collaboration in the form of surveys, interviews, or data-sharing initiatives. This direct approach allowed for a personalized engagement, encouraging higher response rates and fostering meaningful dialogue.
- Data Collection Timeline
  Data collection spanned a period about one month considering the tight timeline of this project, encompassing weekday engagements to maximize accessibility for participants. Surveys were typically conducted over one month, while interviews and follow-up meetings were scheduled as availability permitted. This flexible timeline ensured participants could engage meaningfully without disruption to their schedules.
- Data Collection Locations and Platforms
  Data was collected through multiple channels to accommodate participant preferences and availability. Email surveys were conducted using their company emails, providing a structured and easy-to-use interface. Telephone and online meetings were conducted via Zoom, Microsoft Teams, or direct phone calls, facilitating real-time engagement and deeper exploration of relevant issues.
- Rationale for Data Collection Approach
  The choice of data collection methods was driven by the need to balance comprehensive data gathering with practical considerations. Electronic surveys allowed for broad outreach, efficient data collection, and ease of participant engagement, particularly for those unable to participate in live discussions. In contrast, telephone and online interviews enabled more detailed exploration of complex issues, such as the challenges and motivations related to embodied carbon accounting. This combined approach ensured both depth and breadth in data collection while accommodating participant availability and preferences.

3. PHASE 1 – METHODOLOGY REVIEW

3.1 REVIEW OF METHODOLOGYS ON MEP SYSTEM EMBODIED CARBON ACCOUNTING

3.1.1 OVERVIEW OF STANDARDS AND GUIDELINES

The methodologies related to WBLCA, as well as sub-systems like MEP systems, are fundamentally based on the broad LCA framework, which is standardized by ISO 14040 and ISO 14044(ISO, 2006a, 2006b). These standards provide the overarching structure for assessing environmental impacts across a product's life cycle.

To support detailed disclosure by product suppliers, several standards govern Environmental Product Declarations (EPDs). These include ISO 14025(ISO, 2006c), EN 15084(ECS, 2012), and ISO 21930(ISO, 2017b), which are specifically designed for building products and services. With standardized EPDs providing comparable input data for building components, along with operational data, the carbon emissions across the entire building life cycle can be accurately assessed.

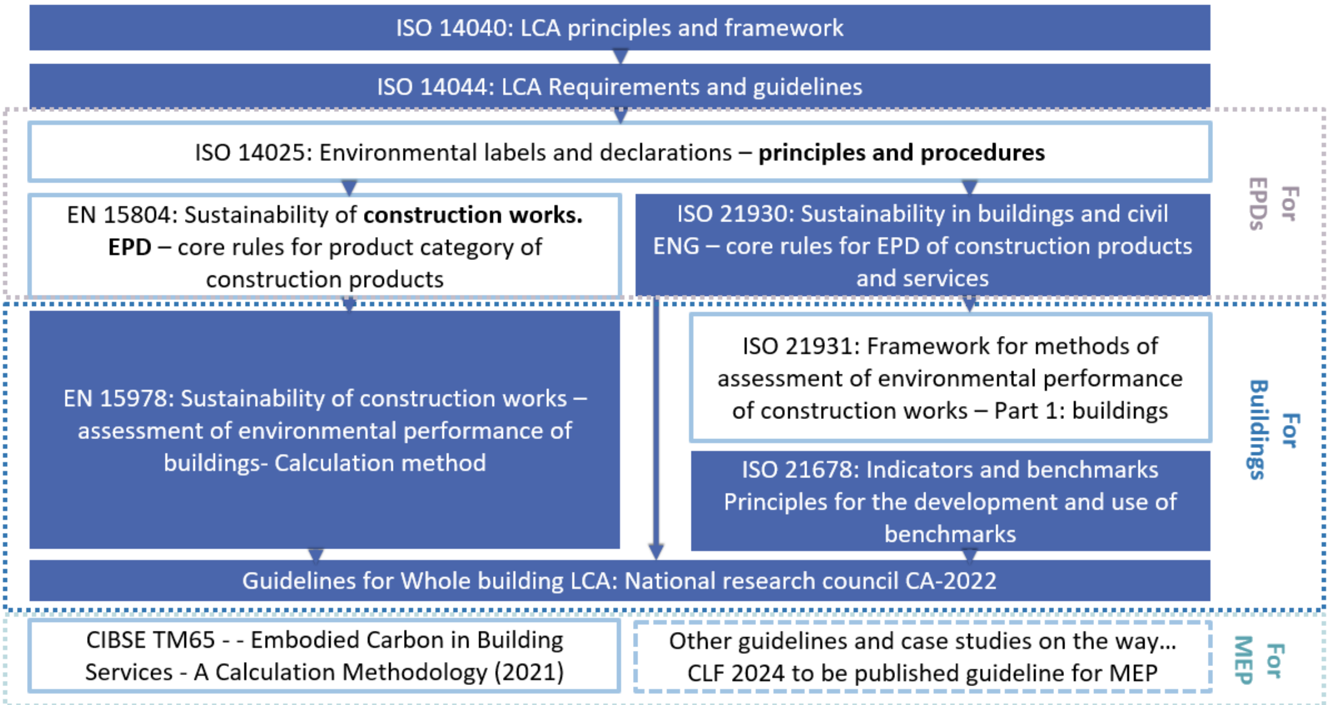


Figure 6 Overview of Standards and Guidelines (BCIT, 2022)

The calculation and benchmarking of WBLCA to compare emission performance between different buildings are covered by standards such as EN 15978(ECS, 2011), ISO 21931(ISO, 2010), and ISO 21678 (ISO, 2021). These standards ensure consistency and comparability in evaluating building emissions. At the federal level, Canada has developed its own WBLCA guidelines(NRC, 2022), which align closely with these international standards (refer to Fig. 6).

Challenges and Gaps at the MEP Level

For MEP systems, the current standards and guidelines are still evolving. Unlike structural components and building envelopes, which are required in WBLCA, MEP systems remain optional in many guidelines. This is despite their crucial role in providing essential building services that ensure comfort and safety, as well as their significantly different configurations and life spans compared to other building components.

Currently, there is only one widely recognized industry guideline specifically targeting MEP embodied carbon assessment: the Chartered Institution of Building Services Engineers (CIBSE) TM65, which was published in 2021(CIBSE, 2021). While TM65 represents an important first step, it has several limitations, such as incomplete methodologies for certain MEP components and a lack of standardized data for calculations. In response to these challenges, the Carbon Leadership Forum is actively developing new guidance, which is anticipated for release by 2025.

In the following sections, a detailed analysis of the TM65 methodology, alongside other methodologies that integrate WBLCA concepts, will be conducted. These methodologies include EPD and LCA database-based WBLCA, BIM model-based WBLCA, and TM65 material-based WBLCA. The goal is not only to compare the strengths and limitations of each approach in assessing MEP embodied carbon but also to identify the most feasible methodology to apply in an experimental assessment of MEP system embodied carbon accounting.

3.1.2 TM65 MATERIAL-BASED WBLCA FOR MEP

The TM65 methodology(CIBSE, 2021), developed by the CIBSE, provides a structured approach to estimating the embodied carbon of MEP systems, particularly when EPDs are unavailable. This methodology aims to enhance the building services industry's capability in embodied carbon accounting by offering interim methods to assess MEP equipment emissions.

The TM65 methodology provides two approaches to estimating embodied carbon, which vary significantly in terms of the level of detail, data requirements, and effort involved when compared to an EPD-based approach (Appendix B for more detailed information of data collection table and requirements comparison).

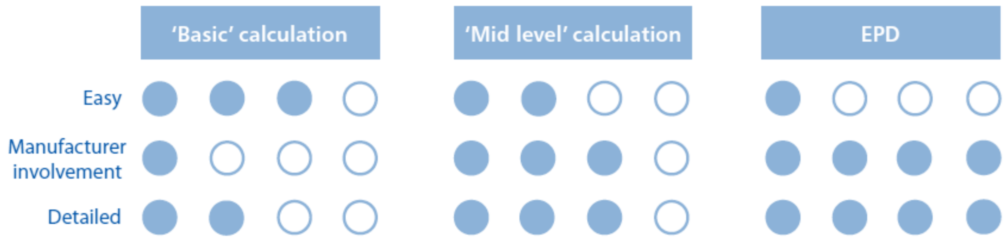


Figure 7 Effort Comparison Between Basic, Mid-Level, and EPD Approaches

- **Basic Calculation Method**: Requires minimal product information, focusing primarily on material content. This method is less detailed but easier to implement, making it suitable when limited data is available.
- **Mid-Level Calculation Method**: Demands more detailed information, including manufacturing energy use and factory location. This approach offers a more comprehensive assessment but requires greater effort and data collection.

- **EPD-Based Approach**: Utilizes detailed EPDs compliant with standards like EN 15084(ECS, 2012). This method provides the highest accuracy but necessitates extensive collaboration with manufacturers and access to detailed product data.

Detailed Overview of Calculation Methods

Both the Basic and Mid-Level Calculation Methods in the TM65 methodology utilize data collected through a standardized "manufacturer form" and follow a step-by-step process aligned with LCA stages (A, B, and C) used in WBLCA (Appendix A). These methods aim to estimate the embodied carbon impacts across different stages of a product's lifecycle.

The Basic Calculation Method as shown in Fig. 8, requires minimal data, focusing on material composition that covers at least 95% of the product’s total weight. The embodied carbon is estimated through steps including Material Extraction (A1) and Repair (B3), while other modules, such as Transport and Manufacturing (A2, A3, A4) and End-of-Life Phases (C2, C3, C4), are assessed using standardized scale-up factors to account for complexity. A Buffer Factor of 1.3 is used to handle uncertainties, and Refrigerant Leakage (B1, C1) is included where applicable. This method is a straightforward approach suited for cases where detailed data is not available, offering a practical approximation.

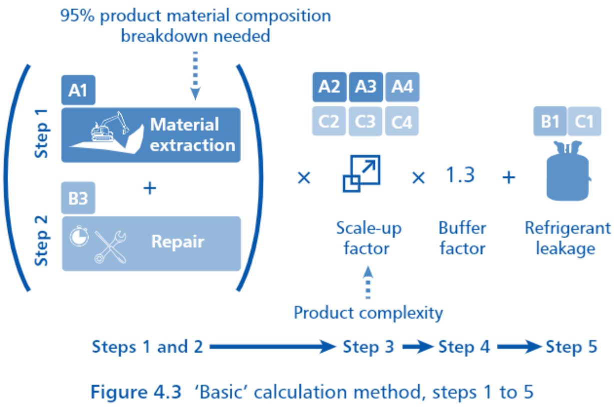


Figure 8 Basic-level Calculation Method for TM65

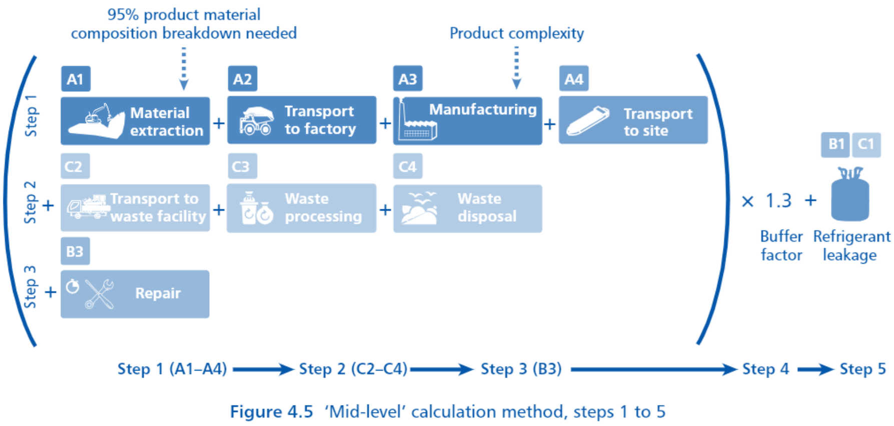


Figure 9 Mid-level Calculation Method for TM65

The Mid-Level Calculation Method demands more detailed inputs, such as energy use in manufacturing and factory location, for a more refined estimate of embodied carbon (Fig.9). It covers the full product lifecycle, from Material Extraction to Transport to Site (A1 to A4), and also considers End-of-Life Phases (C2 to C4) and Repair (B3). A Buffer Factor of 1.3 is similarly applied, and refrigerant leakage is included if applicable. This method, though more data-intensive, provides a more comprehensive and reliable assessment compared to the Basic Calculation Method, offering a balance between detail and feasibility when EPDs are not accessible.

Regional Applicability and Limitations of the TM65 Methodology

The TM65 methodology was initially developed with a focus on the UK and European contexts, making its assumptions and data inputs tailored to these regions. Average values for carbon factors, transport distances, and emission rates are derived from local datasets. However, in 2024, CIBSE extended its guidance to include North America(CIBSE Journal, 2024), publishing "TM65NA: Embodied Carbon in Building Services - A Calculation Methodology for North America," in collaboration with ASHRAE. This new guidance aims to adapt TM65's embodied carbon assessment approach to the unique characteristics of the North American market.

Despite its expanded scope, the TM65 methodology involves substantial estimation. Elements such as the use of refrigerant leakage factors, buffer factors for uncertainties, and reliance on manufacturer-provided data introduce variability that may impact accuracy. A comparative study(Mazzei et al., 2024) analyzing TM65's mid-level calculation against a globally recognized LCA methodology for six different luminaires showed that TM65 results tend to estimate embodied carbon at **2-3 times higher values** than traditional LCA. These discrepancies are largely influenced by factors such as the weight of the products, which play a significant role in the differences observed between methodologies. These findings underscore the inherent variability and the need for cautious interpretation when applying TM65 to projects.

3.1.3 EPD AND LCA DATABASE-BASED WBLCA FOR MEP

Compared with the TM65 methodology, the EPD and LCA database-based approach for MEP systems shifts the focus of data collection and estimation to the equipment level, rather than relying solely on the material level. This methodology incorporates databases from LCA tools, including average material data, EPDs, energy use, and waste estimations across different LCA stages. By leveraging these comprehensive data sources and estimation system, the method aims to capture the embodied carbon impacts associated with MEP systems while addressing uncertainties through specific strategies.

Tools for Incorporating LCA and EPD Databases

There are two primary types of tools used to incorporate LCA databases into this methodology: general LCA tools like GaBi(Sphera, 2024) and SimaPro(SimaPro, 2024), and WBLCA tools such as One Click LCA(One Click LCA, 2024b) and Tally(Revit, 2024b).

General LCA Tools: These tools, such as SimaPro, allow users to analyze specific MEP components by accessing a wide variety of environmental datasets, such as Ecoinvent or Gabi database. These datasets include information on raw materials, production processes, transport, and end-of-life stages, providing comprehensive lifecycle emissions estimates for MEP components. However, the approach often lacks direct integration into the broader building context, limiting its ability to reflect whole-building impacts(Martínez-Rocamora et al., 2016b).

WBLCA Tools: like One Click LCA and Tally, offer a more holistic approach by integrating LCA data with assess the embodied carbon of entire buildings, including MEP systems. One major advantage of WBLCA tools lies in their adherence to Standard-Based Estimation. Tools like One Click LCA incorporate WBLCA standards such as EN 15804(ECS, 2012) and EN15978(ECS, 2011) to align lifecycle analysis across all LCA stages. This standard-based approach ensures consistency in lifecycle boundaries and emissions accounting, contributing to a higher level of reliability. Additionally, Regional Adaptation capabilities allow the emission factors, transport distances, and energy profiles used by WBLCA tools to be adjusted to regional characteristics, thereby improving the representativeness of embodied carbon results across diverse contexts(Sartori, T. et al., 2022). Moreover, WBLCA tools provide robust Scenario Modelling capabilities that allow users to evaluate different material choices, transportation options, local utility application, or lifespan input(Greer et al., 2023). This feature is particularly valuable for MEP systems, as variations in installation, repair, replacement, and maintenance can significantly impact the overall embodied carbon footprint. The flexibility provided by scenario analysis in WBLCA tools supports decision-makers in choosing materials and systems that yield the lowest possible carbon impact throughout the lifecycle(Roberts et al., 2024a).

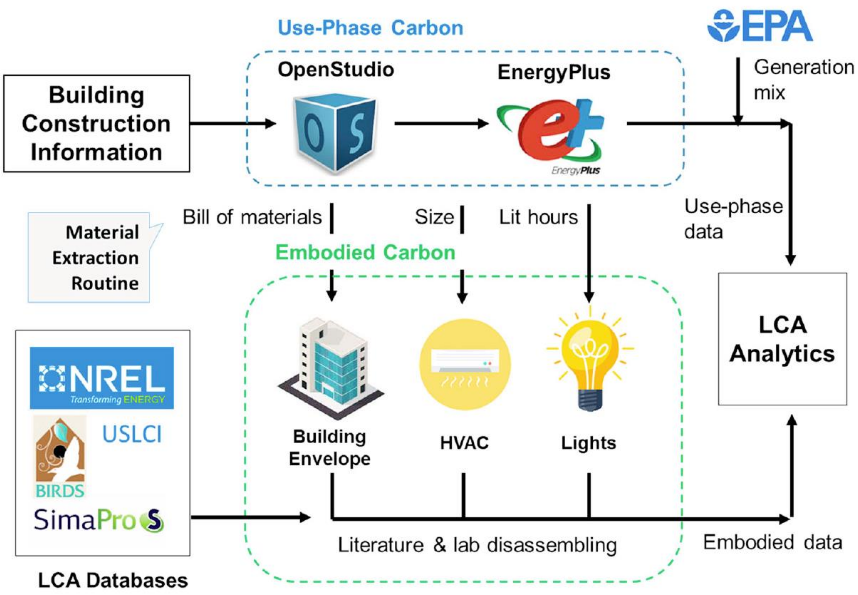


Figure 10 Methodology Sketch for EPD and LCA Database-Based WBLCA of MEP Systems

Data Collection and Estimation Principles

The process for data collection in this methodology typically starts with creating a comprehensive list of equipment and materials for the MEP systems. This list can be derived from as-built documentation if a complete set of installed equipment is available, which leads to a more accurate assessment. However, as highlighted by Rodriguez et al.(B. X. Rodriguez et al., 2020), in most cases, this level of detail is not available, necessitating estimations that can introduce uncertainties. The challenges in obtaining complete lists of installed equipment - especially for older buildings or those without detailed documentation—necessitate the use of assumptions and proxies.

After compiling the equipment and material list, the next step involves setting data quality principles to match the available information with data from LCA tools(Waldman et al., 2020). The best practice for matching data is to use the exact EPD for the product where available, ensuring the highest accuracy. If exact EPDs are not available, the following hierarchy of choices is used:

- Similar EPDs from the same region are preferred, allowing for a comparable estimation.
- Average material data from the LCA database is used when no product-specific data is available.
- General material proxies or scaling from similar products is used for components with no specific data, similar to the approaches described by Rodriguez et al. (B. Rodriguez et al., 2019).

Overall, WBLCA tools are better suited for whole-building assessments, incorporating building-related databases, standard-based estimations, regional adaptations, and scenario modelling to deliver more reliable and context-specific results. The reviewed literature underscores that improving data quality, adopting comprehensive standards, and choosing the appropriate tools with well-interpreted data are crucial for enhancing the reliability and applicability of embodied carbon assessments in MEP system embodied carbon analysis.

3.1.4 BIM-BASED WBLCA FOR MEP

Integrating Building Information Modeling (BIM) with WBLCA represents a significant advancement over traditional EPD-based LCA approaches, particularly in the context of MEP systems. This integration offers a more comprehensive and detailed analysis by encompassing complete equipment and material systems, rather than relying on potentially incomplete equipment lists.

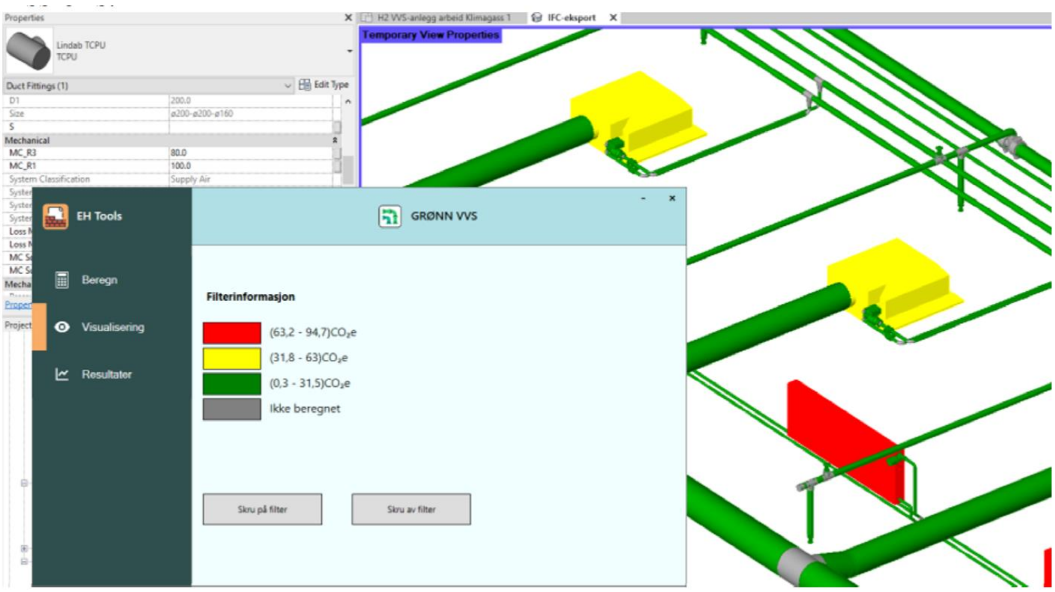


Figure 11 Methodology Sketch for BIM-Based WBLCA of MEP Systems(Petersen et al., 2024a)

Data Requirements and Tools for BIM-Based WBLCA

To successfully perform a BIM-based Whole Building Life Cycle Assessment (WBLCA), several key data sources and tools are required, as shown in Fig. 11.

Standardized EPDs are essential for providing reliable, quantified environmental data for all building materials. These EPDs must comply with standards like ISO 21930(ISO, 2017b) to ensure consistency and comparability across assessments.

BIM Software, such as Autodesk Revit(Revit, 2024a), is used for detailed modeling and integration of material specifications. The BIM model acts as a central repository of all building data, including the material and component details of MEP systems.

LCA Tools like Tally(Revit, 2024b) and One Click LCA(One Click LCA, 2024a) enable seamless integration with the BIM model, allowing for efficient data extraction, analysis, and real-time updating of environmental impacts. This integration ensures that any modifications in the building design are immediately reflected in the LCA outcomes, maintaining alignment between design and sustainability goals.

Integrated BIM and WBLCA Workflow

The first step in the BIM-based WBLCA process is to develop a comprehensive BIM model that incorporates all architectural, structural, and MEP elements. The model must accurately represent material types, quantities, and specifications for each component(Fernández Rodríguez et al., 2024). This enriched BIM model provides a detailed representation, allowing for precise life cycle impact assessments.

Once the BIM model is in place, EPDs for materials and products are integrated into the model. Standardized EPDs are gathered and linked to the corresponding components within the BIM environment. This linkage is performed in WBLCA tools like One Click LCA, enabling automated extraction of environmental data and ensuring that each material's impacts are accounted for in the LCA process(Feng et al., 2022).

After data integration, the life cycle assessment is executed using the integrated LCA tools. This allows for comprehensive calculations of environmental impacts across all life cycle stages, from production and construction to use and end-of-life phases. The automated analysis reduces the need for manual data input, thereby minimizing errors and increasing efficiency.

Key Benefits of BIM-Based WBLCA

BIM-based WBLCA provides a comprehensive analysis of a building's environmental impact by integrating detailed MEP system data directly into the model. This holistic view ensures that assessments are thorough and representative of the building as a whole, rather than isolated components.

Automation and Efficiency are further enhanced by the seamless linkage between BIM and LCA tools. The automation of data extraction and analysis ensures that changes in the design are immediately reflected in the assessment, minimizing manual effort and the risk of errors(Ruchit Parekh & Dario Trabucco, 2024).

Informed Decision-Making is another significant benefit. The BIM-based WBLCA methodology facilitates real-time analysis of environmental impacts, allowing design teams to identify components or materials that contribute significantly to embodied carbon emissions(Feng et al., 2022). Designers are empowered to make data-driven decisions early in the design process. This proactive approach helps to prevent excessive carbon emissions and supports the achievement of sustainability targets well before the final design is completed. BIM-based WBLCA also enables comparison with industry benchmarks, allowing project teams to establish compliance and mitigate environmental impacts effectively.

Limitations and Challenges of BIM-Based WBLCA

Despite its numerous advantages, BIM-based WBLCA faces some key challenges. One of the most significant limitations is data availability. The success of this methodology depends heavily on the availability of standardized EPDs for all materials. In cases where EPDs are unavailable, assumptions must be made, which can affect the accuracy of the assessment(Ruchit Parekh & Dario Trabucco, 2024).

Another challenge involves interoperability issues between BIM and LCA tools(Abdelaal, 2021). Ensuring seamless integration across different platforms often requires additional customization or manual adjustments to ensure data flow effectively between the BIM model and the WBLCA software.

The complexity of modeling detailed MEP systems within BIM is also a major consideration(Leite et al., 2011). Creating a model that includes all materials and components in detail can be resource-intensive and time-consuming. Proper data management practices are essential for maintaining accuracy, especially when dealing with extensive building data that needs frequent updates to reflect design changes.

3.1.5 COMPARISON AND ANALYSIS OF THREE METHODOLOGIES

In order to evaluate the suitability of three different methodologies - TM65 Material-Based WBLCA, EPD & LCA Database-Based WBLCA, and BIM Model-Based WBLCA - for assessing embodied carbon in MEP systems for the UBC residential building project, a series of key criteria have been used. These criteria include the level of industry partner involvement, data availability, database quality, the reasonableness of WBLCA estimation, automation, time and cost, feasibility, and accuracy. Each methodology is assessed through these lenses to determine which is the most suitable, feasible, and accurate for this case study. Table 1 is the comparison between these three methodologies.

Table 1 Comparison between three methodologies for MEP WBLCA

	TM65 MATERIAL-BASED	EPD & LCA DATABASE-BASED	BIM-BASED
Industry Partner Involvement Level	*****	***	*****
Data Availability Level	*	***	*
Database Quality Level	*	***	***
Reasonableness of WBLCA Estimation	*	***	***
Automation and Flexibility	*	***	*****
Time and Cost Level	*****	***	*****
Overall Feasibility Level	*	***	*
Overall Accuracy Level	*	***	*****

The TM65 Material-Based WBLCA methodology heavily relies on high levels of industry partner involvement, primarily requiring collaboration with suppliers to obtain detailed data about the 95% material composition of products. Consequently, data availability is often limited to what suppliers can provide. Additionally, attempts to estimate material data using industry databases usually rely on secondary research and material average-level emission factors, which often lack construction industry specificity. These limitations pose challenges for comprehensive lifecycle assessments, resulting in relatively low data quality.

The reasonableness of WBLCA estimation for TM65 is limited as well, primarily due to the use of a general buffer factor and the lack of context for each component and regional differences. Automation and flexibility are also extremely limited, with most processes being manual, increasing the potential for errors and slowing down updates and recalculations.

Regarding time and cost, TM65 can be resource-intensive due to the detailed communication required with numerous suppliers. However, if the focus is narrowed to a few key components with average material composition, the process can be relatively fast but will produce unreliable results. Without an industry-level averaged database, the accountability of these results is severely compromised. Given the current status of this project—a completed building with MEP systems already installed - it is impractical to expect full supplier involvement in the short timeframe available, making the feasibility and accuracy levels quite low. Prior studies(Mazzei et al., 2024) comparing TM65 to LCA database methods have also demonstrated its limited effectiveness, making it less suitable for our experimental analysis of MEP systems.

The EPD & LCA Database-Based WBLCA methodology leverages industry-recognized databases such as Gabi and Ecoinvent, along with verified EPDs, to gather data for embodied carbon calculations. The industry partner involvement is moderate, as it primarily requires input from design engineers and contractors to provide equipment lists and specifications. Data availability is significantly higher compared to TM65 since existing EPDs and average material-level databases can be accessed for a preliminary analysis, which makes it well-suited for projects like this one, where data on installed systems is largely available.

Data quality is considerably better compared to TM65, as these databases are peer-reviewed and frequently updated to reflect the latest information from both industry experts and governmental databases. The reasonableness of WBLCA estimation is enhanced, given that it takes into account entire lifecycle stages (cradle to grave) based on both EPDs and WBLCA standards, allowing for a balanced and comprehensive estimate of environmental impacts.

In terms of automation and flexibility, EPD & LCA tools rank moderately well. Integration of equipment lifespan, utility localization, and waste percentages into the assessment is feasible, though not as seamlessly as in BIM-based systems. Time and cost requirements are also moderate—while using EPDs and integrating databases and standards reduces estimation errors, gathering and processing these data still requires more resources than TM65.

Overall feasibility for this methodology is high, balancing complexity, data requirements, and achievable accuracy. While the accuracy level is higher than TM65, it falls short of BIM-based WBLCA, given that some data collected from engineers and contractors may not so completed and can not be perfectly matched with the database in WBLCA tool.

The BIM Model-Based WBLCA approach is the most advanced of the three methodologies but is not yet common for MEP systems in the construction industry. Industry partner involvement is high than the EPD-based method, as detailed specifications and a comprehensive BIM model are required during the initial stages. Integrating this data into WBLCA software often presents challenges due to difficulties in matching exact materials and equipment with EPDs, requiring extensive effort to align model components with available databases. While BIM-based WBLCA offers a comprehensive framework, it still demands more development in the industry to make EPD or average data integration more effective.

The reasonableness of WBLCA estimation is relatively high for BIM-based WBLCA, as it naturally considers the interrelationships between different building systems, resulting in a more representative analysis of the building's lifecycle. Automation and flexibility are also the strongest among the three approaches, enabling real-time updates where any changes in the BIM model are instantly reflected in LCA results, leading to highly flexible and dynamic assessments.

However, this automation comes with significant time and cost implications. Developing a detailed BIM model and managing the data integration demand considerable resources, making it less feasible when BIM modeling of MEP is not available in most projects in this industry.

In terms of overall feasibility, BIM-based WBLCA ranks lower than EPD & LCA Database-based WBLCA due to its complexity and high resource requirements. However, its accuracy level is unmatched, as it offers comprehensive integration of building systems, leading to highly granular and adaptable assessments.

Conclusion on Methodology Selection for Experimental Calculation

For the context of the UBC residential building project, the EPD & LCA Database-Based WBLCA method appears to be the most viable. It provides a good balance of feasibility, resource allocation, and accuracy for a study of this nature. The TM65 Material-Based approach could still be valuable for rapid initial assessments, but its applicability is limited due to data challenges and lower accuracy. BIM Model-Based WBLCA, while ideal for the highest level of accuracy, is resource-intensive and more appropriate for projects where a detailed BIM model already exists or can be developed within the project’s scope. Therefore, focusing on EPD & LCA Database-Based WBLCA offers the best chance of achieving reliable insights without excessive resource consumption.

3.2 REVIEW OF TOOLS ON MEP SYSTEM EMBODIED CARBON ACCOUNTING

Since the chosen methodology for this study is EPD and LCA database-based WBLCA, selecting an appropriate WBLCA tool is critical to ensure reliable embodied carbon accounting. As noted by peer-reviewed references(Herrero-Garcia, 2020) and learned in BCIT's lifecycle assessment course(BCIT, 2022), there are three primary WBLCA tools suitable for this purpose: One-Click LCA, Tally, and Athena Impact Assessor. These tools have been developed with integrated WBLCA standards, providing complete lifecycle stages and the necessary assumptions for embodied carbon calculations. Although EC3 is not a complete WBLCA tool but rather a comprehensive database, it will be reviewed here as it provides valuable database, particularly within the North American context. And table 2 provide the comparison of key parameters related to this study.

One-Click LCA, introduced in 2013 by Bionova(Helsinki, 2021), is recognized for its ease of use and extensive database access, making it a preferred tool for lifecycle assessments in building projects globally(Worldwide Computer Products News, 2023). Its widespread adoption in Europe and North America highlights its reliability for delivering standardized, accurate assessments aligned with internationally recognized standards (e.g., ISO 14040 and EN 15804)(Herrero-Garcia, 2020).

The tool provides extensive access to databases such as Ecoinvent, GaBi, and numerous EPDs sourced worldwide, which ensures comprehensive data availability irrespective of regional differences. Moreover, One-Click LCA allows the inclusion of localized data, such as regional energy grid mixes and waste management processes, enhancing the LCA's robustness (Herrero-Garcia, 2020). Its BIM integration through the Revit plug-in also enables efficient data extraction, ensuring changes in design are automatically reflected in the embodied carbon results, which significantly reduces manual input and errors.

One-Click LCA has recently developed a specialized tool for MEP carbon assessment(Aileen, 2024), aligning with the MEP 2040 Challenge and supporting TM65 guidelines for MEP systems. This makes it distinct from other tools. However, since this tool is currently unavailable in the educational license version, the possibility of using it in the future to compare with traditional WBLCA tools provides an area for further exploration.

Table 2 WBLCA Tools Comparison for MEP System Carbon Accounting

	Data Base	Geo-Boundary	BIM Plug-in	Data Availability (Latest Release 2024)	Main benefits/ concerns for MEP modeling
One-Click LCA	Ecoinvent, GaBi, EPDs around world	World	Y (Revit)	Foundations, slabs, walls, columns, beams, roofing, cladding, finishes, balconies, windows, doors, flooring, insulation, structural Systems, **MEP (limited)**	MEP database Localized modification (e.g. electricity) EPD data input if have
Tally	GaBi 8.5 (representative of 2017 U.S. values)	U.S.	Y (Revit)	Ceilings, curtainwall mullions, curtainwall panels, structure, foundations, doors, floors, roofs, stairs/railings, walls, windows, insulation	Interface with EC3 U.S database…
Athena Impact Assessor	self-compiled, average EPDs and U.S. and Canadian LCI data	U.S., Canada	N	Foundations, walls, columns, beams, roofs, floors, window frames, windows, insulation, cladding	Canada LCI But lack of MEP LCI
EC3+ Building Planner Comparison Tool	A1-A3, A4, A5, B6 Tally LCA+ others Specific EPDs	World	N	Cement, concrete, masonry, steel (rebar, structural), aluminum, wood, sheathing, insulation, cladding, glazing, finishes, cabling, asphalt	Verified EPDs But limited LCA scope and limited database

Tally, launched in 2014 by KieranTimberlake in collaboration with Autodesk, is particularly well known for its integration with BIM and early adoption for LCA assessments. It is widely used in the U.S., leveraging GaBi 8.5, a database representative of U.S. conditions(B. X. Rodriguez et al., 2019). This focus gives it high accuracy for U.S.-based projects, but its reliance on a localized dataset limits data availability in other regions.

Tally's strong integration with Autodesk Revit allows seamless incorporation of material data from BIM models, simplifying the process for iterative design assessments(Sun, 2023). Despite its integration advantages, Tally primarily focuses on structural components with limited MEP data coverage, which restricts its utility for projects focused on detailed embodied carbon analysis for MEP systems

Athena Impact Assessor, developed by the Athena Sustainable Materials Institute, is one of the first LCA tools focused on North America, with a particular emphasis on Canadian and U.S. contexts. It incorporates a mix of average EPDs and LCI datasets for Canada and the U.S., making it a reliable tool for regional assessments (Athena Sustainable Materials Institute, 2021). However, its data coverage is primarily tailored for structural elements and lacks comprehensive MEP-related data, reducing its suitability for MEP-specific analysis.

The absence of direct BIM plug-in integration means that data must be imported manually into Athena, which is less efficient compared to One-Click LCA or Tally, and more prone to human errors. Despite its strong regional adaptation for structural elements, its limitations in MEP data integration and absence of automated workflows make it less applicable for comprehensive embodied carbon assessments of MEP systems.

EC3, a relatively new tool developed collaboratively by the Carbon Leadership Forum, focuses on using verified EPDs to enable material comparison and selection(CLF, 2020). Although EC3 has a comprehensive library of cradle-to-gate EPDs, its main focus is on comparing the environmental performance of construction materials rather than performing a complete lifecycle assessment (Kestner et al., 2020). This scope limitation makes EC3 unsuitable as a standalone tool for WBLCA, especially for projects requiring detailed assessments of MEP systems.

Furthermore, EC3 lacks BIM integration capabilities, requiring manual data transfer, which is more cumbersome compared to the seamless integration offered by One-Click LCA or Tally. Although it has advantages in terms of verified EPD use and material transparency, EC3 is not ideal for detailed MEP WBLCA.

Conclusion for WBLCA Tool Selection for Experiment Calculations

For assessing the embodied carbon of MEP systems in the context of a 6-story UBC residential building, One-Click LCA is the most suitable tool. This choice is based on the comparison of tools and the matrix analysis conducted, which revealed One-Click LCA's superior data coverage, especially with respect to EPDs for MEP components, and its capabilities for BIM integration. Moreover, One-Click LCA has already been utilized for the WBLCA of this project building's structure and envelope, which allows for a more consistent comparative analysis.

4. PHASE 2 - EXPERIMENTAL ACCOUNTING FOR MEP SYSTEM

4.1 WBLCA EMBODIED CARBON ACCOUNTING FOR PLUMBING SYSTEM

4.1.1 PLUMBING SYSTEM LCI AND MATCHING TO WBLCA TOOL

The chosen methodology for this project is an EPD and database-based WBLCA, implemented using the One-Click LCA tool. An educational license for One-Click LCA has been obtained, and the detailed methodology, including the scope of experimental calculations, is elaborated in Section 2.2.2.

After initial engagement with BCR-6 project partners, spanning the design, construction, trade, and supplier phases, it became evident that data availability was significantly more limited than initially anticipated. It took approximately one month to acquire the "as-built" drawings for the plumbing system, and even then, these specifications were incomplete, lacking key details necessary for embodied carbon accounting - such as material type, dimensions, and weight for many components.

Figure 12 illustrates the data gathered from different teams across the building lifecycle. Unfortunately, a comprehensive BIM model for the entire MEP system or plumbing system was not available. Although a BIM model for the main mechanical room existed, it was ultimately not received from the trade or contractor team, necessitating a manual input approach for equipment and material details.

The most desired documentation was a reviewed schedule or plumbing system take-offs. However, this information was only fragmentedly available in the drawing package, and the final procurement file for the plumbing system could not be obtained from the trade/contractor team or construction partners. It was noted that similar challenges were encountered during the WBLCA for the building structure and envelope, where vital information was still unavailable after a year of attempts.

As a result, the data used in this assessment is based primarily on what was available through the design team and trade partners. This includes the MEP design specifications and design team-reviewed piping "as-built" and shop drawings for plumbing fixtures.

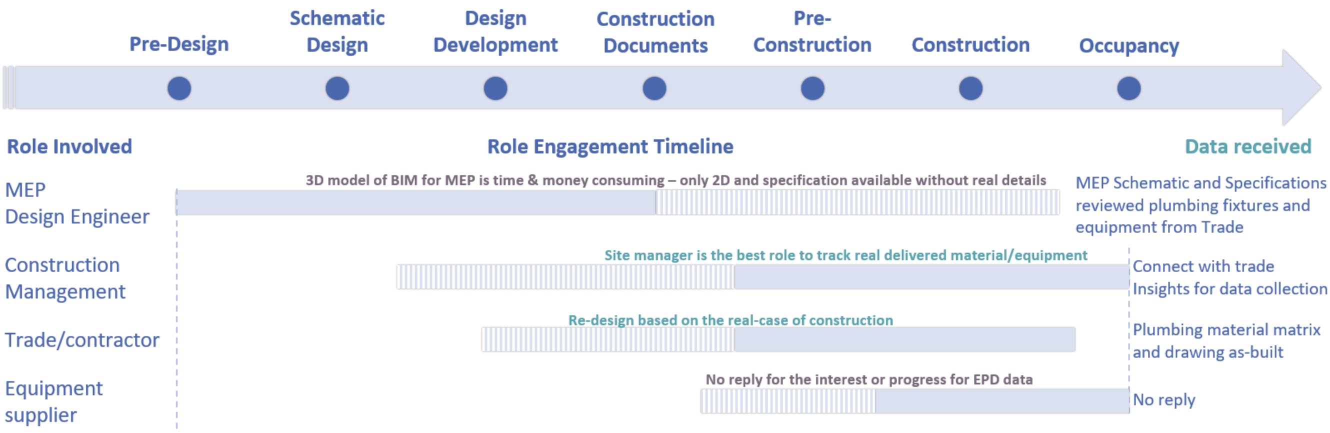


Figure 12 Actual data received from building project partners

Figure 13 presents a summary of the quality of raw data collected for the plumbing system, as well as the quality levels of data integrated through the One-Click LCA tool. Out of a total of 31 material or equipment lines for the plumbing system, only 14 entries (45%) included explicit weight information, while the remaining 55% had to be estimated based on dimensions or comparable equipment from the available database.

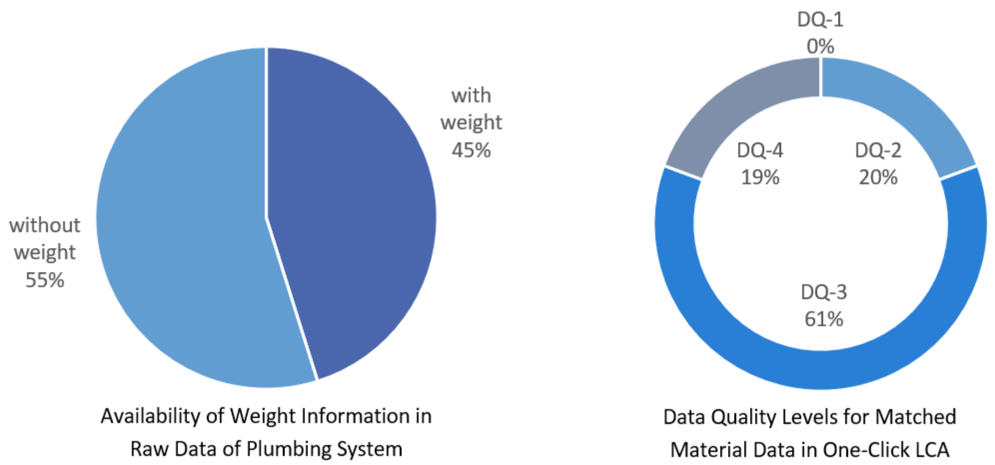


Figure 13 Data Quality in Raw Data and WBLCA Tool

Regarding the quality levels of data used in the One-Click LCA tool, a majority (61%) fell into Data Quality Level 3 (DQ-3). This level indicates that these items were matched with similar EPDs from other regions, which then required scaling up or down in weight based on available raw data information. Only 20% of the data achieved Data Quality

Level 2 (DQ-2), which corresponds to matching similar EPDs within Canada. Notably, no data was available at Data Quality Level 1 (DQ-1), indicating an absence of exact EPDs for the specific equipment installed in this project.

The figure illustrates the challenges faced in achieving high data quality levels for embodied carbon assessments. Most of the matched data relied on regional adaptations, which inherently introduced uncertainties, while the lack of direct data for our exact equipment installations posed limitations for achieving a precise WBLCA.

Special Data Quality and Uncertainty: Piping System Quantification

A significant source of data quality issues and uncertainty involves the quantification of the piping system. Since the material take-offs for the piping system were not provided, quantification had to be performed manually using measurements from piping drawings. Without direct engineering assistance, there is a substantial risk of errors in translating drawings into quantities, leading to potential omissions or inaccuracies in component identification. This limitation introduces considerable uncertainty, particularly given the complexity of industry documents and building systems.

WBLCA Tool Limitations

In selecting tools within One-Click LCA for the plumbing system and embodied carbon accounting, different standards were employed. The WBLCA of structure and envelop analysis in this building project has utilized EN 15978, which aligns with Whole Building Life Cycle Assessment standards, but this specific tool was not accessible under the educational license used for the current study. Consequently, EN 15804, which primarily focuses on construction EPD standards, was selected instead. These differences in standards introduced variations in estimation factors, impact factors, and the databases used for the WBLCA(Irene_igbc, 2023). As a result, the outputs generated from the EN 15804-based tool are not necessarily comparable to the WBLCA results for the building's structure and envelope, which were conducted using the EN 15978 tool.

Tool/Database Description in One-Click LCA

- Life-Cycle Assessment (EN-15978): This tool conducts building life-cycle assessments according to the European Standard EN 15978, covering stages from cradle to grave. It provides separate reporting for the product stage, construction process, use stage, operational energy, and end-of-life phases. The associated datasets are compliant with ISO 14040/14044 and EN 15804 standards, and the software is also compliant with Active House Specification requirements.
- Level(s) Life-Cycle Assessment (EN 15804 +A2): This tool provides life-cycle assessment aligned with Level(s) overarching assessment tool 7, focusing on cradle-to-cradle life cycle assessment.

For this study, the EN 15804 database was used, with efforts made to align data across several factors that could impact GHG emissions. Transportation was estimated using the tool's default values. The localization of data, intended to reflect region-specific factors such as electricity grid mixes or material sourcing, was not applied in this analysis, as the available datasets did not allow for such modifications for all products. Waste percentages were derived from default tool data.

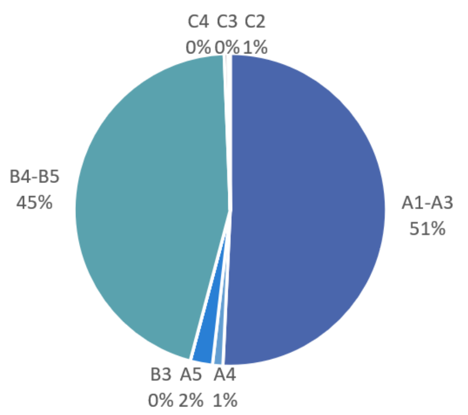
The service lifetime data of each piece of equipment or material was referenced from either National WBLCA guidelines(NRC, 2022) or average lifespan information sourced from similar products available online. For the equipment expected to be replaced over the building's 60-year life cycle, emissions were multiplied by the number of replacements to yield the total lifecycle emissions. Further details about the raw data and its matching within the LCA tool can be found in Appendix D.

4.1.2 PLUMBING SYSTEM WBLCA RESULTS

The comparative analysis between the lifecycle stages of the plumbing system and the overall building structure and envelope provides valuable insights into how embodied carbon emissions accumulate and differ based on the life cycle stages and function of building components.

Lifecycle Stage Contribution Analysis

The pie chart illustrates the Global Warming Potential (GWP) contributions of each lifecycle stage for the plumbing system. Notably, the A1-A3 stages (Product Stage: Material extraction, processing, and manufacturing) account for 51% of total emissions. This highlights the substantial carbon footprint associated with the production phase of the plumbing materials. The significance of A1-A3 stages in the overall lifecycle analysis is due to the energy-intensive nature of raw material extraction and component manufacturing, which dominate the lifecycle emissions for plumbing system.



Life Cycle Stage	Unit	Building Structure and Envelope GWP	Plumbing System GWP
A1-A3	t CO_2e	4,979	248.3
A4	t CO_2e	134	5.3
A5	t CO_2e	198	11.3
B3	t CO_2e	-	-
B4-B5	t CO_2e	428	221.3
C2	t CO_2e	101	2.0
C3	t CO_2e	37	0.2
C4	t CO_2e	1	0.9
Total	t CO_2e	5,879	489.2
Total intensity, GFA 1	kg CO_2e/m^2	366	30.98

Figure 14 Life Cycle Stage GWP Contribution Analysis of Plumbing System

The B4-B5 stages (Replacement and Refurbishment) are the second largest contributors, responsible for 45% of total emissions. These stages represent emissions associated with the replacement of plumbing system components during the building's 60-year lifecycle. The need for multiple replacements, due to the shorter lifespan of plumbing systems compared to the building itself, significantly inflates the overall carbon footprint. The A4, A5, C2, C3, and C4 stages (Transportation, Construction, End-of-Life) together contribute a small percentage, collectively under 4%, indicating their minimal impact compared to the production and replacement stages.

Comparison with Building Structure & Envelope WBLCA

The total GWP of the building structure and envelope is 5,879 t CO_2e, whereas the plumbing system contributes 489.2 t CO_2e. This significant difference is reflected in the GHG intensity, where the structure and envelope have 366 kg CO_2e/m^2, compared to only 31 kg CO_2e/m^2 for the plumbing system. These value differences indicate that while the plumbing system represents a small value (about 1/10) compared with the embodied carbon in structure and envelope, its contribution remains unegligible within WBLCA.

The distribution of emissions between the systems also shows noteworthy contrasts. For the structure and envelope, A1-A3 (material production) is the dominant stage, accounting for approximately 85% of total emissions. In contrast, for the plumbing system, A1-A3 represents 51%, with B4-B5 (replacement and refurbishment) being nearly equally impactful at 45%. This highlights the heightened significance of replacement emissions in MEP components compared to structural elements. The importance of replacement (B4-B5) in MEP WBLCA cannot be understated. Unlike the building structure, which has minimal replacement needs (7% contribution from B4-B5), the plumbing system's emissions are heavily influenced by the need for multiple replacements over the 60-year building lifecycle. Therefore, strategies to extend component lifespan or use more durable materials could be particularly impactful in reducing the carbon footprint of MEP systems.

In summary, while the A1-A3 production phase dominates for both systems, the replacement phase (B4-B5) plays a far greater role in the lifecycle emissions of the plumbing system. Addressing this through durability improvements and replacement reduction is key for minimizing MEP embodied carbon impacts.

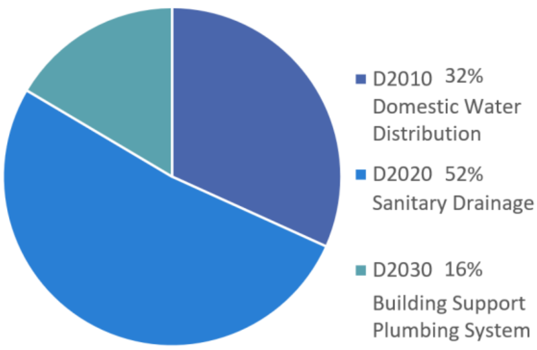


Figure 15 GWP Contribution by Plumbing System Sections (Based on OmniClass)

Analysis of Plumbing System Section Contributions

The GWP analysis (Fig. 15) highlights that the sanitary drainage system (D2020) accounts for 52% of total emissions, mainly due to carbon-intensive sanitary fixtures like tub and toilet. Domestic water distribution (D2010), contributing 32%, involves high-carbon components such as pumps and piping. Building support plumbing systems (D2030) make up 16%, primarily consisting of cast iron storm and sanitary risers, which are heavy and carbon-intensive.

Top Material Contributions Analysis

The figure 16 analyzing the top materials contributing to GWP reveals critical insights into areas of high carbon intensity in the plumbing system. The acrylic shower tub stands out as the largest contributor, accounting for 25% of the emissions, and for 34% combined with the acrylic shower base. Acrylic is a popular material for its versatility and affordability, but it is associated with high carbon emissions during production. Notably, the lifespan of acrylic products is relatively short - around 15 years - which implies that these components may require multiple replacements over the building's 60-year life cycle, further exacerbating their GWP contribution. This highlights the importance of considering both material selection and expected replacement frequency to reduce overall emissions.

Top 3 GHG emission Materials:

- 25%: Acrylic shower tub
- 16: Cast iron pipes – storm and sanitary risers
- 9%: Acrylic shower base

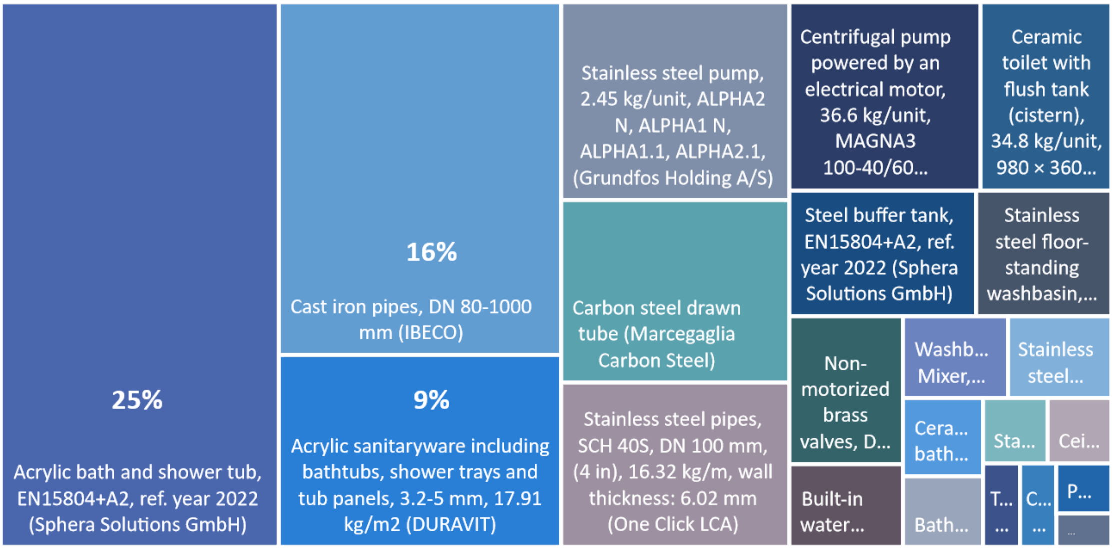


Figure 16 Top materials contributing to GWP in plumbing system WBLCA

Cast iron pipes used for storm and sanitary risers contribute 16% of the total emissions, reflecting the significant carbon intensity of cast iron production. Interestingly, for this analysis, an EPD was chosen that reported an impact value of 2.4 kg CO_2 per kg of cast iron. This value is considerably higher than the 1.5 kg CO_2 per kg of cast iron indicated in the data published by City of Winnipeg(City of Winnipeg, 2024). This discrepancy shows how the choice of data source or specific EPD can significantly influence the results of a lifecycle assessment. Therefore, choosing conservative or high-impact EPDs, such as the one used in this analysis, may lead to a higher reported GWP than other potentially valid sources, emphasizing the need for careful consideration of data sources in embodied carbon accounting.

In summary, reducing GWP in the plumbing system hinges on selecting lower-carbon, longer-lasting materials and using reliable data sources for accurate assessments. Acrylic fixtures and cast iron risers can be key targets for improving sustainability.

4.2 ESTIMATION OF EMBODIED CARBON FOR MECHANICAL AND ELECTRICAL SYSTEMS

4.2.1 BUILDING CONTEXT AND CONSIDERATIONS

The building under study is a six-story UBC faculty/staff residential building with a total floor area of 15,978 m². For this WWBLCA, the focus is on assessing the embodied carbon of the MEP systems, excluding the district energy heating system used for the building. However, the heat pump system used for cooling has been included, as well as the impacts of refrigerant leakage. Considering that MEP systems generally have shorter lifespans than the primary building structure, the assessment incorporates replacement cycles, including three times full replacement within the building's 60-year lifespan.

The inclusion of refrigerant leakage, especially for heat pumps, also aligns with current environmental assessments, as refrigerant emissions are a known significant contributor to greenhouse gases when not properly managed (GlacierGrid, 2024). The embodied carbon of the mechanical and electrical systems will be estimated using a literature review of MEP system embodied carbon, selecting a reasonable average value to provide a more comprehensive analysis for this study.

4.2.2 REPORTED MEP SYSTEM EMBODIED CARBON DATA

Based on the available literature, MEP system embodied carbon data varies considerably across building types and contexts. For instance, studies conducted on residential buildings report the GWP of MEP systems as approximately 40 kg CO_2/m^2 for a typical concrete structure with a floor area of 3,085 m^2(Emami et al., 2019). Another study examined multiple residential building configurations, including a three-bedroom terraced home and a two-bedroom apartment, showing that MEP systems contribute between 3% and 25% of the total embodied carbon over 60 years. When refrigerant leakage was included, the embodied carbon could reach 832 kg CO_2/m^2, depending on the type of heating system used, such as variable refrigerant flow (VRF) systems(Louise et al., 2022). Research on eight office buildings reported MEP embodied carbon ranging between 100 and 240 kg CO_2/m^2, depending on assumptions about system lifetime and refrigerant leakage(Brown, 2020).

Despite limited studies focused explicitly on residential buildings, findings suggest that MEP embodied carbon contributions for residential structures are generally lower compared to those found in commercial or office buildings, where impacts can exceed 70% of the overall embodied carbon, particularly for retrofit scenarios(Ghina, 2024b).

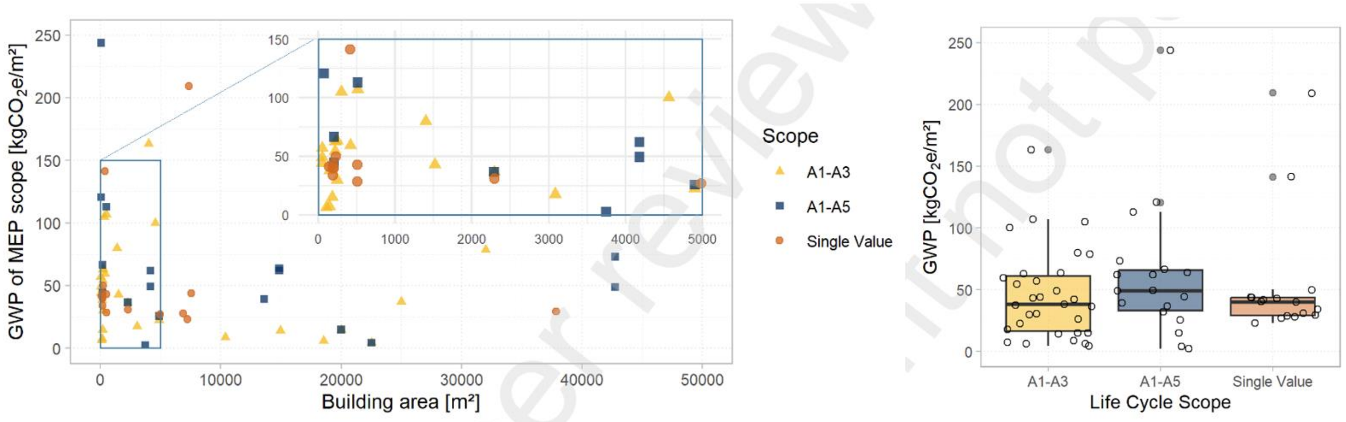


Figure 17 GWP of MEP literature review data from a study

A comprehensive study compiling 54 cases of MEP embodied carbon assessment - including 13 single-family residences, 10 multi-family residential buildings, and 25 commercial buildings - demonstrates significant variation in MEP system impacts based on building type and life cycle stages(Roberts et al., 2024b). As illustrated in Figure X, the study presents data on buildings up to approximately 15,000 m^2, showing that the average GWP for MEP systems is around 25 kg CO_2e/m^2 for life cycle stages A1-A3 (which includes material extraction, manufacturing, and transport). For the broader scope of A1-A5 (which extends to include construction activities), the GWP is approximately 50 kg CO_2e/m^2. The study also highlighted the substantial impact of MEP system replacement and refrigerant leakage on overall embodied carbon.

For the studies that separate the data of mechanical system, data also varies significantly. In Finland, a residential building with a floor area of 3,085 m^2 reported approximately 120,000 kg CO_2 emissions for its MEP system, with 80,000 kg CO_2 attributed specifically to the mechanical systems, equating to about 25 kg CO_2/m^2. This estimate does not include lifetime considerations or refrigerant leakage(Emami et al., 2019). In a separate study conducted by the University of Washington on a typical office building of around 20,000 m^2 - a size comparable to our project - the mechanical system GWP was estimated at 20-25 kg CO_2/m^2. However, when including refrigerant leakage at a 2% rate over a 25-year period, the total contribution increased significantly, highlighting the notable impact of refrigerant use, adding roughly 80 kg CO_2e over a 60-year building lifecycle(B. X. Rodriguez, 2019). Another study presented at the E3S Conference estimated that the mechanical system in an office building, considering stages A1-A3, A4, A5, B4, and C2-C4 over a 50-year calculation period, contributed about 30 kg CO_2/m^2 but no refrigerant considerations(Petersen et al., 2024b)

4.2.3 ESTIMATION OF MEP SYSTEM EMBODIED CARBON IN THIS STUDY

Given the variability reported across different building types and systems, this study adopts a middle-ground approach by selecting an average embodied carbon value for MEP system.

Based on reviewed studies and available data, the embodied carbon for the mechanical, electrical, and plumbing (MEP) systems in this project is estimated at 210 kg CO_2/m^2 over a 60-year building lifecycle. This value incorporates the complete lifecycle, including component replacements and refrigerant leakage. For the A1-A3 lifecycle stages - covering material extraction, transport, and manufacturing - the estimated embodied carbon is 50.7 kg CO_2/m^2, derived from average data for plumbing systems and overall MEP contributions.

Table 3 Estimation of MEP system GWP

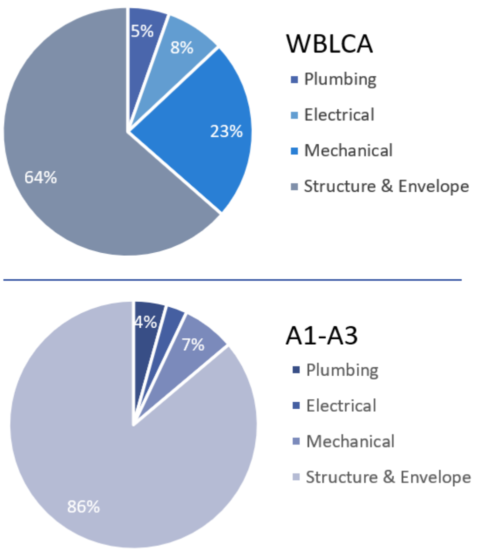
GWP – kg CO2e/m2	Mechanical	Electrical	Plumbing	MEP
A1-A3	25	10	15.7	50.7
Refrigerant Leakage	60			60
Total WBLCA (60 yrs)	135	44	31	210

Specifically, the mechanical system contributes 25 kg CO_2/m^2 in A1-A3, aligning with values from similar-sized buildings, while the electrical system adds 10 kg CO_2/m^2. Additionally, refrigerant leakage contributes approximately 60 kg CO_2e over the 60-year span. These contributions are summarized in Table 3, providing a complete overview of the MEP system's GWP estimation.

4.3 WBLCA EMBODIED CARBON COMPARISON BETWEEN SYSTEMS

The WBLCA results, detailed in Figure X, show the distinct contributions to embodied carbon from various building systems, including the structure and envelope, plumbing, electrical, and mechanical components. The total embodied carbon intensity for the structure and envelope is **366 kg CO_2e/m^2**, compared to **210 kg CO_2e/m^2** for the entire MEP system. While the structural components have the highest overall impact, the substantial contribution of the MEP systems - particularly when considering component replacements and refrigerant leakage over a 60-year building lifecycle - highlights the importance of targeting these systems for potential carbon reduction.

From a WBLCA perspective over a 60-year building lifecycle, the structure and envelope dominate the total embodied carbon, contributing 64% of overall emissions. This substantial share reflects the extensive use of materials in structural elements and their fundamental role in maintaining the building's integrity. However, the mechanical system also represents a significant contributor, accounting for 23% of total emissions, highlighting the high embodied carbon of HVAC equipment and the impact of material choices and refrigerant use. The electrical and plumbing systems contribute 8% and 5%, respectively, due to their comparatively lower material and energy demands.



Life Cycle Stage	Unit	Building Structure and Envelope GWP	Plumbing System GWP	MEP GWP (Estimation)
A1-A3	t CO_2e	4,979	248.3	801
A4	t CO_2e	134	5.3	
A5	t CO_2e	198	11.3	
B3	t CO_2e	-	-	
B4-B5	t CO_2e	428	221.3	
C2	t CO_2e	101	2.0	
C3	t CO_2e	37	0.2	
C4	t CO_2e	1	0.9	
Total	t CO_2e	5,879	489.2	3,316
Total intensity, GFA 1	**kg CO_2e/m^2**	**366**	**30.98**	**210**

Figure 18 Embodied Carbon Comparison Across Systems in WBLCA

In the A1-A3 life cycle stages - covering material extraction, transport, and manufacturing - the structure and envelope again lead with 86% of emissions. The mechanical system follows with 7%, while the electrical and plumbing systems contribute 4% and 3%, respectively. This distribution illustrates the substantial upfront carbon impact associated with fabricating building structures. Although MEP systems play secondary roles in this phase, their shorter lifespans lead to a cumulative GWP contribution over time. Notably, opportunities arise for improvement during replacements, particularly for electrical systems such as lighting fixtures, which have a shorter lifespan(National LED, 2020) (approximately 15 years) and higher GWP impact(B. X. Rodriguez, 2019).

In summary, while the structure and envelope contribute the most to embodied carbon, MEP systems collectively account for a significant portion of total emissions. This underscores the importance of considering service life for accurate carbon accounting and decarbonization strategies, beginning at the design stage. Moreover, MEP retrofits offer opportunities for carbon reduction, particularly through enhanced refrigerant management and more efficient material choices, which can significantly improve sustainability throughout the building's remaining lifespan.

5. DISCUSSION

5.1 PLUMBING SYSTEM WBLCA INTERPRETATION

The experimental WBLCA calculations focused solely on the plumbing system with data limitations for whole MEP system. As such, the following interpretation is exclusively based on the experimental results obtained from the plumbing system analysis.

5.1.1 METHODOLOGY EFFECTIVENESS

The EPD and database-based WBLCA methodology proved to be effective for assessing the embodied carbon of the plumbing system, even after the construction and installation phases. The available data, while not perfect, was sufficient to conduct parametric research and derive a meaningful evaluation of embodied carbon impacts.

Result Comparison with Existing Research

In comparison to other studies, the estimated GWP of our plumbing system appears reasonable. Specifically, a study supported by the Carbon Leadership Forum reports a GWP of approximately 6-10 kg CO_2e/m^2 for plumbing pipes and steel components in an office building context(Rodriguez et al., 2018). This estimate excludes the contributions from plumbing equipment, which makes it less comprehensive compared to our approach. Our more detailed analysis - which includes pipes, fixtures, and associated equipment - presents a broader view of embodied carbon contributions. Unfortunately, comparable studies that specifically report on the full plumbing system in residential buildings are sparse, limiting cross-verification options.

Advanced Analysis

Our research offers a comprehensive view of the embodied carbon associated with the plumbing system. This includes breakdowns by OmniClass section and a detailed analysis of material and equipment contributions. Notably, acrylic fixtures, which unexpectedly showed a significant impact, were found to contribute heavily to the overall GWP due to their high embodied carbon and shorter lifespan. These findings point to substantial opportunities for decarbonizing plumbing systems, particularly through the selection of alternative materials with lower GWP and longer service lives.

5.1.2 SOURCES OF UNCERTAINTY

The uncertainty in our results can be attributed to several key factors:

- **Raw Data Collection and Material Quantification:** Due to data limitations, less than 50% of components had complete weight information, which is critical for accurate calculations. Moreover, much of the material quantification had to rely on estimations, given the lack of complete documentation and engineer interpretation for the entire plumbing system (especially for piping).
- **LCI Data to Database Matching:** Most of the data matched with the LCA databases were classified as DQ-3 (approximately 60%), indicating reliance on similar EPDs from other regions. This introduces potential inaccuracies due to differences in material compositions and regional variations.
- **LCI to Impact Calculations:** There were further uncertainties introduced at the impact calculation stage. The WBLCA tool utilized a different standard from that of the structure and envelope analysis, reducing

comparability. Additionally, there was no transportation data included, which may affect results, especially when materials are imported. Furthermore, despite the standardization of EPDs, the comparability between EPDs can be limited by differing scopes and optional inclusions in accounting - potentially leading to substantial variability in impact assessments.

5.1.3 KEY LIMITATIONS OF PLUMBING SYSTEM WBLCA

- **Data Gaps and Estimation Without Engineer & Supplier Input:** The incomplete data provided by the project team, including the absence of take-offs or detailed material quantity data, required significant estimations. These estimations, compounded by the lack of direct interpretation or validation by engineers & suppliers, introduce substantial uncertainty into the embodied carbon calculations.
- **Inconsistent Standards and Limited Life Cycle Scope:** The WBLCA analysis used different standards for evaluating the structure, envelope, and MEP systems, primarily due to the limitations imposed by the education license of One-Click LCA. Additionally, the data input was limited to the A1-A3 life cycle stages (material extraction, transport, and manufacturing), no data from supplier available like transportation, maintenance, and refrigerant leakage, which are particularly significant for mechanical systems.
- **Data Quality and Regional Variability:** The reliance on DQ-3 level LCI data introduces uncertainty due to regional differences, as EPDs from other regions may not accurately reflect local production conditions.
- **Uncertainty in EPD Comparability:** The lack of EPD comparability checks is a significant limitation due to the workload involved, and not all of the selected data could be verified against their source EPDs. Despite the standardization efforts by One-Click LCA, there may still be errors. Additionally, even with standardization, differences in assumptions, optional accounting, and other parameters in EPDs can still introduce variability, limiting comparability and affecting the overall reliability and cross-system evaluations.

5.2 LIMITATIONS IN MEP SYSTEM ACCOUNTING

5.2.1 DATA AVAILABILITY LIMITATIONS

- Complexity and Limited Information: The mechanical system includes over 70 pieces of equipment, roughly three times that of the plumbing system, with more complex specifications. However, none of these components have dedicated EPDs available.
- Limited Supplier Engagement: Suppliers provided no feedback for data discussions or interpretation over one-month, restricting access to detailed specifications and further validation.
- Absence of BIM Models: BIM models for the entire MEP system were unavailable, consistent with broader industry practices, except for partial models like mechanical rooms in larger projects. This lack of BIM integration limits the ability to leverage LCA tools for a complete material inventory.
- Tool Limitations: One-Click LCA has a limited EPD database, particularly for larger mechanical equipment such as tanks, pumps, and heat pumps. Delays in responses from One-Click LCA regarding their new “MEP Tool” introduction add uncertainty to its applicability for comprehensive MEP assessments.
- Data Gaps in Electrical Systems: The electrical system posed even greater data challenges. Equipment schedules were difficult to obtain, and supplier information remained fragmented throughout, complicating the analysis.

5.2.2 BENCHMARKING LIMITATIONS

- Limited Case Studies Using Similar Methodology: Few case studies have applied the same WBLCA methodology for MEP systems as used for the structure and envelope. Most studies rely on typical material inputs and broad estimations, which makes detailed system classification and lifecycle stage comparisons challenging.
- Incomplete Equipment Listings: Equipment listings were not as comprehensive as expected, only dozens of equipment with insufficient material data or EPD quality, these studies are difficult to define as reliable benchmarks.
- Lack of Residential Building Data: There is a notable lack of data specifically for MEP systems in residential buildings, particularly larger multi-unit residential projects. Many available case studies use office buildings, which limits their applicability to this research.
- Absence of MEP-Specific Benchmarks: There are no established benchmarks available for the embodied carbon of MEP systems. The absence of clear methodologies and standards for benchmarking MEP system embodied carbon also limits the effectiveness of comparative analysis.

5.3 INDUSTRY POLL AND INTERVIEW INSIGHTS

5.3.1 INDUSTRY POLL: LACK OF ENGAGEMENT AND READINESS

We initiated an industry poll by sending survey emails to relevant stakeholders but received no responses after over one month of waiting. This lack of engagement may reflect the industry's current lack of readiness regarding material data and life cycle information for equipment production. It also suggests limited interest in exploring these aspects at present. Notably, our outreach might not have targeted the correct individuals, emphasizing the need to establish these relationships and conversations earlier in the project lifecycle, particularly from the procurement stage.

5.3.2 INTERVIEW INSIGHTS

Based on the interviews conducted, several key insights emerged regarding the challenges and current practices related to MEP system design and embodied carbon data tracking.

- **Tracking Material and Equipment Inventory when Construction:** The most reliable way to track the actual material and equipment inventory is through the construction company's site management team. Site managers, responsible for real orders and overseeing the delivery of materials and equipment, possess the most accurate information regarding the inventory used in MEP systems. However, accessing this information from the procurement team remains challenging, as such data is often considered sensitive.
- **Easier Data Collection with Limited Details**: Equipment schedules are relatively easier to obtain since they are part of design or construction documentation, though they often lack detailed information such as material composition and weight. Contractors can estimate material needs for simple systems like piping, including connections and distribution. However, even these estimates can be time-consuming, often requiring several hours or days of effort.
- **Final System Design Responsibility**: Contractors or trade partners are responsible for adapting or modifying the initial MEP design to accommodate construction requirements. This includes adjustments for construction convenience and pre-assembly to streamline on-site installation. The design team mainly

oversees major components, while contractors manage detailed distribution and piping work. This suggests that detailed, final installation information should ideally be sourced from the contractors.

- Effort Required for MEP BIM Modelling: Design teams indicated that MEP systems are generally modelled in 2D with specifications detailed for construction, as the industry standard does not mandate comprehensive 3D modelling. Such detailed modelling is often viewed as unnecessary, costly, and time-consuming. Typically, only mechanical rooms are modelled in 3D using software like Revit, which can integrate with WBLCA tools. For larger projects, such as hospitals, converting 2D designs into a detailed 3D BIM model could take at least a month, while for smaller projects, it may require about a week.
- Importance of Early and Continuous Data Requests: Effective embodied carbon tracking requires initiating data and material requests from the outset of the project. Continuous maintenance of documentation and consistent communication across all stages - particularly during construction - is crucial to ensure accurate and comprehensive data collection.

6. RECOMMENDATIONS

To support future case studies in embodied carbon accounting, guide UBC's embodied carbon guidelines, and contribute to broader building decarbonization strategies, the following actions are recommended, ranging from short-term to long-term initiatives and research directions:

6.1 ACTION RECOMMENDATIONS

6.1.1 SHORT-TERM ACTIONS

Data Collection and Engagement Initiatives

- Plan Early and Engage Stakeholders: Integrate embodied carbon accounting into all project phases from the design stage onwards. Actively engage designers, contractors, and construction teams, and maintain well-organized documentation. Require the availability of take-offs and bill of quantities in standardized formats (e.g., Excel). Ensure engineers are involved in validating take-offs and discussing data accuracy.
- Engage Suppliers for Data Collection: During procurement, directly contact suppliers to obtain Environmental Product Declarations (EPDs), specifications, and other relevant life cycle data to enhance the accuracy of embodied carbon estimates.
- Improved Record-Keeping by Site Management: Site managers should maintain up-to-date records of material deliveries and equipment specifications, and consistently share this information with design and LCA teams.

6.1.2 MID TO LONG-TERM ACTIONS

- Tool and Data Quality Improvement
  Understand WBLCA Tool Databases: Collaborate with LCA software providers, such as One-Click LCA, to understand and explore the tools used for embodied carbon analysis of MEP systems, particularly for mechanical equipment. Advocate for the inclusion of equipment-specific EPDs and standardized databases to improve the comparability of existing datasets.

- Industry Engagement and Collaboration
  Partner with initiatives like the MEP 2040 Challenge from the Carbon Leadership Forum to use the experimental building as a case study for industry collaboration. Leverage these platforms to explore MEP decarbonization opportunities, promote best practices from design to retrofit stages, encourage long service life for fixtures, and prioritize local materials. This type of industry involvement can drive live data collection and contribute to long-term decarbonization efforts.

6.2 RESEARCH RECOMMENDATIONS

6.2.1 DEVELOPMENT OF MEP EMBODIED CARBON ACCOUNTING GUIDELINES

Level of Accounting Quality and Feasibility

- Baseline Approach (Most Feasible but Less Accurate): Apply the methodology used in this plumbing system study by leveraging average WBLCA tool data and similar EPDs based on available material and equipment inputs.
- Advanced Incorporation of TM65 Standards: Integrate TM65 requirements as a second step, collaborating with suppliers to obtain 95% of material data for MEP equipment, while using WBLCA tools to input more comprehensive data for different life cycle stages, including replacement and refrigerant leakage.
- BIM Integration for High-Quality Accounting: For the highest quality results, adopt BIM modeling to represent the entire MEP system. Start with simpler projects to practice comprehensive data integration from design stage, enabling scenario analysis and decarbonization opportunities early in the design process.

Comparative Study of Different Methodologies: If the opportunity arises to conduct all three levels of study, compare results to establish an acceptable threshold for data quality. Define what percentage of key materials or equipment data must be available to achieve reliable embodied carbon results - e.g., could 70% coverage provide sufficient data for key decarbonization decisions? And how about the acceptable data quality level?

Create MEP-Specific Benchmarks:

Develop benchmarks that consider data completeness, quality, tool selection, and EPD comparability. Benchmarks should encompass all life cycle stages (as done for structure and envelope systems) while standardizing the service life and leakage considerations for MEP equipment. Different building types and functions should have separate benchmarks to align with other embodied carbon standards.

6.2.2 IMPROVE DATA COMPARABILITY AND QUANTIFY UNCERTAINTY

- Conduct research to investigate the variability of EPDs across MEP systems, including discrepancies due to different scopes, reporting methodologies, and optional accounting practices. The aim is to quantify uncertainty and develop improved EPD standardization methods and improve results reliability.
- Refinement of Critical Parameters: Conduct sensitivity analysis to determine which variables - such as plumbing materials or type of an equipment - significantly impact uncertainty. This can help target efforts to reduce data uncertainty, improve the reliability of outcomes and provide guidelines on a reliable way for database choosing.

6.2.3 EXPLORING MEP SYSTEM DECARBONIZATION OPPORTUNITIES

Investigate alternative low-GWP materials for MEP systems, such as local and renewable materials, refrigerant alternatives, and efficient management practices. Assess the benefits of retrofitting existing MEP systems, focusing on key decarbonization areas like refrigerant management and high-GWP equipment replacements. Develop good-practice cases to support retrofit opportunities and long-term decarbonization initiatives.

7. CONCLUSION

This report presents an in-depth analysis of the embodied carbon contributions of the mechanical, electrical, and plumbing (MEP) systems for Building C of the BCR-6 project at UBC. It underscores the often overlooked but crucial role of MEP systems in whole building life cycle assessments (WBLCA). The research involved a thorough review of MEP embodied carbon accounting methodologies, experimental WBLCA calculations for the plumbing system, and literature-based estimations for the mechanical and electrical systems. Furthermore, the study explored industry readiness, identified limitations, and gathered insights from data collection challenges through surveys and interviews to guide more effective future practices.

Key findings are as follows:

The embodied carbon accounting methodology was found to be effective, particularly for experimental calculations of the plumbing system using Environmental Product Declarations (EPDs) and available databases. Despite data limitations—particularly concerning raw data completeness and quality in the WBLCA tool—the chosen method proved applicable and effective for post-construction assessment. The experimental WBLCA calculations for the plumbing system showed a GWP of 30.98 kg CO_2e/m^2, which was higher than expected, highlighting significant decarbonization opportunities, especially from acrylic shower tubs and bases.

For the broader MEP system, literature-based estimations indicated a total embodied carbon intensity of 210 kg CO_2e/m^2, factoring in component replacements over a 60-year building lifecycle and estimated refrigerant leakage. Comparative analysis revealed that the structure and envelope contribute the majority (64%) of total embodied carbon, while the MEP systems collectively account for 36%, with the mechanical system alone contributing 23%. This underscores the substantial role of MEP systems in achieving overall building decarbonization, especially considering lifecycle replacements and refrigerant impacts.

The recommendations provided focus on levelizing embodied carbon accounting practices, emphasizing early stakeholder engagement from design through procurement, improved data collection processes, and enhanced use of LCA tools and databases. Further research is needed to compare methodologies based on varying levels of data quality and completeness, exploring acceptable thresholds for reporting and benchmarking, reducing uncertainties, and identifying decarbonization strategies.

In summary, this report underscores the significant contributions of MEP systems to the overall embodied carbon footprint and offers a viable approach for MEP embodied carbon accounting. The experimental findings stress the importance of integrating embodied carbon tracking from the early design stages to enable proactive decarbonization and maintain data quality throughout the project lifecycle. Achieving effective building decarbonization requires proactive stakeholder engagement, robust data collection, and the establishment of industry-wide benchmarks and standards that include MEP systems as a central focus.

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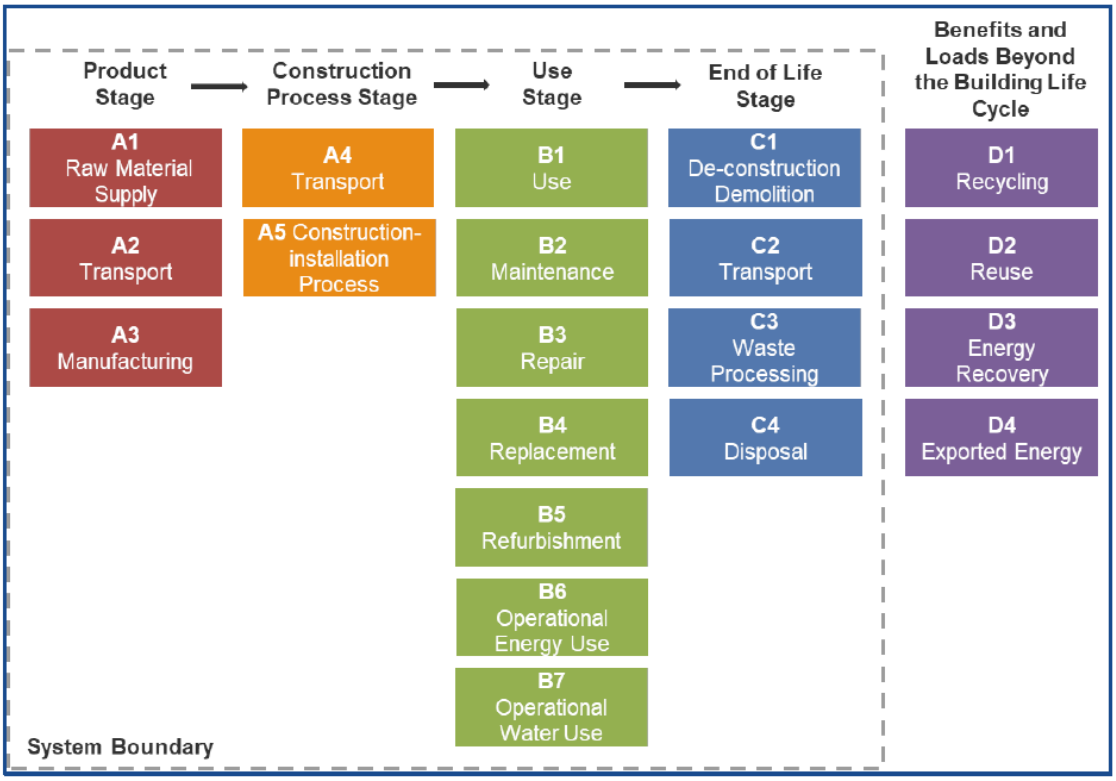
APPENDICES

Appendix A. WBLCA boundary framework and nomenclature



Nomenclature per ISO 21930 and EN 15978

Appendix B. Communication email for industry readiness poll

Dear Partners,

I'm Joan, a researcher from the UBC SEED program, working on assessing the embodied carbon of the MEP system for Building C of the BCR 6 project at UBC Westbrook.
While I understand that life cycle material data can be challenging to identify, it is crucial for decarbonizing buildings from an embodied carbon standpoint specially in this time to support 2030 decarbonization targets in BC.

I would greatly value your insights on below quick survey. If you are not the right contact, I kindly ask that you forward this invitation accordingly.
Please feel free to reach out if you have further questions or wish to talk more.

1-Have you received many requests for embodied carbon data related to your equipment/components?
(If possible, please specify the number, e.g., over 10 requests this year.)

2-Are you currently taking steps to identify the embodied carbon in your equipment?
(Examples: Environmental Product Declarations, material data collection, data tracking procedures, etc.)

3-What are the key challenges you face in tracking and identifying embodied carbon data?
(Consider life cycle stages such as material extraction, transportation, manufacturing, transport to sites, maintenance, and recycling.)

4-Would you be open to a brief conversation about industry challenges, current embodied carbon methodologies, and potential ways to advance?
(Please share your preferred communication method: email or phone.)

Thanks so much for your kind feedback and really wish to talk with you for **the potential collaboration**, especially if you already have some information to share.

Appendix C. Data collection and information comparison for TM65 methods

General information	Input	Notes
Type of product	Emergency	If you would like this form to be used for more than one product, please complete a new tab for each product. To copy the tab, simply right click on the tab name below (where it says 'CIBSE TM65 Manufacturer Form'), select 'move or copy', tick the box beside 'make a copy', and click 'OK'. Then rename the tabs to indicate the respective products.
Manufacturer		
Name of the product	EscapeForm 5 Recessed	
Contact details (email address)	info@formationlighting.com	

A. Essential information for 'basic' calculation	Input				Notes
Capacity/size of equipment (kW; m³; litres; etc.)	Insert size here		Insert unit here		For heating/cooling equipment, please indicate whether the capacity is for heating or cooling, as appropriate
	3		Watts		
Product service life (years)	8 Years				
Product weight (kg)	0.293				
	Material	Material % by weight	Insert origin location, if known	Insert recylced content (%), if known	Insert origin location and recycled content, if known
	ABS				
	Aluminium	8%	UK		
	Brass				
	Cast iron				
	Ceramic				
	Copper	1%	UK		
	Electronic component				
	Expanded polystyrene				
	Glass				
	Insulation (general)				
	Iron				
	Lithium				
	Plastics (general)				
	Polyamide				
	Polycarbonate	44%	CHINA		
Material % breakdown for at least 95% of product weight (excluding refrigerant charge)	Polyethylene				
	Polyurethane foam				
	Printed wiring board, mixed mounted	17%	CHINA		
	PVC pipe				
	PVC				

CIBSE TM65 Manufacturer Form

Table 4.1 Comparison of the life cycle stage modules needing to be calculated and the type of information required per life cycle stage module for the two calculation methods and an EPD

Preliminary information		'Basic' calculation	'Mid-level' calculation	BS EN 15804+A2 compliant EPD*
Capacity of equipment/size		Mandatory	Mandatory	Mandatory
Product service life (years)		Mandatory	Mandatory	Optional
Refrigerant used, GWP, charge (kg)		Mandatory	Mandatory	Mandatory
Stage	**Module**	**'Basic' calculation**	**'Mid-level' calculation**	**BS EN 15804+A2 compliant EPD***
A	A1 (material extraction)	Mandatory	Mandatory	Mandatory
	A2 (transport to factory)	Scale-up factor	Mandatory	Mandatory
	A3 (manufacturing)		Mandatory	Mandatory
	A4 (transport to site)		Mandatory	Optional
	A5 (installation)	—	—	Optional
B	B1 (use)	Mandatory for refrigerant based system	Mandatory for refrigerant based system	Optional
	B2 (maintenance)	Scale-up factor	Optional	Optional
	B3 (repair)	Mandatory	Mandatory	Optional
	B4 (replacement)	—	—	Optional
	B5 (refurbishment)	—	—	Optional
	B6 (operational energy)	—	—	Optional
	B7 (operational water)	—	—	Optional
C	C1 (deconstruction)	Mandatory for refrigerant based system	Mandatory for refrigerant based system	Mandatory
	C2 (transport)	Scale-up factor	Mandatory	
	C3 (waste processing)			
	C4 (disposal)		Mandatory	
D	D (reuse, recover, recycle)	—	—	

* Compliant with BS EN 15804:2012+A2:2019, therefore modules C and D are mandatory whereas they are optional for BS EN 15804:2012+A1:2013

Appendix D. raw data and its matching within the LCA tool

System	Equipment No.	Make	Model	Quantity	material	weight-KG	DQ-1	DQ-2	DQ-3	DQ-4	life span	OmniClass	one-click data resource
Heat Exchanger	HX-DHWR-C-01	Bell & Gossett	BPDW 422-24	1	copper	23-155.8KG CO2			1		20	D2010	Horizontal tubular heat exchanger, 5.22 kg/unit, RECH40CAL (NICOLL)
Expansion Tank	ET-C-1	AMTROL	AX-80(V)	1	fabricated steel	109			1		20	D2010	Stainless steel buffer tank, EN15804+A2, ref. year 2022 (Sphera Solutions GmbH)
Expansion Tank	ET-C-2	AMTROL	AX-40(V)-DD	1	fabricated steel	68			1		20	D2010	Stainless steel buffer tank, EN15804+A2, ref. year 2022 (Sphera Solutions GmbH)
Expansion Tank	ET-C-3	Bell & Gossett	PTA-449	1	steel	102			1		20	D2010	Stainless steel buffer tank, EN15804+A2, ref. year 2022 (Sphera Solutions GmbH)
Expansion Tank	ET-C-4	AMTROL	ST-450C	1	carbon steel	181			1		20	D2010	Steel buffer tank, EN15804+A2, ref. year 2022 (Sphera Solutions GmbH)
Chilled Water Tank	BT-C-1/2	AMTROL	CWBT300-6-125	2	carbon steel	940			1		20	D2010	Steel buffer tank, EN15804+A2, ref. year 2022 (Sphera Solutions GmbH)
Pumps	P-DCW-ABC-01/02/03	Bell & Gossett	33SV30GL4E60	1	304 stainless steel	800(Est.)			1		20	D2010	Stainless steel pump, 2.45 kg/unit, ALPHA2 N, ALPHA1 N, ALPHA1.1, ALPHA2.1, (Grundfos Holding A/S)
Pumps	P-CWR-C-01/02	Bell & Gossett	E-80SC 4*4*11B	2	cast iron, bronze, stainless steel,	595			1		20	D2010	Centrifugal pump powered by an electrical motor, 36.6 kg/unit, MAGNA3 100-40/60 (Grundfos Holding A/S)
Pumps	P-CWR-C-03/04	Bell & Gossett		2	cast iron, bronze, stainless steel,	640			1		20	D2010	Centrifugal pump powered by an electrical motor, 36.6 kg/unit, MAGNA3 100-40/60 (Grundfos Holding A/S)
Pumps-circulator	P-DHWR-C-01+P-DHW-C-01	Bell & Gossett	NBF 36	2	stainless steel	10.5		1			20	D2010	Stainless steel circulator pump, single-head, 0.07 kW, 18 m3/h, 19 kg/unit (One Click LCA)
Flanges	P-DHWR-C-01-F	freedom	110254SF	6	stainless steel	NA						D2010	assume already included in pumps
Water Closet	PB-01	Water Closet – Caroma 829110W Some		229	Ceramic	44.2		1			40	D2020	Ceramic toilet with flush tank (cistern), 34.8 kg/unit, 980 × 360 × 430 mm (One Click LCA)
Water Closet seat	PB-02	Water Closet seat – Caroma 829109W S		229	NA	NA		1			20	D2020	Toilet seat set from thermoplast material (PP), 1.10 kg/unit (Hamberger Sanitary GmbH)
Kitchen Sink (Double)	PB-03	Kitchen Sink (Double) SS – Fluid FSN-UDF		88	304 stainless steel	NA		1			30	D2020	Stainless steel floor-standing washbasin, 14 kg/unit, 830 x 375 x 430 mm (One Click LCA)
kitchen sink (single)	PB-04	Fluid FSN-USR2518 SS sgle 25"x18"x9" ki		51	304 stainless steel	NA		1			30	D2020	Stainless steel wall-mounted washbasin, 12 kg/unit, 115 x 700 x 440 mm (One Click LCA)
basin	PB-05	Fluid FB2421140W china white 21"x15"		229	Ceramic	NA		1			60	D2020	Ceramic bathroom washbasin, 16.7 kg/unit, 850 × 460 × 150 mm (One Click LCA)
tub	PB-06	Hytec AC3745L acrylic white 60"x30" ski		146	acrylic sheet, reinforced with fibr	47.6			1		15	D2020	Acrylic bath and shower tub, EN15804+A2, ref. year 2022 (Sphera Solutions GmbH)
TUB W&O	TUB W&O	1-1/2" FR-PRO 25-50 lift&turn waste & c		146	PVC-assume 0.6kg/unit	87.6			1		60	D2020	Plastic floor drain for indoor drainage systems, MaxiFlex/MultiFlex (Purus AB)
shower base	PB-07	Hytec ACR3798L acrylic white 60"x30" sl		82	acrylic sheet, reinforced with fibr	26				1	15	D2020	Acrylic sanitaryware including bathtubs, shower trays and tub panels, 3.2-5 mm, 17.91 kg/m2 (DURAVIT)
shower drain	SH DRAIN	2" FR-PRO 25/50 shower drain - ss		82	stainless steel	NA			1		50	D2020	Stainless steel floor drain covers, Vieser Gratings (Vieser Oy)
kitchen faucet	PB-08	Fluid F827-1.5 sgle hdle kitchen faucet, 1		139	PVD Stainless Steel Finish	NA			1		20	D2020	Bathroom and kitchen faucets, 1.46 kg/unit (GROHE FRANCE)
sgle hdle lav faucet	PB-09	Fluid F24011CP-10 sgle hdle lav faucet w		229	Polished Chrome, PVD Brushed N	NA			1		15	D2020	Washbasin Mixer, Azur (Ahlsell AB)
pressure balance valve	PB-10-1	Fluid F1012B-PEX-W volume control pre:		82	copper	NA				1	20	D2020	Non-motorized brass valves, DN 65, 2.4 kg/unit (One Click LCA)
shower head & handshower trim kit	PB-10-2	Fluid F242004TCP-15_ shower head & ha		82	Chrome	NA			1		20	D2020	Ceiling shower set with thermostatic mixer and hand showerhead, 2.103 kg/unit (Ahlsell AB)
2-way diverter	PB-11-1	Fluid F1012B-PEX-W volume control pre:		146	copper	NA				1	20	D2020	Non-motorized brass valves, DN 65, 2.4 kg/unit (One Click LCA)
lever hdle & tub spout	PB-11-2	Fluid F242005TCP-15_ tub/shwr trim w/l		146	Chrome	NA- 2KG? Est			1		15	D2020	Built-in water mixer sets (tap, shower, bath) (d line)
HWR,HWS,CWS,DHW, DCW,DHWR,risers			1-1/2"		PEX	738.74				1	50	D2010	Cross-linked polyethylene (PEX) pipe for water distribution networks, DN 32 mm (1 1/4 in), 0.37 kg/m, wall th
DCW			6"		Sch.10 Stainless Steel	5,750.96				1	100	D2010	Stainless steel pipes, SCH 40S, DN 100 mm, (4 in), 16.32 kg/m, wall thickness: 6.02 mm (One Click LCA)
HWR, HWS,CWS,CWR			4"		Sch40 Carbon steel	127.54			1		20	D2010	Carbon steel drawn tube (Marcegaglia Carbon Steel)
HWR, HWS,CWS,CWR			6"		Sch40 Carbon steel	10,720.34			1		20	D2010	Carbon steel drawn tube (Marcegaglia Carbon Steel)
pvc-drian			4"		Perforated PVC Sewer Drain Pipe	1,449.36				1	100	D2020	Polyvinyl chloride (PVC) pipe for drainage and sewerage networks, DN 100 mm (4 in), 4.37 kg/m, wall thickne:
S.S-Sanitary - riser			all sizes		Cast Iron	29,490.89			1		60	D2030	Cast iron pipes, DN 80-1000 mm (IBECO)