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A review of embodied life cycle assessment tools used to support the building design process

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Abstract. Buildings and construction have a significant effect on our natural environment and are major contributors towards global energy use and greenhouse gas emissions. Understanding and improving the environmental performance of buildings is critical to reducing these effects. While there has been some success reducing the operational effects of buildings, the significance of embodied environmental effects is rising. Built environment professionals must be better equipped to understand and integrate these considerations into iterative decision-making processes. Life cycle assessment (LCA) is a commonly used technique to quantify environmental effects across the life cycle of a building, however, it is not widely used by building designers. This is partially due to time constraints, the complexity of conducting detailed LCA, and the limited amount of building information available during early building design. The aim of this review is to identify the breadth of LCA tools available that support the building design process, with a focus on embodied environmental effects. A review of literature is conducted which identifies attributes and properties of these tools including: software attributes, relevance to design phases, features for building design, life cycle coverage, and data attributes. The review finds a lack of consistency between LCA tools, with varying levels of data transparency and completeness, and challenges for incorporating these tools into prevalent design workflows.

1. Introduction

Buildings and cities place a considerable burden on the natural environmental and are major contributors to global greenhouse gas emissions and energy use [1]. To avoid irreversible damage to our natural systems, the building sector must make rapid and wide-ranging transformations to reduce the environmental effects of buildings [2]. Environmental effects can be broadly separated into two categories; firstly, operational environmental effects associated with the ongoing operation of buildings such as heating, cooling, and utility usage. Secondly, embodied environmental effects associated with the manufacturing of construction goods and products, and the construction, replacement, maintenance, and end of life stages of a building. This review focuses on embodied environmental effects, recognising that there is an urgent need to better understand and to rapidly reduce embodied environmental effects such as those resulting from the environmental flows of water, energy, waste, resources and greenhouse gas emissions [3–6]. The significance of embodied environmental flows in buildings is rising in both absolute terms, and relative to operational flows [7]**.** This is due in part to an increasing demand for low energy buildings that often rely on additional materials to achieve energy reductions [8]. Materials with high embodied environmental flows are also likely to further compound current environmental issues by causing upfront spikes [6]. Despite the focus on embodied environmental effects in this review, it is critical that operational and embodied effects are assessed concurrently, and all life cycle effects are included in the building design decision-making process, to avoid shifting the environmental burden.

This review examines life cycle assessment (LCA) tools that support designers to make informed decisions about the environmental performance of a building throughout the design process, with a focus on embodied environmental effects. LCA tools are widely recognised as one of the most comprehensive ways to quantify environmental effects during the building design process [9]. Despite this, they are not widely adopted by building practitioners [8], or are included too late in the design process to have a meaningful contribution [10]. Reasons for lack of uptake among building designers include time constraints (particularly during the early design phase), complexity of conducting detailed LCA, limited building information in early design, and tools not being fit for purpose [11].

The aim of this review is to identify the breadth of LCA tools for building design that support the design process, highlighting limitations and challenges, data variations between LCA tools, features that support the design process, and the appropriateness of these tools across the building design phases.

2. Method

This review focuses on specialist LCA tools for building design and excludes generic LCA tools such as Gabi and Simapro. In the context of building design, LCA can be conducted for structural/design optimisation, certification, research and education, benchmarking, to support the design process, and as a requirement of the building approval process. The primary audience for these specialist LCA tools includes architects, but also construction professionals, developers, homeowners, and other stakeholders who are actively involved in the building design process. Tools are available across various platforms including web-based platforms, spreadsheets, standalone assessment programs, building information modelling-LCA (BIM-LCA), and LCA directly integrated into 3D design programs.

Due to the mixture of stakeholders, platforms and purposes, it is extremely difficult to directly compare LCA tools [12]. The intention of the review is therefore to identify the breadth of LCA tools available for the building designer; not to provide an exhaustive list of available tools, or to test/rank tools in terms of suitability. Each of the selected LCA tools are assessed on software attributes, coverage of life cycle stages, applicability to the design phases, features for building design, and data attributes. This is achieved through a review of academic literature, grey literature and software documentation. User tests are not conducted; therefore, further research is needed for verification of results and examination of individual tools. The inclusion criteria are that tools must have been updated since 2017, are designed to support the building design process, and include embodied environmental flows in their assessment. Sampling includes government, academia, and commercial software; a representation of free, open-source and closed-source options; and a selection of BIM-LCA, parametric, web-based, and standalone software. EPiC Grasshopper and Totem are included as the authors have detailed information regarding these tools, although comparable parametric tools and government alternatives are available.

2.1. *Software attributes*

Key attributes of the selected LCA tools are collated from software documentation. This includes publisher details, country of publication, last update, platform, and software type. The software type is broadly categorised into open-source, closed-source freeware, closed-source commercial, and closed-source government software. The licencing type is considered important as there are a lack of open-source LCA tools available for building designers [13]. Pauliuk et al. argue that increased availability of open-source LCA software encourages transparent and higher-quality results [14].

2.2. *Life cycle stages*

A review of software documentation is conducted to determine the LCA method used, and the reported coverage of life cycle stages according to the European standard EN 15978:2011.

2.3. Building design phases
For the purposes of this review, the building design work plan stages are simplified into two distinct phases: *early design*, and *detailed design*. These align with the 7 stages of the RIBA Plan of work: 0. strategic definition, 1. preparation and briefing, 2. concept design, 3. spatial coordination, 4. technical design, 5. manufacturing and construction, 6. handover, and 7. use [15]. Early design covers stages zero to two, and detailed design covers stages three to five, with the recognition that minor design changes can still be made during construction. Post construction stages six and seven are excluded.

During early design, the effort required to achieve reductions in embodied environmental flows is significantly less than during the later design stages. Early design also poses some unique challenges, as there are high levels of uncertainty, and building information required by many LCA workflows is often lacking [11]**.** A simplified LCA approach can be used to overcome these issues [16], however, over simplification in the absence of data can lead to results not being representative of a building's final environmental performance [17]. From detailed design onwards, additional building information is available allowing for a more reliable/complete estimation of environmental flows. There is also typically less opportunity for major design changes, and while LCA results can help inform structural optimisation and material considerations, building massing studies, orientation, floor area, and other fundamental decisions have often already been finalised.

A review of software documentation and literature establishes if the selected LCA tools are intended for use in early design and detailed design, although does not assess their suitability for these phases.

2.4. Features for building design
Not all specialist LCA tools are compatible with the building design process, and many tools are targeted specifically for use by LCA experts rather than building designers [11]. There is a risk of tools being overly technical, time-consuming, cost-prohibitive and not adequately integrated into the design process [11]**.** To ensure uptake of LCA in building design, tools should be easily accessible and integrate with existing workflows, including CAD and 3D modelling programs with results that can be quickly generated and easily interpreted by the designer [11]. In recognition that LCA results can be complicated and difficult to interpret, Hollberg *et al.* (2021) provide recommendations on how LCA tools could be made more accessible, for a wide range of stakeholders, by improving LCA visualisations and interactive dashboards [18]. In addition to this, researchers have identified key features of LCA tools that can enhance the interpretation of assessment results and support the decision-making process for building design. These include: integration with 3D software [11], linkage to certification/benchmarks [11,18], design comparison [11,12,18], hotspot analysis [12,18], optimisation [11,12], temporal distribution [18], and sensitivity/uncertainty analysis [11,12,18].

This review establishes the presence of these features in the selected LCA tools through a review of academic literature and user documentation. Linkage to benchmarks and certification is included with the recognition that continued advancements to policy, building regulations, certification schemes and benchmarks help to incentivise, legitimise, and validate the inclusion of environmental considerations in the building design process [19] and can help address the lack of uptake of LCA tools among practitioners. Hotspot analysis refers to the aggregation of assessment results, enabling designers to identify areas for potential improvement. Aggregation can be at the level of building elements, materials, or life cycle stages. Optimisation refers to multi-objective optimisation using genetic algorithms (or similar). Temporal distribution refers to the graphical representation of yearly environmental flows across the life cycle of a building. Uncertainty analysis focuses primarily on data uncertainty (see section 2.6), rather than uncertainty related to user inputs. Analysing data uncertainty can assist the designer in understanding the potential effect of these uncertainties on assessment results [20].

2.5. Integration of LCA throughout the building design process
Many standalone LCA tools lack the flexibility to work across all stages of the building design process [21]. Parametric LCA workflows offer some solutions, particularly regarding optimisation and integration in early design [22]. These approaches directly integrate into 3D and CAD software and

enable real-time assessment of environmental performance based on changes to input geometry and other variables. Hollberg and Ruth (2016) explain how user efforts can be minimised using a parametric approach, demonstrated through a multi-residential and retrofit case study [23]. Parametric design does have its limitations, not least of which is the relatively low uptake among building designers, and limited number of parametric LCA tools available [10], many of which require specialist software expertise.

BIM-LCA is another workflow that enables designers to incorporate LCA considerations throughout the building design process. It also provides a platform to engage with consultants and engineers from the early design stages. Hollberg, Genova and Habert (2020) establish that it is possible to integrate BIM-LCA throughout the building design process, noting some limitations, and indicating that results can be misleading in the early design phase where a simplified LCA is used [24]. Due to a high level of complexity, these workflows are not always viable for smaller projects or for early design [23].

For this review, a selection of BIM-LCA, parametric, standalone, and web-based LCA tools are assessed, to compare features and attributes between these approaches.

2.6. LCA environmental data

The reliability of LCA findings is determined not only by user inputs, but also underlying environmental data, typically taken from life cycle inventory (LCI) databases that quantify embodied environmental flows for construction materials and processes. To ensure the success of LCA studies, selected databases should be comprehensive and up to date [25]. The collation of LCI data is an extensive process and data must be collected for individual geographical regions for it to be as representative as possible, which makes updating data very challenging and time consuming [7]. Due to this, there is a lack of available data for many countries. Existing databases also vary in compilation methodologies, geographical and temporal attributes, system boundaries, and underlying data assumptions [20]. Discrepancies in these data can dramatically alter LCA results [26], and are likely to influence design decisions [27], although more research is needed to understand this relationship. Increased data transparency can assist researchers and practitioners in identifying errors and discrepancies [20]. A lack of transparency can occur when there is a low resolution of data, or data are protected by restrictive licencing that does not allow detailed interrogation of environmental flows [28].

LCI databases are compiled using three primary methods: process analysis, environmentally extended input-output (EEIO) analysis, and hybrid analysis. The process analysis approach is generally considered the most reliable and uses detailed manufacturing information to estimate environmental flows for processes and materials in the supply chain [29]. EEIO analysis is typically the most comprehensive in terms of system boundaries and uses top-down economic data supplemented with environmental data to estimate environmental flows based on the cost of a product produced by a specific economic sector [29]. Hybrid analysis combines process and EEIO data to capitalise on the high reliability of process analysis and the comprehensiveness of EEIO analysis. Details and limitations of these approaches are further explained by Crawford, Bontinck and Stephan (2018) [29]**.** To demonstrate the effect of using different LCI methods, Crawford, Stephan and Prideaux (2019) evaluated the life cycle energy of a residential dwelling in Melbourne, Australia using both hybrid and process-based data, showing that the use of hybrid data raised the share of embodied energy from 19% to 39% over the building life cycle [30].

Another type of process-based data are environmental product declarations (EPDs). These provide independently verified, standardised environmental information for specific construction products, rather than the generic versions of materials that are often represented in LCI databases. EPDs are becoming more widely used and recognised among building designers. The consistency of data used for EPDs is improving, supported by the development of various schemes and regulations, although there remains a high level of variability at the product level when comparing life cycle effects [31]. In addition to this, it is not always apparent how building designers should incorporate information from EPDs into LCA, as variations between databases of generic materials and EPDs can be significant [32], and direct comparisons between products is not always possible or reliable.

The selected LCA tools are assessed on their data attributes, including underlying LCI databases and methods used, the geographical specificity of these data, and associated licence agreements. They are also assessed on the inclusion of EPDs and ability to accept custom data from the user.

3. Results

LCA tools selected for this review are broadly classified into three categories: those with a focus on reporting and certification (Totem), those designed to support the building design process (EPiC Grasshopper), and a mixture of both (Athena Impact Estimator for Buildings, One Click LCA, and Tally). Full results are recorded in Table 1.

Table 1. Life cycle assessment tools for building design

		Athena Impact Estimator for Buildings [a]	One Click LCA [b]	EPiC Grasshopper [c]	Totem [d]	Tally [e]
Software attributes	Last update	2020	2022	2022	2022	2022
	Platform	Standalone	Web based/ plugins	Grasshopper plugin	Web-based	Revit® plugin
	Cost	Free	Paid/paid*	Free*	Free	Paid*
	Software type	Closed-source freeware	Closed-source commercial	Open-source freeware	Closed-source government	Closed-source commercial
Design Phases	Early design	X	X	X	X	X
	Detailed design	X	X	X	X	X
Features for building design	3D/CAD integration	–	X	X	–	X
	Certification/benchmarks	p	X	–	X	p
	Design comparison	X	X	X	X	X
	Hotspot analysis	X	X	X	X	X
	Optimisation	–	O	O	–	O
	Temporal distribution	–	–	–	–	–
	Uncertainty analysis	p	–	p	p	–
Life cycle stages	Stages includes in life cycle assessment	A1-A5 B2p,B4, B6 C1,C2,C4 D	A1-A5 B1-B7 C1-C4 D	A1-A3 B2 p,B4	A1-A5 B2,B4,B6 C1-C4	A1-A5 B2-B6 C2-C4 D
Data attributes	Database	Athena database	Varies	EPiC AU	Ecoinvent 3.6/ EPDs	Gabi
	Last update	2018	2022/varies	2019	2019/2022	2018
	Methodology	Process	Varies	Hybrid	Process	Process
	Geographical specificity	USA/Canada	Global	Australia	Belgium	USA
	Licence	Licenced	Varies	Open access	Licenced	Licenced
	Custom data allowed	p	p	X	p	p
	EPD selection available	X	X	–	X	X

[a] Athena Sustainable Materials Institute, Canada. Available from: www.calculatelca.com
[b] Bionova Ltd., Finland. Available from: www.oneclicklca.com
[c] UC Louvain & The University of Melbourne, Australia. Available from: www.epicdatabase.com.au
[d] OVAM, SPW & Brussels Environment, Belgium. Available from: www.totem-building.be
[e] Building Transparency, USA. Available from: www.buildingtransparency.org
X – Full functionality
O – Can be achieved with the use of plugins
* – Requires purchase of parent software package
[p] Partial integration OR user request required

3.1. Software attributes and features

A mix of commercial, government and research tools are represented in the results; this includes paid, freeware and open-source software. Features for building design were difficult to assess with complete reliability, due to the variety of reporting approaches between tools, and gaps in documentation. While the assessed LCA tools could all be reportedly used during the early design and detailed design phases, there were noticeable gaps in features, such as integration with 3D/CAD software, optimisation, linkages with certification/benchmarks, temporal distribution, and uncertainty analysis. 3D/CAD integration was only possible with Tally, One Click LCA and EPiC Grasshopper. Optimisation was not provided 'out of the box' for any of the LCA tools, although multi-objective optimisation could be achieved through additional functionality and plugins available in Grasshopper and Revit. Design comparison and hotspot identification were available for all the assessed LCA tools, with hotspot identification provided at the element level (all), and for life cycle stages (all except EPiC Grasshopper).

3.2. Data attributes and LCA stages

Each LCA tool provided different life cycle coverage for the assessments, and while some tools had lengthy documentation detailing system boundaries, others only provided brief statements about the life cycle stages covered. All LCI tools mentioned data uncertainty in their documentation; One Click LCA/Tally provided an explanation of the data and methods used, Totem/Athena Impact Estimator for Buildings provided a detailed manual of the data and methods used, but only EPiC Grasshopper provided full access to the underlying LCI database and assumptions made for each of the datasets. All LCI databases had been updated in the last 5 years, and the majority of databases used a process-based approach, except for EPiC Grasshopper which used a hybrid approach, and One Click LCA, which used a variety of data sources, each with differing methodologies, geographical and temporal specificity. The data were typically limited to a small geographical region, apart from One Click LCA, which offered global coverage through a broad collection of data sources. EPiC Grasshopper accepted custom data, while others only accepted custom data on request, or through the lodgement of an approved EPD. All tools except for EPiC Grasshopper included a selection of EPDs for use in LCA.

4. Discussion and conclusion

There is a wide range of LCA tools available to quantify the embodied environmental effects of buildings. Despite this, these tools are not commonly used by building designers to inform design decisions and are only rarely used in the early design stage when there is the greatest opportunity to influence the environmental performance of a building. While some advancements have been made towards the integration of LCA tools throughout the design process, noticeably with improved BIM-LCA and parametric workflows, considerable progress still needs to be made.

Results from this review highlight two major barriers for the integration of LCA tools in the building design process. Firstly, there are substantial challenges with the provision of data for LCA [7], particularly regarding data consistency, transparency and geographical coverage. While data are improving, with an increasing number of LCI databases and construction material EPDs available, many countries are lacking data, and there are variations in methodologies, completeness, and transparency between databases. This is demonstrated by the lack of data consistency between LCA tools assessed in this review. Data variations are likely to directly impact design decisions [27], and more research is needed to better understand how these data variations, including those between generic data and specific data found in EPDs, might influence design decisions and a building's final environmental performance.

Secondly, LCA tools must be better aligned with the building design process and associated workflows [11]. This is a complex problem, as the building design process is not standardised. While some building designers utilise complex digital workflows, other designers prefer analogue design methods. Architecture firms vary in size and purpose, as do the type and scale of projects, client requirements, preferred design tools, consultants, and other factors. In addition to this, LCA tools must balance the need for detailed and robust assessment, while also supporting rapid and iterative decision-making at each stage of the design process. All LCA tools reviewed in this paper were theoretically usable for early design and detailed design stages, however, there were noticeable gaps in design-supportive features, such as integration with 3D/CAD software, linkage with certification/benchmarks, optimisation, temporal distribution, and uncertainty analysis. Without these features, conducting assessments and the interpretation of results are likely to be time consuming and challenging.

To overcome these challenges and to streamline LCA in the building design process, further tool development and research is required. LCA tools must be versatile and flexible enough to integrate with building design workflows, provide decision-supportive results that can be quickly and easily interpreted by designers, with context specific environmental data that is consistent, transparent, and complete.

5. References

[1] IPCC. Climate Change 2022: Mitigation of Climate Change [Internet]. 2022 [cited 2022 Apr 5]. Available from: https://www.ipcc.ch/report/ar6/wg3/

[2] WGBC. Advancing Net Zero Status Report 2021 [Internet]. 2021 [cited 2022 Apr 14]. Available from: www.worldgbc.org/advancing-net-zero-status-report-2021

[3] Ajayi SO, Oyedele LO, Ilori OM. Changing significance of embodied energy: A comparative study of material specifications and building energy sources. J Build Eng. 2019;23(May 2019):324–33. Available from: https://doi.org/10.1016/j.jobe.2019.02.008

[4] Chastas P, Theodosiou T, Bikas D. Embodied energy in residential buildings-towards the nearly zero energy building: A literature review. Build Environ. 2016;105:267–82. Available from: https://doi.org/10.1016/j.buildenv.2016.05.040

[5] Mirabella N, Allacker K. The Assessment of Urban Environmental Impacts through the City Environmental Footprint: Methodological Framework and First Approach to the Built Environment. In: Procedia CIRP. Elsevier B.V.; 2018. p. 83–8.

[6] Röck M, Saade MRM, Balouktsi M, Rasmussen FN, Birgisdottir H, Frischknecht R, et al. Embodied GHG emissions of buildings – The hidden challenge for effective climate change mitigation. Appl Energy. 2020;258:114107. Available from: https://doi.org/10.1016/j.apenergy.2019.114107

[7] Röck M, Sørensen A, Steinmann J, Lynge K, Horup LH, Tozan B, et al. Towards embodied carbon benchmarks for buildings in Europe - #1 Facing the data challenge. 2022; Available from: https://zenodo.org/record/6120522

[8] Anand CK, Amor B. Recent developments, future challenges and new research directions in LCA of buildings: A critical review. Renew Sustain Energy Rev. 2017;67:408–16.

[9] Jusselme T, Rey E, Andersen M. Surveying the environmental life-cycle performance assessments: Practice and context at early building design stages. Sustain Cities Soc. 2020 Jan 1;52:101879.

[10] Roberts M, Allen S, Coley D. Life cycle assessment in the building design process – A systematic literature review. Build Environ. 2020 Nov 1;185:107274.

[11] Meex E, Hollberg A, Knapen E, Hildebrand L, Verbeeck G. Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design. Build Environ. 2018;133:228–36. Available from: https://doi.org/10.1016/j.buildenv.2018.02.016

[12] Haapio A, Viitaniemi P. A critical review of building environmental assessment tools. Environ Impact Assess Rev. 2008 Oct 1;28(7):469–82.

[13] Ekundayo D, Babatunde SO, Ekundayo A, Perera S, Udeaja C. Life cycle carbon emissions and comparative evaluation of selected open source UK embodied carbon counting tools. Constr Econ Build. 2019 Dec 1;19(2):220–42.

[14] Pauliuk S, Majeau-Bettez G, Mutel CL, Steubing B, Stadler K. Lifting Industrial Ecology Modeling to a New Level of Quality and Transparency: A Call for More Transparent Publications and a Collaborative Open Source Software Framework. J Ind Ecol. 2015;19(6):937–49. Available from: http://dx.doi.org/10.1111/jiec.12316

[15] RIBA. RIBA Plan of Work [Internet]. 2020 [cited 2022 Mar 20]. Available from:

www.architecture.com/knowledge-and-resources/resources-landing-page/riba-plan-of-work
[16] Marsh R. LCA profiles for building components: Strategies for the early design process. Build Res Inf. 2016;44(4):358–75. Available from: https://doi.org/10.1080/09613218.2016.1102013
[17] Bueno C, Pereira LM, Fabricio MM. Life cycle assessment and environmental-based choices at the early design stages: an application using building information modelling. Archit Eng Des Manag. 2018;14(5):332–46.
[18] Hollberg A, Kiss B, Röck M, Soust-Verdaguer B, Wiberg AH, Lasvaux S, et al. Review of visualising LCA results in the design process of buildings. Build Environ. 2021 Mar 1;190:107530.
[19] Trigaux D, Allacker K, Debacker W. Environmental benchmarks for buildings: a critical literature review. Int J Life Cycle Assess. 2021;26(1):1–21. Available from: https://doi.org/10.1007/s11367-020-01840-7
[20] Crawford RH, Stephan A, Prideaux F. The EPiC database: Hybrid embodied environmental flow coefficients for construction materials. Resour Conserv Recycl. 2022 May;106058.
[21] Ariyaratne CI, Moncaster AM. Stand-alone Calculation Tools are not the Answer to Embodied Carbon Assessment. Energy Procedia. 2014 Jan 1;62:150–9.
[22] Feng K, Lu W, Wang Y. Assessing environmental performance in early building design stage: An integrated parametric design and machine learning method. Sustain Cities Soc. 2019 Oct 1;50:101596.
[23] Hollberg A, Ruth J. LCA in architectural design—a parametric approach. Int J Life Cycle Assess 2016 217. 2016;21(7):943–60. Available from: https://doi.org/10.1007/s11367-016-1065-1
[24] Hollberg A, Genova G, Habert G. Evaluation of BIM-based LCA results for building design. Autom Constr. 2020 Jan 1;109:102972.
[25] Karunaratne S, Dharmarathna D. A review of comprehensiveness, user-friendliness, and contribution for sustainable design of whole building environmental life cycle assessment software tools. Build Environ. 2022 Mar 15;212:108784.
[26] Esram NW, Hu M. Knowledge infrastructure: The critical path to advance embodied carbon buildings codes. 2021. Available from: www.aceee.org/sites/default/files/pdfs/Embodied Carbon in Buildings 12-2-21 final.pdf
[27] Dixit MK, Fernández-Solís JL, Lavy S, Culp CH. Need for an embodied energy measurement protocol for buildings: A review paper. Renew Sustain Energy Rev. 2012 Aug;16(6):3730–43.
[28] De Wolf C, Simonen K, Ochsendorf J. Initiatives to Report and Reduce Embodied Carbon in North American Buildings. Embodied Carbon Build Meas Manag Mitig. 2018;463–82. Available from: https://doi.org/10.1007/978-3-319-72796-7_21
[29] Crawford RH, Bontinck PA, Stephan A, Wiedmann T, Yu M. Hybrid life cycle inventory methods – A review. Vol. 172, Journal of Cleaner Production. 2018. p. 1273–88. Available from: https://doi.org/10.1016/j.jclepro.2017.10.176
[30] Crawford RH, Stephan A, Prideaux F. A comprehensive database of environmental flow coefficients for construction materials: Closing the loop in environmental design. Vols. 2019-Novem, Proceedings of the International Conference of Architectural Science Association. 2019. p. 353–62. Available from: http://hdl.handle.net/11343/233408
[31] Passer A, Lasvaux S, Allacker K, De Lathauwer D, Spirinckx C, Wittstock B, et al. Environmental product declarations entering the building sector: critical reflections based on 5 to 10 years experience in different European countries. Int J Life Cycle Assess. 2015;20(9):1199–212. Available from: https://doi.org/10.1007/s11367-015-0926-3
[32] Lasvaux S, Habert G, Peuportier B, Chevalier J. Comparison of generic and product-specific Life Cycle Assessment databases: application to construction materials used in building LCA studies. Int J Life Cycle Assess. 2015;20(11):1473–90.