

A parametric tool to quantify the life cycle embodied environmental flows of built assets

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Abstract: The construction and maintenance of buildings and infrastructure assets are the main drivers of raw material extraction and are responsible for significant embodied environmental flows such as energy and water use as well as greenhouse gas emissions. It is critical to empower actors of the built environment with advanced tools to quantify the life cycle environmental performance of different designs to inform design decisions. This paper presents one such parametric tool, EPiC Grasshopper, developed as a plugin for the Rhinoceros 3D and Grasshopper 3D environment. EPiC Grasshopper is a bottom-up parametric tool that operationalises the Environmental Performance in Construction (EPiC) Database of hybrid environmental coefficients for construction materials. The paper presents the architecture of EPiC Grasshopper, verifies its calculations and validates its output by comparing its application to a case study house in Australia to figures from a previous study. Results validate the plugin and show minor variations of the total life cycle embodied energy (-2%) at a whole building level as well as very minor variations in the contribution of each material to the total life cycle embodied energy, as compared to the figures from the previous study (maximum 1.7% of variation). The visualisation of results directly within the Rhinoceros 3D and Grasshopper 3D environment is also showcased. Future research includes demonstrating the parametric aspect of EPiC Grasshopper and developing more advanced functionalities. This will enable actors of the built environment to include life cycle embodied environmental performance directly into their workflows in a streamlined yet advanced manner.

Keywords: EPiC Grasshopper; bottom-up; embodied carbon; model.

1. Introduction

Constructing and maintaining buildings and infrastructure assets is the main driver for raw material extraction, notably of non-metallic minerals (UNEP, 2016). These raw materials need to be processed, manufactured and transported to be incorporated into built assets. Manufacturing processes require

energy and often result in greenhouse gas emissions, due the reliance on fossil fuels. Embodied environmental flows, such as the aforementioned energy and emissions, represent an increasing share of the total life cycle environmental flows of buildings, notably energy (>70%, see Stephan *et al.* (2013)) and greenhouse gas emissions (Röck *et al.*, 2020). As the operational energy efficiency of buildings increases and net zero operational energy buildings emerge, embodied environmental flows can represent up to 100% of the life cycle environmental flows of a building (Stephan and Stephan, 2020).

A range of tools have been developed to quantify the embodied environmental flows of buildings (Hollberg and Ruth, 2016) and to a lesser extent infrastructure assets. These tools vary in terms of scope and functionalities, as reviewed by Hollberg and Ruth (2016). Recently, algorithms to quantify embodied environmental flows have been bundled into plugins for existing 3D software (e.g. Bombyx (Basic *et al.*, 2019), Cardinal LCA (Chen *et al.*, 2021)). This enables designers to capitalise on existing design workflows and parametric approaches while incorporating embodied environmental flows from the onset.

Yet, existing tools tend to be characterised by their reliance on process data which can underestimate embodied environmental flows (energy, water and greenhouse gas emissions) by an average of 50-57% as compared to hybrid figures, and up to 99% for a specific material (Crawford *et al.*, 2021). Furthermore, existing tools do not systematically offer an easy-to-use graphical interface or flexible functionalities. As such, there is a need to develop an open-source, open-access, bottom-up, parametric tool to integrate the quantification of life cycle embodied environmental flows at the early stage of design.

1.1. Aim and scope

The aim of this paper is to introduce EPiC Grasshopper, a parametric plug-in for Grasshopper3D that quantifies the life cycle embodied environmental flows of buildings and infrastructure assets using a hybrid life cycle inventory approach.

This paper focuses solely on describing the functionalities of the tool developed by the authors, its design, verification and its validation using a case study residential building in Melbourne, Australia. EPiC Grasshopper quantifies embodied energy, water and greenhouse gas emissions, the three environmental flows considered in the Environmental Performance in Construction (EPiC) Database, developed by the authors (Crawford *et al.*, 2019b; 2021).

2. Method

2.1. Overall research approach



Figure 11: Overall research approach

Figure 11 depicts the overall research approach followed to develop EPiC Grasshopper. The software functionalities are first determined based on a review of studies on life cycle assessment tools for buildings as well as the scientific literature. These functionalities are implemented into the plugin using the Python programming language. The calculations of the resulting plugin are verified for correctness and the output is validated against manual calculations for a case study house.

2.2. Tool functionalities

In light of existing parametric tools to quantify embodied environmental flows and recommendations from existing literature on the topic, Table 9 presents the core functionalities of EPiC Grasshopper.

Table 9: Core functionalities of EPiC Grasshopper.

Functionality	Objective	Comment
Use of a hybrid life cycle inventory approach in the quantification of embodied environmental flows	Ensure that embodied environmental flows are quantified using comprehensive system boundaries	All existing parametric tools to quantify embodied environmental flows rely on process analysis for their assessment
Simple and intuitive workflow	Enable users to directly and intuitively user EPiC Grasshopper with a mellow learning curve	Existing tools often provided complicated workflows with the need to connect to a database, select materials by layer, or other (e.g. Cardinal LCA).
Simple-to-use user interface with minimum amounts of Grasshopper components	Facilitate user interaction and enable a rapid analysis through a streamline workflow	Most existing tools included multiple components that were hard to differentiate in terms of icons (e.g. Bombyx, Cardinal LCA).
Data visualisation and export from within the tool	Enable a rapid feedback on design decisions and changes to the user and the ability to slice the data in multiple manners	Most existing tools enable basic data visualisation and/or exports with limited capacity for data slicing and detailed exports.
Open-access and open-source database, tool and code	Enable users to access the tool freely and scrutinize its back-end code enabling further development	Only the Bombyx tool is available in open-access and in open-source with an open access database. Yet, the database itself is not transparent in terms of how it was compiled, as compared to the EPiC database.

2.3. Tool design

EPiC Grasshopper is designed around three main principles. Firstly, there is a clear separation of data, back-end code and front-end user interface on Grasshopper3D. The Grasshopper3D components contain the bare minimum of code and act only as input/output components. Each component creates an instance of a class on the back-end, e.g. an EPiC Material Component creates an EPiCMaterial instance. Only EPiCMaterial instances read from the EPiC database (which is a single file) and the data flows from Materials to the Analysis. Secondly, EPiC Grasshopper adopts the nested systems approach described in (Stephan *et al.*, 2022). This helps replicate the physical built environment, with materials nested into

construction assemblies, nested into built assets, which are analysed. Thirdly, the code is written as open-access and open-source. The python code of any Grasshopper3D component is accessible by double-clicking on the component on the Grasshopper3D canvas. The back-end python code is also available openly on Github. Finally, all the detail behind the EPiC Database is available on its website, alongside fully transparent hybrid inventories for each main material in the database.

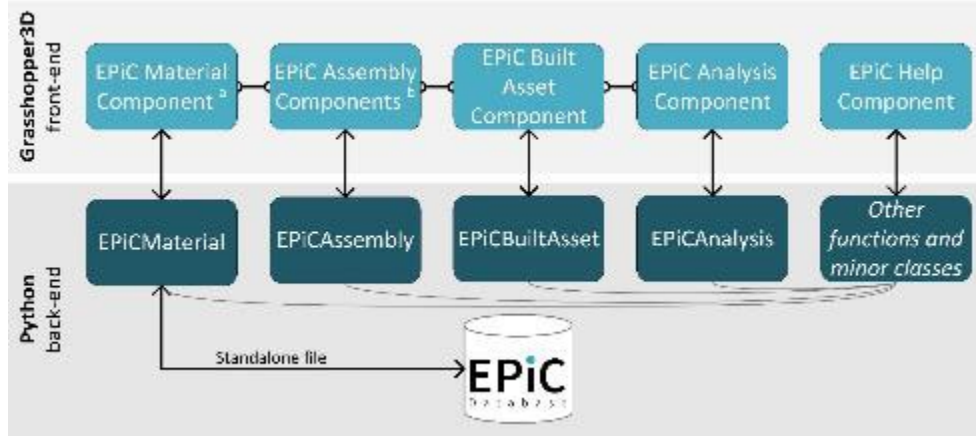


Figure 12: Design of EPiC Grasshopper. Note: ^a EPiC Custom Material enables creating custom materials and is not linked to the EPiC Database. ^b There are four types of Assembly components: EPiC Assembly Unit, EPiC Assembly Linear, EPiC Assembly Surface, and EPiC Assembly Volumetric.

2.4. Quantifying embodied environmental flows

Life cycle embodied environmental flows as quantified as per Equation 1 below. This is done by multiplying the quantity of each material within each assembly by the hybrid coefficient of the material from the EPiC database and by an on-site wastage coefficient. This is repeated for each material replacement, given by dividing the period of analysis by the average service life of material m .

$$LCEF_{an} = \sum_{b=1}^B \sum_{a=1}^A \sum_{m=1}^M (Q_{m,a,b,an} \times WC_m \times FC_m) + \sum_{b=1}^B \sum_{a=1}^A \sum_{m=1}^M \left[\left[\frac{POA_{an}}{SL_m} - 1 \right] \times (Q_{m,a,b,an} \times WC_m \times FC_m) \right] \quad (1)$$

Where:

$LCEF_{an}$ = Life cycle embodied flow of an analysis an (e.g. in GJ for energy); B = Total number of built assets in the analysis; A = Total number of construction assemblies in built asset b ; M = Total number of materials in an assembly a ; $Q_{m,a,b,an}$ = Quantity of material m in assembly a within built asset b , in analysis an (e.g. m^2 of double-glazing (m) in windows (a) in a house (b) being analysed within a neighbourhood (an)); WC_m = On-site wastage coefficient of material m , e.g. 1.05 for concrete 25 MPA; FC_m = Hybrid

embodied flow coefficient of material m , in environmental flow unit (e.g. GJ for energy) per functional unit; POA_{an} = Period of analysis an , in years; and SL_m = Service life of material m , in years.

2.5. Verification

Verification, as part of a software development, consists of ensuring that the mathematical operations of the algorithm are correct. In this paper, we verify variables related to selected geometries in Rhinoceros3D and Grasshopper3D, calculations of material quantities by assembly, calculations of embodied environmental flows at the assembly, built asset and analysis level, data visualisation correctness and data exports. For each step, we used simple test cases where we measured or calculated manually the result and compared that to the output of EPiC Grasshopper. We imposed a relative difference of maximum 0.01%. In addition, where a variable was obtained by a simple arithmetic operation of two other variables (e.g. $c = a \times b$), we assumed that if a and b are verified, then c is also verified.

Based on the above, we successfully verified all variables and outputs of EPiC Grasshopper. In the process, we identified a few issues (notably related to collecting data from Rhinoceros3D geometries) that we resolved to match the verification benchmark.

2.6. Description of case study for validation

In software development, validation consists of measuring if the model provides a realistic enough approximation of reality. Within the context of EPiC grasshopper, validation consisted of comparing the output of EPiC Grasshopper in terms of life cycle embodied environmental flows for a given house to those of an existing study by the authors. This enables a robust comparison of the outputs of EPiC Grasshopper. As infrastructure assets, e.g. roads, are simpler than a house in terms of material composition and geometry, we did not include a case study infrastructure asset in this paper due to space limitations.

Table 10: Case study characteristics.

Characteristic	Value
Period of analysis	60 years
Areas	135.4 m ² net conditioned floor area (NCFA) 9.8 m ² unconditioned utilities (bathroom and laundry) 38.9 m ² unconditioned Garage 36.68 m ² glazing
Roof	Concrete tile attic-type roof with 160 mm fibreglass insulation batts (U-value=0.29 W/(m ² ·K)) and a 60 mm reflective blanket (U-value=0.77 W/(m ² ·K)) Metal deck roof to garage, no insulation
External walls	Brick veneer walls with 90 mm fibreglass insulation batts (U-value=0.5 W/(m ² ·K)) plus single sided reflective foil Single brick walls to garage, no insulation
Internal walls	Plasterboard on stud frame, 90 mm fibreglass insulation batts (U-value=0.5 W/(m ² ·K)) to unconditioned spaces
Floors	Concrete slab on ground, no insulation, tiles in wet areas, carpet in other living spaces. Concrete finish in garage
Windows	Timber framed, clear single glazing

A typical Australian house was chosen for validation because it was previously modelled and studied by the authors (Crawford *et al.*, 2019a) using the EPiC database. This offered a benchmark against which EPiC Grasshopper could be validated. Only embodied energy figures are compared as data for embodied water and greenhouse gas emissions are not available. However, given that the embodied water and greenhouse gas emissions are calculated using the exact same algorithm as embodied energy, and that the hybrid coefficient within the EPiC database are validated, the calculations of embodied water and embodied emissions are also validated. Table 10 presents the main characteristics of the case study house for which Figure 13 depicts the Rhinoceros3D model. It is important to flag that some construction assemblies, such as the driveway, fencing or plumbing were not modelled as part of the validation and are therefore not taken into account.

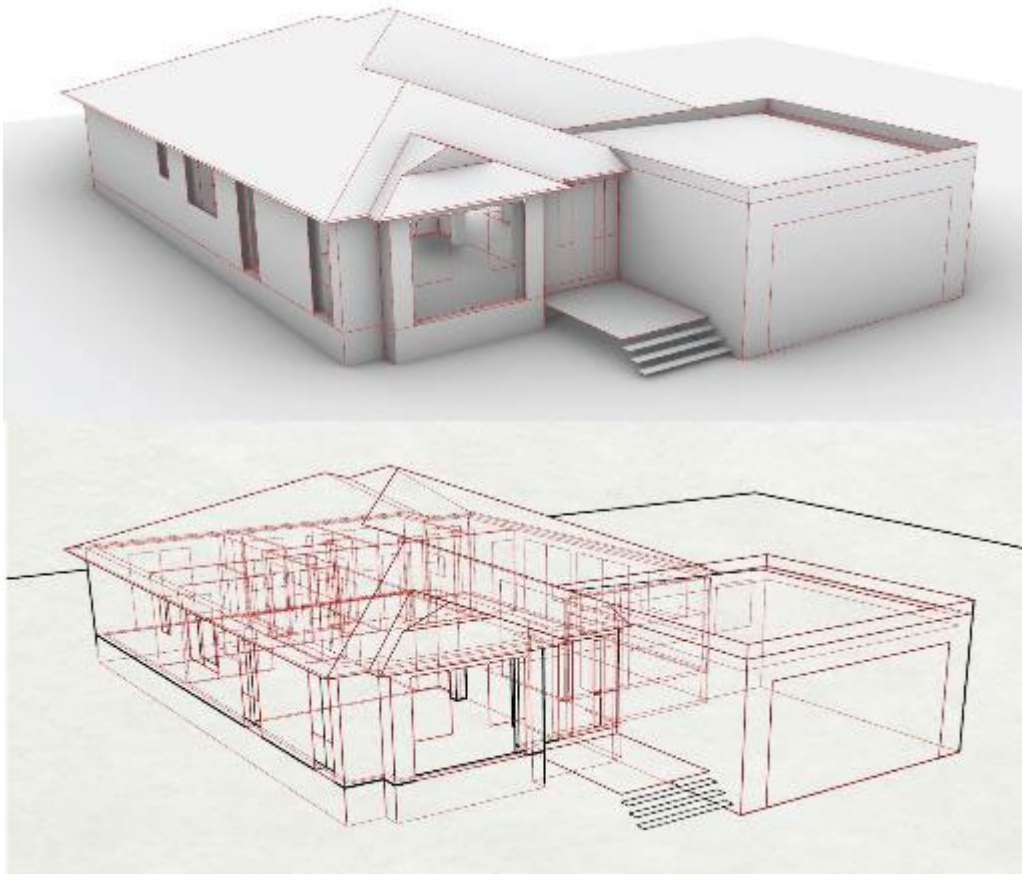


Figure 13: Case study house as modelled in Rhinoceros 3D (top: rendered, bottom: wireframe). Red lines represent geometries selected by EPiC Grasshopper for quantifying embodied environmental flows

3. Results of the validation case study

Results demonstrate insignificant differences in life cycle embodied energy figures at a whole building level with the benchmark case study representing 1,291 GJ and the EPiC Grasshopper results representing 1,267 GJ (-2%). These differences are due to the way geometry is inferred in EPiC Grasshopper, leading to the exclusion of wall intersections, minor approximations in terms of the quantities of finishes, as well as the way materials are modelled per functional unit of construction assembly. This nested modelling approach accumulates approximations, propagates them, and is discussed in Section 4.

Figure 14 compares the percentage contribution of each material to the life cycle embodied energy of the case study house, as calculated with EPiC Grasshopper and manually from Crawford *et al.* (2019a). Results show that the contribution of each material to the total varies slightly between the two models, notably because of the way materials are modelled. For instance, cement mortar is calculated by mass or volume in the bill of quantities but is inferred by the mass of cement per m² of brick wall in EPiC Grasshopper. This mass is in turn modelled based on the thickness of the bricks and the surface ratio of bricks to joints per m². These modelling approximations, and assumptions are behind most shifts in contribution to the total.

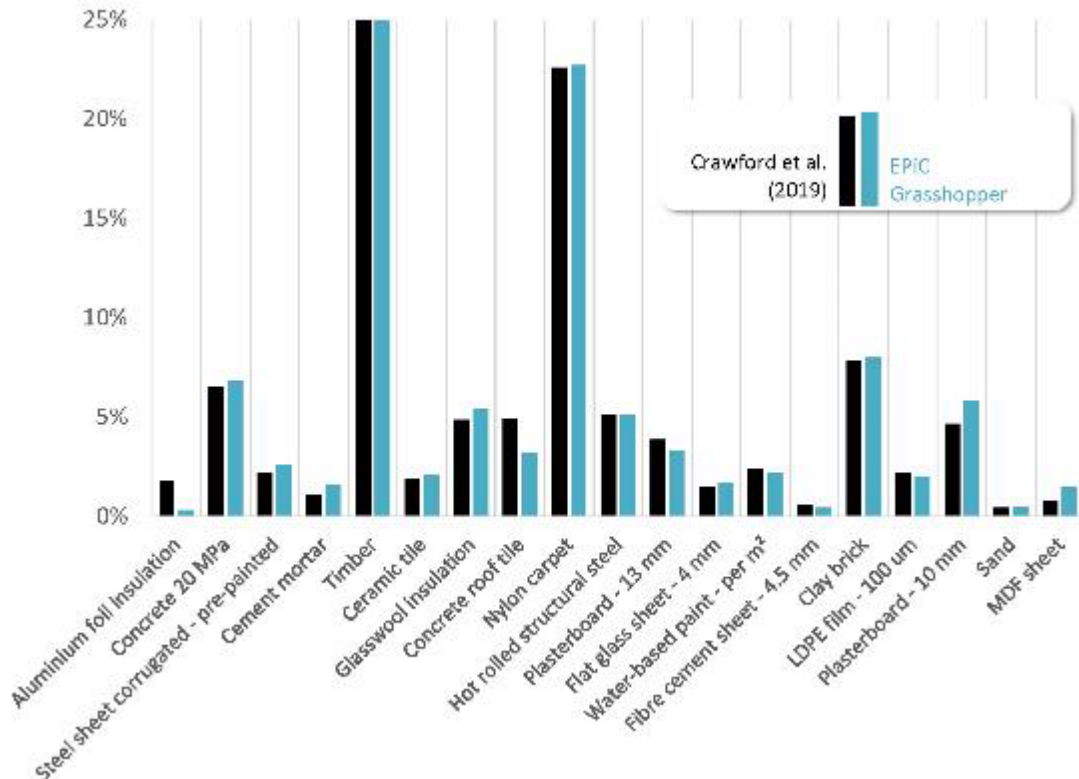


Figure 14: Comparison of the contribution to the life cycle embodied energy of the case study house, by material, using data from Crawford *et al.* (2019) and EPiC Grasshopper

Overall, variations between the contribution of individual materials to the life cycle embodied energy of the case study house were limited to $\pm 2\%$ (using absolute differences we obtain: mean=0.46%, median=0.24%, standard deviation=0.11%, minimum=0.01%, maximum=1.7%). This validates the outputs of EPiC Grasshopper.

Figure 15 showcases one of the ways results can be visualised directly within Rhinoceros3D, using EPiC Grasshopper. The user can either show results at the whole building level, by assembly, by material and by material within each assembly. This provides the user with powerful means to understand the life cycle embodied environmental flows profile of their designs, to compare them and to improve them.

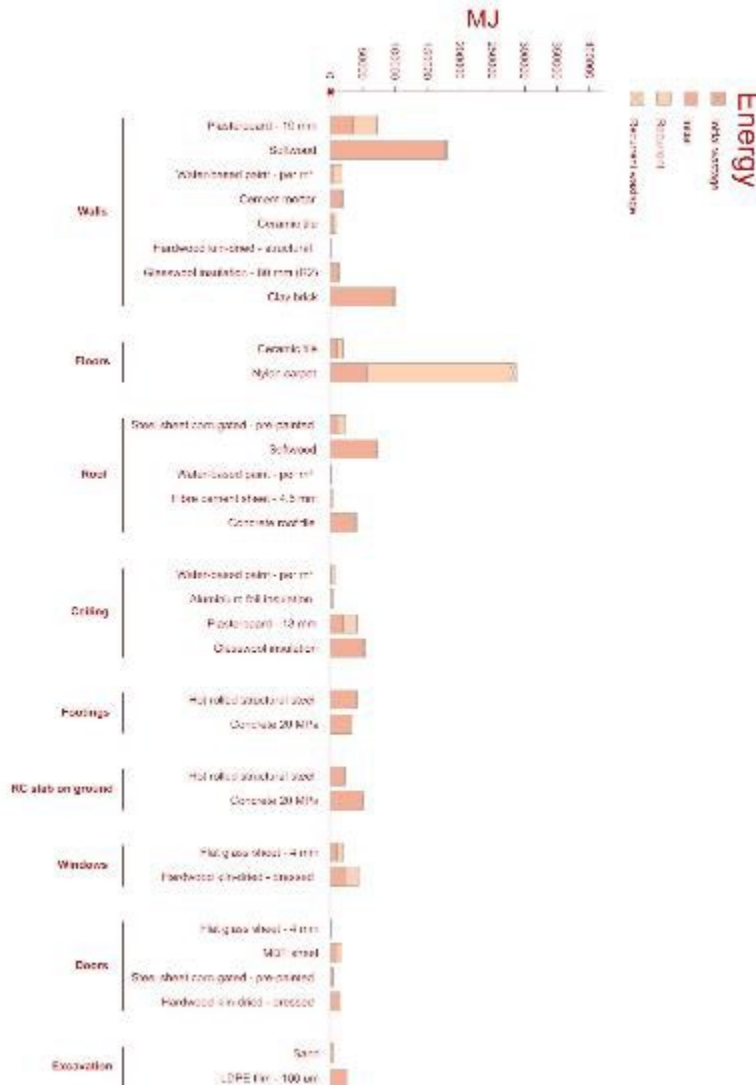


Figure 15: Breakdown of life cycle embodied energy of the case study building directly within Rhinoceros 3D, using EPiC Grasshopper, by material. Note: This figure is a direct screenshot, without any post processing.

4. Discussion and Conclusion

This paper has presented for the first time EPiC Grasshopper, a bottom-up parametric tool, operating within the Rhinoceros 3D and Grasshopper 3D environment, to quantify life cycle embodied environmental flows using the EPiC database. EPiC Grasshopper is the first plugin to operationalise a hybrid life cycle inventory database for construction materials. This study has validated the plugin by comparing its life cycle embodied energy results to those of a benchmark case study, previously studied by the authors. The embodied energy of that case study was calculated manually using the EPiC database. This comparison demonstrates that EPiC Grasshopper produces reliable figures with a minor deviation at a whole building level (-2%) and deviations in the contribution of each material to the total of less than 2% (average of 0.46% variation between the benchmark and the EPiC Grasshopper model).

These slight variations are mostly due to the modelling approach within EPiC Grasshopper. Since EPiC Grasshopper adopts a nested modelling approach, using construction assemblies that include EPiC Materials to model a building, the total quantities of materials within a building might differ from what is reported in a bill of quantities. This is one of the limitations of this approach. However, at the early stage of design, using assemblies to rapidly compare alternatives for geometry and material compositions significantly streamlines the process of exploring different designs.

On top of relying on the consistent, transparent and complete EPiC database (Crawford *et al.*, 2019b; 2021), EPiC Grasshopper provides advanced features that other existing plugins, such as Bombyx (Basic *et al.*, 2019) and Cardinal LCA (Chen *et al.*, 2021), do not cover. These include built-in visualisation of results (see Figure 15), detailed data exports directly from within Grasshopper by exporting data from panels or by relying on the 'export to csv' function of the EPiC Analysis component.

This paper suffers from limitations, as any scientific inquiry. Its scope is limited to validating the figures obtained with EPiC Grasshopper to those from a benchmark. As such, the parametric features of EPiC Grasshopper are not explored and are part of future research. Furthermore, EPiC Grasshopper itself suffers from limitations. To date, it only covers stages A1-A3 and B4 according to European Standard 15978 (2011) and does not include transport from factory to site, nor the construction process. Importantly, EPiC Grasshopper does not yet include a material selector and forces the user to choose a particular material. A more advanced manner would be to filter materials by attributes and propose different alternatives to a user. While the visualisation already enables a powerful analysis within the Rhinoceros/Grasshopper environment, further refinement is needed, notably enabling graphs of embodied environmental flows per year. These limitations will be addressed in future releases of the plugin.

By developing user-friendly tools that enable a parametric approach to the life cycle assessment of buildings and infrastructure assets, within existing design workflows, we aim to empower actors of the built environment to act on the climate and resource emergency. This will help achieve designs of buildings and infrastructure assets that result in net life cycle environmental performance.

Acknowledgements

This research was funded by a seed funding grant from the Faculty of Architecture, Architectural Engineering and Urban Planning, Université Catholique de Louvain, Belgium and by the Belgian Fund for Scientific Research (F.R.S.-FNRS) *Mandat d'Impulsion Scientifique* grant (F.4547.21).

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