# A Comparative Study of Embodied Carbon Calculation Tools for Application in Geotechnical Engineering and Construction

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## ABSTRACT

The built environment significantly influences global energy consumption and carbon emissions. Foundations are a crucial component of the built environment, contributing substantially to overall energy and resource consumption. The European Federation of Foundation Contractors (EFFC) and Deep Foundations Institute (DFI) developed one of the first tools to calculate the embodied carbon of geotechnical construction projects ten years ago, the EFFC/DFI Carbon Calculator. Recently, these organizations have formed a joint Task Group to further refine and expand the capabilities of that tool. As part of that process, and in collaboration with the American Society of Civil Engineers (ASCE) Geo-Institute (GI), an effort is underway to assess the current state of practice in embodied carbon calculation tools in geotechnical engineering, the results of which are presented in this paper. A comparative review of several tools was conducted to understand differences in scopes, calculation methods, and applicability to the industry. Their relative strengths and weaknesses are discussed, and based on these findings, recommendations for improvement of the EFFC/DFI calculator are presented. The outcomes of this study can serve as guidance for practitioners to accurately calculate embodied carbon, identify impactful project phases and, ultimately, make design decisions to reduce carbon emissions.

## INTRODUCTION

The built environment significantly contributes to global energy consumption and carbon emissions, with the building and construction sector responsible for 37% of global energy-related CO2 emissions in 2021. Carbon emissions from building operations reached 10 $GtCO_2$, and material production contributed an additional 3.6 $GtCO_2$. Construction materials alone accounted for 86% of nonfuel minerals used in the United States in 2020 (United Nations Environment Programme 2022). By 2050, the growth in global building stock is expected to double the total consumption of raw materials.

Embodied carbon refers to emissions released during the manufacturing, transportation, construction, and end of life phases of all built infrastructure. While these emissions have historically been overshadowed compared to those related to building operations (e.g., heating and cooling efficiency), it is projected that between now and 2050, embodied carbon emissions will contribute up to half of the total carbon footprint of new construction (World Green Building Council, 2019). Though much of the global initiative relating to the building and construction sector pertains to the structural engineering discipline, the underlying principles are translatable to the geotechnical engineering profession as well.

Geotechnical engineering projects play a large role in the civil infrastructure system, making substantial contributions to the construction sector in terms of energy and resource consumption. As such, practitioners have the opportunity to implement sustainability as a design criterion (e.g., minimizing carbon emissions). To accomplish this, several tools have been developed over the last decade that quantify embodied carbon through environmental product declarations (EPDs) or life cycle assessments (LCAs).

Several tools have been developed to quantify embodied carbon associated with engineering projects. The European Federation of Foundation Contractors (EFFC) and Deep Foundations Institute (DFI) developed one of the first tools to calculate the embodied carbon of geotechnical construction projects, the EFFC/DFI Carbon Calculator, a decade ago. A joint Task Group by the EFFC, DFI, and the American

Society of Civil Engineers (ASCE) Geo-Institute (GI) was established to enhance that tool. A comparative review of six tools — EC3, eTool, Athena Impact Estimator, ECOM, SimaPro, and the EFFC/DFI Carbon Calculator — was conducted to quantify differences in scopes, methods, and applicability to the industry. Recommendations for improving the EFFC/DFI calculator are discussed, guiding practitioners in accurate embodied carbon calculations and informed decision making.

## ENVIRONMENTAL IMPACT QUANTIFICATION METHODS

Numerous methodologies are available for evaluating environmental impacts, each serving distinct purposes. Among the most commonly used approaches are life cycle assessment, carbon footprinting, and environmental product declarations. While these methods share certain similarities, they each have distinct characteristics and adhere to various standards. Specific attributes of each method are discussed in further detail in this section.

### *Life Cycle Assessment*

Life cycle assessment (LCA) is a systematic analytical framework to evaluate the environmental impacts of a product or system over its entire life cycle. Several organizations have created standards to define the perimeter of calculations, propose relevant processes for which they should be carried out, and outline general principles for calculations. Though numerous standards exist, the most widely recognized procedures are included in the 14000 series of the environmental management standards for the International Organization for Standardization (ISO), particularly ISO 14040 (principles and framework) and ISO 14044 (requirements and guidelines). ISO 14000 Standards are primarily concerned with process-based methodology, which is usually defined in four phases: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation (ISO, 2006). These steps are generally included in other standards as well.

In the goal and scope definition phase, the purpose, approach, audience, functional unit, and system boundary for a LCA are determined. Another decision made at this stage is the set of environmental impacts to be included. ISO 14040 (ISO 2006) standard requires that multiple impact categories be considered. The scope of an LCA is often described as either “cradle-to-grave” (A-C), which includes impacts from the raw material extraction phase until the product or system end-of-life, or “cradle-to-gate,” which only includes impacts until the last manufacturing process phase before the product passes through to the site (A1-A3). A schematic of each life cycle stage and their respective components can be seen in Figure 1.

The next phase is the LCI, which quantifies the relevant environmental flows of inputs (e.g., raw materials, water, and energy resources) and outputs (e.g., emissions to air, water, and land and waste generation) of the system. LCI data sources include established databases (e.g., ecoInvent, GaBi, and JLCA), primary data, published literature, and expert opinion. In the LCIA phase, environmental flows contained in the LCI are translated into indicators of impacts to the environment and human health. Different LCIA methods, such as CML, TRACI, and RECIPE (EC-JRC 2011), use a specific set of indicators for the impact categories they consider. An LCI and LCIA can be compiled in a spreadsheet or dedicated software, as further discussed in this paper. The final phase is interpretation, in which results of the LCI and LCIA are analyzed, often involving determination of data sensitivity and uncertainty, guiding conclusions and recommendations.

### *Carbon Footprint*

Carbon footprint (CF) and LCA are related but distinct methods for assessing environmental impacts of a product or system. While CF applies life cycle principles and accounting methods, it is based on one single impact category — greenhouse gas (GHG) emissions related to climate change, often quantified as global warming potential (GWP). LCAs, on the other hand, evaluate other environmental impacts, such as energy use, water consumption, and air pollution (Motta 2022).

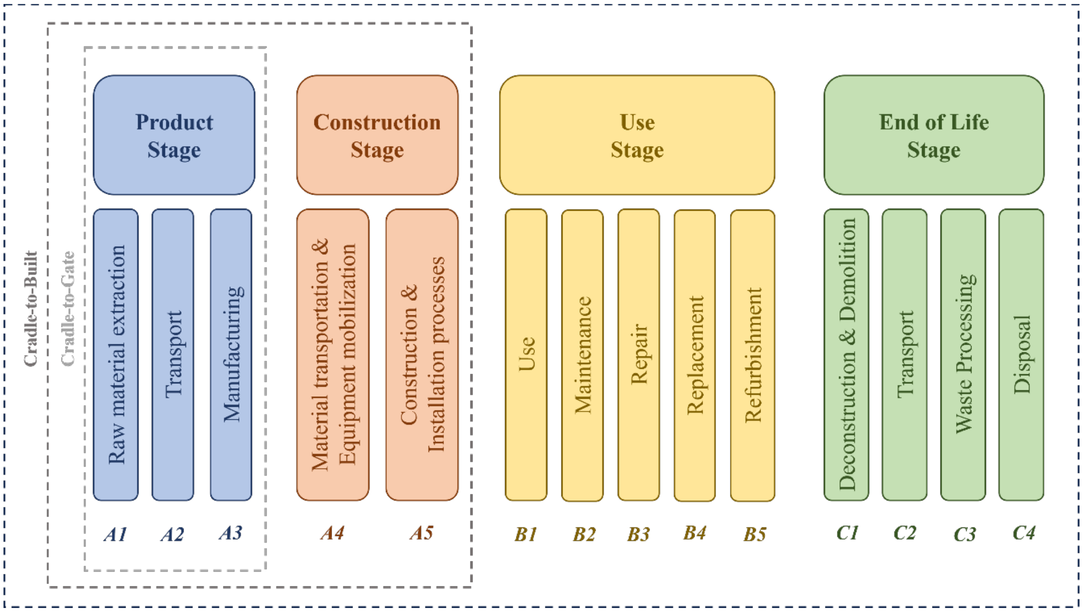


**Figure 1:** Life Cycle Stages (EN 15978 and ISO 21930)

As with LCA, several standards exist to normalize CF procedures for both corporate and product analysis. The Greenhouse Gas Protocol Corporate Standard (GHG Protocol) is the most widely used international emission accounting standard and has formed the basis for most other standards, including those developed by the ISO. ISO 14064 establishes standards for quantification, monitoring, and verification of GHG emissions of organizations (ISO 2018). ISO 14067:2018, conversely, is a product reporting standard based on the current ISO standards related to LCA (ISO 2006, 2018). Another commonly used product reporting standard is the PAS 2050:2011, a publicly available method for assessing GHG emissions of good and services, following the main GHG Protocol principles (BIS 2011). The GHG Protocol also released the Product Life Cycle Accounting and Reporting Standard in 2011, which can be used to calculate life cycle emissions of a product (Motta 2022).

Although LCA has the advantage of considering several environmental impacts, this may increase the complexity of the assessment, analysis, and subsequent decision making. By focusing on a single impact category, CF limits this complexity, leading to a relatively rapid assessment and facilitating carbon reporting and identification of management strategies.

***Environmental Product Declaration***

An EPD is a verified and registered document that conveys information about the life cycle environmental impact of a product adhering to standards like ISO 21930 and EN 15804 for the building and construction sector (EN 2012; ISO 2017). While EPDs may vary in scope, they typically consider a cradle-to-gate scope, as material manufacturers cannot predict the eventual use of their products postproduction. However, current standards do allow for expanded scopes, such as cradle-to-built and cradle-to-grave. EPDs can be used to promote the environmental attributes of products and are often the required for certain materials for public projects to encourage selection of most sustainable options. Furthermore, EPDs served as a valuable open-source data for conducting comprehensive LCAs.

## EXISTING TOOLS

Six carbon calculation tools were compared in this study. A summary of these can be seen in Table 1.

***Embodied Carbon in Construction Calculator (EC3)***

EC3 is a web-based tool that allows users to determine the embodied carbon of building materials and structures based on third-party verified EPDs. EC3 is a database of hundreds of EPDs, sorted geographically by country, that allows users to find and compare impacts of materials and buildings. Within each material category, users can define material-specific performance characteristics (e.g., yield strength and recycled content), geographic location, and specialized filters (e.g., manufacturer, product name, production date). When a search has been performed, the overall range of embodied carbon is presented as a box-and-whisker, highlighting the range of low and high reported in $kgCO_2e$ per functional unit in the EPDs. This plot includes the Carbon Leadership Forum baseline values, as well as a conservative threshold at the $80^{th}$ percentile (i.e., 20% of EPDs returned have a GWP higher than this value) and a $20^{th}$ percentile achievable target (i.e., 20% of EPDs returned have a GWP lower than this value).

EPDs can also be compared based on manufacturer, production plant, material description. Users can access other impacts associated with materials (e.g., eutrophication, acidification, and ozone depletion potentials), resource use indicators (e.g., recovered energy and renewable materials), and waste and output flows (e.g., materials for recycling and waste disposed). It is important to note that this is not a feature of EC3 itself, but rather determined by manufacturers who develop EPDs, as it is up to their discretion which impact categories to report. An important characteristic of this tool is the life cycle scope included in the GWP calculation. A cradle-to-gate life cycle is considered, meaning that only the supply chain, transport to manufacture, and manufacture of materials are considered. This scope omits transport to site, installation, use, operation and maintenance, and end of life.

Users can evaluate embodied carbon of buildings by manually adding EPDs for structural components (e.g., foundations, superstructures, exterior enclosures, and interior construction) or importing from a building information modeling (BIM) model, such as Autodesk BIM 360. This includes material transportation to the construction site and construction activities in the scope (A4 & A5 life cycle stages).

EC3 addresses uncertainty in EPDs by calculating an "uncertainty-adjusted" GWP based on product category and uncertainty source, offering transparency about embodied carbon variability. If the adjusted GWP is less than a specified limit, there is an 80% confidence that the true GWP is also below this limit. EC3 provides the flexibility to choose from several LCIA methods, enhancing precision by considering regional factors affecting GHG conversions. Furthermore, EC3 is free and user-friendly. It is important to note that the tool's scope is primarily geared toward superstructures, limiting its applicability to geotechnical projects.

***eTool***

eTool, a web-based application, serves as a tool for evaluating the environmental impacts of projects and identifying areas for improvement. It provides templates for construction components, energy, and water use, allowing users to customize models with specific life cycle stages and indicators and compare them to relevant benchmarks and standards. For custom models, LCI sources must be selected based on project location. Templates clearly define LCI sources, reducing ambiguity in decision making. Users can specify critical site attributes, including electricity, gas, water supply, and wastewater treatment grids based on geography by country, and in some instances, specific region (e.g., US Midwest or South Australia). The model's complexity can be tailored to meet specific needs by adding inputs related to personnel, equipment, materials, energy, and water usage. Existing templates and pre-calculated impacts from equipment and transportation can be integrated into custom models, streamlining data input, and reducing user workload. Additionally, eTool provides a database of EPDs to model material impacts and is compatible with BIM.

The interface generates concise impact summaries for both individual components and entire project models. Models can also be submitted for certification by the eTool team for quality assurance. This certification not only validates the model, but also offers actionable strategies to mitigate activities that significantly contribute to environmental impacts. eTool also offers a comprehensive financial costing analysis as part of its toolkit for project assessment. It combines environmental impact assessment with financial analysis, allowing users to understand the economic feasibility of design decisions and potentially more sustainable options.

eTool is primarily focused on construction and building projects, and its suitability for modeling geotechnical engineering projects is limited. The tool does include some EPDs specifically for concrete bored piles, secant piles, floor slabs, precast and poured concrete, stripped footings, and reinforcements, and templates for excavation, backfilling, and compaction. Depending on the templates, assembly (i.e., labor) may be included. Most templates are locked and would require external calculations to extrapolate the results to other specifications, which may not always be possible due to convolution of calculations in the tool. Some features are reserved for paid user subscriptions.

***Athena Impact Estimator for Buildings***
Athena Impact Estimator for Buildings (Athena IE) is a software tool designed to assess the environmental impacts of building materials and assemblies from cradle to grave. Users are prompted to input details such as building location (applicable for the United States and Canada only), type, area, and service life. Based on these inputs, geographically appropriate data for electricity grids, transportation nodes and distances, and product manufacturing are selected. Assemblies within the building model are then created through inputs such as bay sizes and loads, which are utilized to generate a bill of materials. Alternatively, users can import a bill of materials from any CAD program.

Following completion of a model, the software provides comprehensive reports on environmental impact measures, specifically focusing on footprint data in accordance with the latest US EPA TRACI methodology. This includes assessments of total primary energy, non-renewable primary energy, fossil fuel consumption, global warming potential, acidification potential, human health respiratory effects potential, ozone depletion potential, smog potential, eutrophication potential, and fossil fuel consumption. Athena IE is in designed in accordance with ISO 14040 and 14044 standards. Athena IE also offers an end-of-life module that simulates the energy and disposition of materials post demolition.

Although Athena IE is a valuable tool for conducting LCA in the construction industry, it has some limitations and potential drawbacks. For users not familiar with life cycle methodologies and terminology, the software may pose a steep learning curve. The interface is complex, which could be a barrier to organizations or individuals that may not have the time and resources to fully understand its capabilities, though webinars and other demonstration videos are available. It is also difficult to specify inputs like transportation distances, mobilization vehicles, and other construction activities. Additionally, the customization for regional factors can be a limitation, as the coverage only spans the United States and Canada. Though the impacts associated with these life cycle stages are reported, the methodology behind the calculations is not easily accessible.

***ECOM – Embodied Carbon Estimator***
Embodied Carbon Order of Magnitude (ECOM) is a web-based estimator developed by the Structural Engineering Institute (SEI) that allows users to determine approximate embodied carbon of material products, assembling of framing, or entire structural frame. This tool relies on data sourced from publicly available EPDs. It is important to note that ECOM does not explicitly show variations in impacts within specific materials' EPDs. ECOM prompts users to input total area and materials and returns embodied carbon totals and intensities without distinguishing between life cycle phases.

This is a valuable tool for quick estimations of embodied carbon in structural projects. The interface is easy to comprehend and does not require significant research prior to use. However, users are limited to a small selection of material types and strengths and cannot model life cycle stages beyond material production. Consequently, results may not provide a comprehensive assessment of the total environmental impacts associated with structural projects.

***SimaPro***

SimaPro is a software and web-based tool developed widely used for sustainability reporting, carbon, environmental, social and water footprinting, biodiversity assessments, and sustainable product design. This tool allows users to model LCAs of products, processes, and systems, as well as auxiliary products within a life cycle chain. To build a system, users input process details related to materials, energy, transport, processing, use, and waste management. Uniquely, SimaPro provides waste scenarios that allow users to model end of life stages based on disposal method (e.g., landfill, incineration, or recycling).

SimaPro houses an extensive database of LCI data, such as ecoInvent v3, Agri-footprint, US LCI Database, and Industry data library. Moreover, it incorporates six categories of LCIA methods with five steps — characterization, damage assessment, normalization, weighting, and single score. Of these, only characterization is required; the others are optional steps used to present data in different manners. Users can select their chosen LCI method and LCIA steps to include after a model has been developed. Results are then shown as networks, which only show processes once, or trees, which show processes along with every input. Users can select which indicator or product flow will be represented by the thermometers, produce a Sankey diagram, or analysis diagrams for the different LCIA steps. Furthermore, uncertainty can be quantified based on sensitivity analyses of transportation distances and modes and material origin.

SimaPro is versatile across industries, making it suitable for assessing environmental impacts of products, processes, and systems in diverse contexts. Users can customize models extensively, and the tool provides comprehensive reports and visualizations for effective communication of LCA results. While powerful, SimaPro has drawbacks like cost and complexity. Licensing options may limit collaboration, and its in-depth analysis capabilities may create a steep learning curve.

***EFFC-DFI Carbon Calculator***

The EFFC-DFI Carbon Calculator is an Excel-based tool dedicated to calculating embodied carbon of foundations and ground improvement methods, including compaction, grouting, and soil mixing. The calculator accounts for several emission sources within the embodied carbon calculation including material manufacturing, material transportation, energy consumption, people’s transport, equipment transportation, equipment manufacturing, waste transportation, and waste management.

**Table 1**: Summary table of major characteristics of the carbon calculation tools

| **Tool** | **EC3** | **eTool** | **Impact Estimator for Buildings** | **Embodied Carbon Estimator (ECOM)** | **SimaPro** | **EFFC DFI Carbon Calculator** |
|---|---|---|---|---|---|---|
| **Organization** | Building Transparency | Cerclos | Athena Sustainable Materials Institute | Structural Engineering Institute | Pre Sustainability | EFFC-DFI |
| **Activity Sector** | Building | Building | Building & Pavements | Structural Engineering | Several | Geotechnical Engineering |
| **Geographic Regions** | Global | Global | USA & Canada | North America | Global | Global* |

| | | | | | | |
|---|---|---|---|---|---|---|
| **Standard** | ISO 21930<br>EN 15804 | ISO 14040/44, 27001, 21930<br>EN 15978, 15804<br>PAS 2080 | ISO 21930, 14040/44 | EN15978 | ISO 14040/44 | ISO 14067<br>PAS 2050:2011 |
| **Impact Categories** | GWP** | GWP ** | GWP ** | GWP | GWP ** | GWP |
| **LCA Scope** | A1-A3 | A-C | A1-A4, B4, B6, C1, C2, C4, D | A1-A3 | A-C | A-B, C2 |
| **LCIA Method** | Various | CML | TRACI | CML | Various | Assigned Factors |
| **BIM Plug-In** | ✓ | ✓ | ✓ | × | × | × |
| **Cost** | Free | 600-7,500 USD/yr (based on features) | Free | Free | 2,600-7,275 EUR/yr (based on features) | Free |

*: *Global emission factors for electricity grid; US, France, and UK specific emission factors for materials*

**: *Other impact categories reported*

In the context of deep foundation activities, it is common practice to consider a cradle-to-gate scope, as the use and end-of-life stages typically contribute negligibly to the overall impacts. To determine which activities were primary emission sources (i.e., represent at least 5% of the total footprint for the technique) and secondary emission sources (i.e., represent less than 5% of the total footprint for the technique), 5–10 examples of carbon footprints for each technology were conducted, and sources were categorized and labeled based on their respective contributions to total embodied carbon.

The EFFC-DFI calculator requires a series of inputs for each emission source category. For instance, in material manufacturing, users are prompted to specify material type, quantity, and additional information like cement type and steel shape.

These details enhance the accuracy of embodied carbon estimates, recognizing that emission factors differ based on these aspects. Users can further enhance the assessment by indicating recycled and reused material quantities. For on-site energy use, such as fuel oil and electricity, users must input geographic region, as these emission factors rely on local and national production mix. Additionally, users can account for personal travel and freight transportation to and from the site. Notably, the EFFC-DFI calculator also considers asset depreciation. It factors in the GHG emissions stemming from equipment manufacture, considering the equipment's lifetime and project duration. Waste impacts are limited to transportation, as waste management scenarios tend to vary widely.

It is important to highlight that this tool assigns recommended emission factors from different databases for each input, although users have the option to utilize country specific databases for materials (France, United Kingdom, and United States) and electricity grids, following ISO 14067 and PAS 2050:2011 standards. Moreover, users can create subprojects, allowing them to compute the carbon footprint of specific project segments. These can be consolidated to model the embodied carbon of an entire project. Results can be generated for subprojects, projects, and comparisons between multiple projects. The calculator automatically creates pie and bar charts of results, providing a visual representation of the data.

## COMPARISON BETWEEN TOOLS

To date, the EFFC-DFI Carbon Calculator is the only tool specifically designed to model environmental impacts of geotechnical projects. In contrast, tools like EC3, eTool, and Athena IE primarily target the building sector, while SimaPro offers broader applicability across various industries. While it is possible to adapt these tools for geotechnical projects, doing so requires extensive data manipulation to align inputs with the specific requirements of each calculator. This is especially relevant for material specifications, such as cementitious content, aggregate, sand, bentonite, and water ratio in concrete. The EFFC-DFI Carbon Calculator allows users to specify these inputs, which have significant influence over total embodied carbon. EC3, on the other hand, allows users to specify compressive strength, cement type, water cement ratio, and secondary cementitious material percentages, but impacts are limited to the EPDs available. For some combinations of characteristics, EPDs may exist, thus introducing a barrier to application. In some calculators, like eTool, users can only edit some EPDs, limiting the customization possible. As such, practitioners may be forced to use EPDs that only partially align the desired material specifications. In Athena IE, users can only alter the concrete compressive strength and rebar density.

More comprehensive tools, like SimaPro, allow users to incorporate specific elements, such as aggregates, based on the available LCI datasets, putting the burden on the practitioner correctly manipulate inputs to model different contributions of concrete. A sample calculation was performed to better understand how each tool calculates GWP. This was done for 1 $m^3$ of concrete with compressive strength of 30MPa with 2% steel rebar reinforcement. For ease of comparability, only impacts from life cycle phases A1-A3 were assessed. The results of this can be seen in Table 2. Values from SimaPro are not reported because modeling in this software is limited to paid versions.

**Table 2:** GWP for 1$m^3$ of concrete with 28-day compressive strength of 30 MPa and 2% steel rebar reinforcement as calculated by each tool

| GWP (kg $CO_2$e) | EC3 | eTool | Impact Estimator for Buildings | Embodied Carbon Estimator (ECOM) | SimaPro | EFFC DFI Carbon Calculator |
|---|---|---|---|---|---|---|
| Concrete | 378.9 | 333.0 | - | 365.5 | - | 353.0 |
| Steel Rebar | 202.4 | 398.0 | - | 140.3 | - | 290.4 |
| Total | 581.3 | 731.0 | 615.0 | 505.8 | - | 643.4 |
| ± % Difference from Average | 5.7% | -17.2% | 0.0% | 19.5% | - | -4.5% |

As seen in these results, there are considerable differences in total GWP between the tools. This is likely due to the discrepancies between allowable user inputs as previously discussed. The tabulated value for EC3 is an average of over 32,393 product EPDs with a standard deviation of 24.3%, demonstrated the large variation in impacts reported in this tool. For eTool, dozens of EPDs were available, and the value presented herein is of only one. ECOM only reports one value with little information beyond the compressive strength of concrete. The default amounts of concrete aggregate, sand, water, and bentonite were used in the EFFC-DFI Calculator to calculate GWP. The specificity of this tool is paramount to modeling different materials for geotechnical projects.

In addition to this modeling limitation, the results may not be generated in a manner appropriate for geotechnical projects. Tools that rely on EPDs as the basis for calculating GWP often do not extend their data beyond the material processing stage, excluding on-site activities, which could represent a significant opportunity for emission reduction in geotechnical projects.

This could also be improved in the EFFC-DFI Carbon Calculator, where results are presented in categories like materials, freight, transportation, energy, mobilization and demobilization, assets, and waste. Though users can compare subprojects, it may be beneficial for practitioners to see GWP broken down for each specific activity (e.g., drilling and driving of piles) in an entire project rather than providing a consolidated value for the categories. As evident in the baseline results for various techniques, materials and energy use tend to dominate GWP.

Nevertheless, it is important to consider other contributors throughout the project's life cycle, notably equipment and methods used for installation, which hold the potential for substantial optimization and a reduction in overall environmental impacts.

Another point of comparison is ease of use. Although tools like SimaPro offer more flexibility in modeling processes and scopes, this introduces a further level of complexity. This could add a barrier for new users. In contrast, the EFFC-DFI Carbon Calculator streamlines much of the user activity required in other tools, making it more accessible and efficient to implement. However, this comes with some trade-offs, as users are limited to a predefined set of materials, energy, and transportation options based on the emission factor database.

To further enhance its utility, the EFFC-DFI Carbon Calculator could consider expanding its database to encompass additional input flows, allowing for modeling of more diverse processes and systems. Additionally, increasing standard compatibility would enable the tool to be used for various applications based on clients' specific needs. It is important to note that several video demonstrations and webinars are provided to aid users in navigating and maximizing the tool's potential.

**Conclusions**

A comparative literature review was conducted to assess the current state of practice in embodied carbon calculation tools in civil engineering. Five tools, in addition to the EFFC-DFI Carbon Calculator, were analyzed to understand their scopes, standards and characterization factors, calculation methodologies, and other unique characteristics.

Based on this study, the following conclusions can be made:

- To date, the EFFC-DFI Carbon Calculator is the only tool specifically designed to model the environmental impacts of geotechnical projects, with a focus on deep foundations.
- Numerous tools exist for analysis of the built environment, though they vary in scope and applied methodology.
- eTool, Athena Impact Estimator for Buildings, and SimaPro stand out for their ability to perform comprehensive LCA, as opposed to other that are limited to CF assessments. These tools enable users to evaluate multiple environmental impact categories concurrently, allowing for a more holistic analysis that ensures design changes do not inadvertently shift environmental burdens from one category to another.
- While the EFFC-DFI Carbon Calculator is relatively more user-friendly, its usability could be further improved by supplying instructional tutorials and guides and incorporating BIM plug in compatibility.
- The EFFC-DFI Carbon Calculator could be enhanced by expanding its database to encompass additional input flows. This would broaden the range of applications and adaptability to meet specific project needs.

Ultimately, while these tools facilitate comprehensive environmental studies, their value and accuracy depend on quality of input data and the user's proficiency in understanding the underlying methodologies and assumptions. Therefore, practitioners need to carefully select the most suitable tool tailored to the requirements of their project to guarantee meaningful and reliable results. In the context of geotechnical engineering projects, the EFFC-DFI Carbon Calculator stands out as the most appropriate option. By incorporating the recommendations made herein, this tool could be further enhanced to help identify carbon hotspots and reduction opportunities in an accessible manner.

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