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Full length article

Whole life cycle environmental impact assessment of buildings: Developing software tool and database support for the EU framework Level(s)

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ABSTRACT

The European Commission has published a framework on the environmental sustainability of buildings, called Level(s), a set of indicators addressing the resource efficiency and environmental impact of buildings. This framework is now a key element of European initiatives to develop a circular economy and aims to address whole life cycle greenhouse gas (GHG) emissions and to drive a renovation wave for existing buildings. Analysis of the whole life cycle environmental impact of buildings, with an emphasis on GHG emissions, is also the focus of initiatives in several EU Member States. To support users, Level(s) was accompanied by a list of Life Cycle Assessment (LCA) software tools and databases for calculating such indicators. A need was identified for practical, user-orientated information about the scope, consistency, cost, and accessibility of LCA software tools and databases. Therefore, a list of LCA tools and databases used in Europe for the assessment of the whole life cycle environmental impacts of buildings was compiled in 2017–2020 and their characteristics analysed based on a set of criteria. This paper describes the policy context of Level(s) and discusses criteria that can be used for the characterisation of LCA software tools and databases from the list compiled for Level(s). The methods included a literature review, surveys/interviews, and the co-creation of criteria for the categorization of tools and databases. The results are criteria including construction-specificity, system boundaries & scope, indicators, modelling granularity, methodological adherence to Level(s) and EN standards, data quality, transparency and verification, accessibility, data exchange and interoperability, cost, training and support, as well as additional information. By providing greater visibility regarding the features of tools and databases, this paper contributes to the mainstream use of Level(s) and also to the implementation of key EU policy initiatives aimed at enhancing the environmental sustainability of the built environment, such as the EU Renovation Wave, the New European Bauhaus, and the EU taxonomy for sustainable activities.

1. Introduction

The latest IPCC report stated that buildings need to decarbonize by 2050 to achieve the necessary carbon emission reduction targets [(Intergovernmental Panel on Climate Change (IPCC) ,2022; International Energy Agency (IEA) ,2021)]. Worldwide, the building and construction sector is responsible for more than a third of final energy use and total direct and indirect energy-related emissions – calculated in terms of equivalents of CO_2 emissions (CO_2 eq) – as found in a report coordinated by the United Nations Environmental Programme (GlobalABC, IEA, and UNEP ,2020; WorldGBC and Ramboll 2019). The building and construction sector in Europe is estimated to account for 50% of all materials used (Herczeg et al., 2014) and generates more than one third of all waste (Eurostat 2021). Globally, the challenge for all stakeholders of the built environment is to respond to building needs while reducing environmental impact. The International Energy Agency (IEA) also states that the building sector needs to be "zero-carbon" by 2050 to meet the targets necessary to check the global mean temperature rise at 1.5 °C and avoid extreme climate catastrophes (IEA 2021). This is reflected in the Communication of the European Commission (EC) on the European Green Deal (EC 2019), which highlights that significant amounts of natural resources (e.g., energy sources, water, construction materials) are used in the life cycle of buildings, i.e., from the extraction, processing and transport of materials, to the construction, operation,

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maintenance, renovation, and demolition stages. There is a need for harmonized Life Cycle Assessment (LCA) tools and databases for buildings in order to monitor their whole life cycle (WLC) environmental impact performance transparently.

1.1. EU initiatives to implement LCA

Across the EU, a range of national initiatives have sought to establish methodological, data, and reporting frameworks for the whole life cycle performance. The Joint Research Centre (JRC) of the EC (Dodd et al., 2016) and the Buildings Performance Institute Europe (BPIE 2021) have documented various European countries' initiatives to integrate WLC Global Warming Potential (GWP) and LCA requirements:

- Public procurement: Germany, the UK, and Switzerland have introduced LCA requirements for public buildings and projects (BPIE 2021).
- Current building regulations: Denmark, the Netherlands, and France all have whole life cycle GHG emissions accounting and reporting requirements and various means of mitigating carbon impact (BPIE 2021).
- Future building regulations: Finland (by 2025) and Sweden (by 2027) plan to introduce CO_2 eq limits for new buildings based on whole life cycle GHG emissions accounting (BPIE 2021).

On a Member State level, multi-project pilots of WLC GWP and LCA methodologies have been carried out by national institutions – such as the Centre Scientifique et Technique du Bâtiment (CSTB) for the French government (CSTB 2021; ADEME 2017), the German Sustainable Building Council (Deutsche Gesellschaft für Nachhaltiges Bauen [DGNB]) (DGNB 2017), and the Environment Ministry in Finland – to support the development of building regulations (Häkkinen, 2012).

The governments of Belgium, France, the Netherlands, and Denmark have supported the development by research institutions of bespoke LCA tools and supporting databases for use by building professionals – namely TOTEM in Belgium (Totem 2021), ELODIE/INIES in France (HQE 2012; Lasvaux, 2014), Nationale Milieudatabase in the Netherlands (Milieudatabase 2021), and LCAByg in Denmark (Birgisdottir and Rasmussen, 2019). These different initiatives have sought to help users (e.g., DGNB) by providing streamlined calculation tools and datasets complemented by training.

Integrated LCA and Life Cycle Costing (LCC) tools in Denmark have been studied for their integration into Level(s) (Kanafani et al., 2019). National building assessment schemes have also developed tools including, amongst others, the DGNB simplified method and free tool, and the Haute Qualité Environnementale (HQE)/French national tool (ELODIE) and EPD database (INIES) (DGNB 2017; HQE 2012; Lasvaux, 2014). The BREEAM assessment scheme includes a screening of LCA tools for their suitability and approval (BREEAM 2021).

Finally, public-private initiatives have also been taken forward in Member States and run across multiple countries. OneClick LCA published a report funded, in part, by the Finnish government that reviews 216 environmental sustainability certifications and regulations across 26 countries (OneClick LCA Ltd 2018). The report discusses which systems focus on embodied carbon and highlights policies and tools to help capture embodied carbon impact (OneClick LCA Ltd 2018).

These activities all reflect the status of the market and adoption of such methods across the EU. This is also reflected in the review conducted of the state of the art in 2019–2020 by the World Green Building Council (WGBC) (WorldGBC 2020). The subsequent work of the Buildings Performance Institute Europe (BPIE 2021) also picked up on this assessment and the need to mainstream and harmonize WLC GHG emissions methods and support. Indeed, initiatives arose on a national level, as described above. The abovementioned EU initiatives have sought to mainstream WLC assessment and make it more accessible to practitioners by addressing barriers. For example, DGNB sought to make their LCA criteria more accessible in later versions. This paper analyses how consensus can be reached on harmonising these criteria.

1.2. The concept, inception, and use of Level(s)

To tackle environmental challenges posed by buildings and construction materials, the EC defined the concept of Level(s) in its Communication on resource efficiency opportunities in the building sector in 2014 (EC 2014). Following its first development phase during 2015–2017, Level(s) was tested in more than 100 building projects throughout the EU and methodologically refined (Dodd et al., 2017; Dodd et al., 2017; EC 2021).

Level(s) responds to the need for a common language for the environmental impact of buildings by defining a core set of indicators that can be used to measure and manage the performance of residential and office buildings across Europe. The objective of Level(s) is to mainstream the environmental considerations of professionals who play a role at different stages of building projects (e.g., planning, design, financing, execution), as well as to provide a reference for the alignment of certification schemes, reporting projects, and public sector initiatives across Europe. For each indicator, operational guidance is provided to facilitate the quantification and interpretation of results by users with different levels of expertise (N. EC 2021; Dodd et al., 2021; Dodd et al., 2021; N. EC 2021).

The Level(s) framework consists of 16 core indicators (Fig. 1) addressing six macro-objectives (Table 1) of policies at the EU and global level. Three of the macro-objectives of Level(s) relate directly to environmental goals. The indicators under these macro-objectives enable users to measure the environmental impact performance for issues of relevance for buildings – such as contribution to GWP, material flows and water consumption, as well as health and comfort aspects – based on a combination of existing EU standards, life cycle-based approaches, and circularity principles.

The framework is split into three levels that follow the stages of project execution from conceptualisation to the handover and operation of the completed building:

- **Level 1)** to set qualitative objectives at the conceptualisation stage.
- **Level 2)** to assess quantitative performance at the design and construction stages.
- **Level 3)** to evaluate and monitor the performance after completion for as-built and in-use performance.

The higher the Level achieved, the better the data reflects the actual performance of the as-built building.

Level(s) has been referred to in the European Green Deal and follow-up EU policy initiatives such as the 2017 and 2021 Circular Economy Action Plans. It plays a key role in EU research and innovation (N. EC 2021), as well as in other policy and financial initiatives promoting enhanced environmental sustainability in the building sector. Clear examples are:

- The Green Public Procurement criteria for office buildings (Dodd et al., 2016), which aims to help public authorities ensure that building projects are developed and implemented so as to yield environmental improvements, healthy workplaces, and reduced life cycle costs.
- The Renovation Wave (N. EC 2020), boosting the renovation of the EU building stock to improve the efficiency of use of energy and other resources, and help reach the EU's 2050 objective of climate neutrality.
- The New European Bauhaus (N. EC 2021), that aims to shape more sustainable and inclusive forms of living together in the built environment.

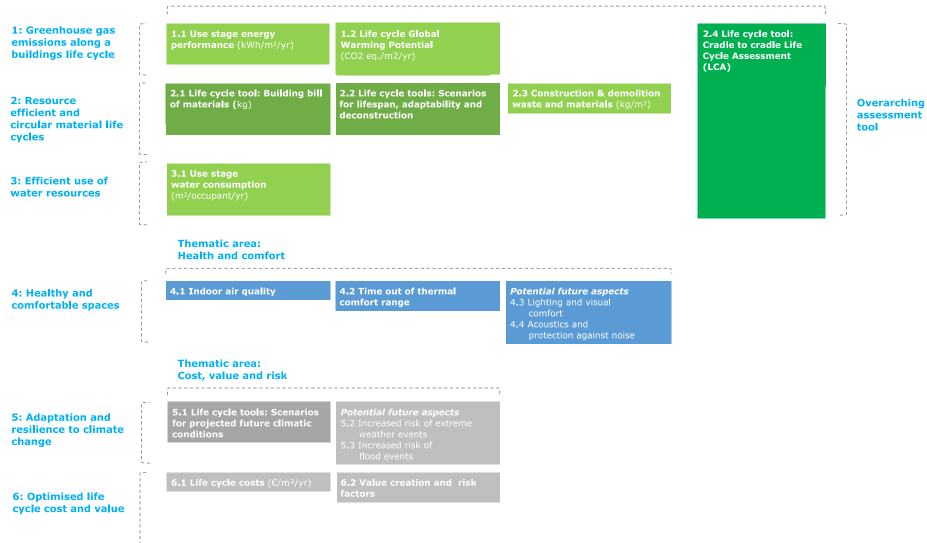

Fig. 1. Level(s) framework with its indicators (Dodd et al., 2017).

Table 1
Six macro-objectives of Level(s).

	Macro-objective	Description
1.	Greenhouse gas (GHG) emissions along a building's life cycle	Minimise the total GHG emissions and air pollutants from cradle to grave, with a focus on emissions from operational and embodied energy.
2.	Resource-efficient and circular material life cycles	Optimise the building design, engineering, and form in order to support lean and circular flows, extend long-term material utility, and reduce significant environmental impacts.
3.	Efficient use of water resources	Make efficient use of water resources, particularly in areas of identified long-term or projected water stress.
4.	Healthy and comfortable spaces	Create buildings that are comfortable, attractive and productive to live and work in, and which protect human health.
5.	Adaptation and resilience to climate change	Futureproof building performance against projected changes in the climate, in order to protect occupier health and comfort and to minimise long-term risks to property values and investments.
6.	Optimised life cycle cost and value	Optimise the life cycle cost and value of buildings to reflect the potential for long-term performance improvement, inclusive of acquisition, operation, maintenance, refurbishment, disposal, and end of life.

- Horizon Europe (N. EC 2021), a funding programme for research in supporting EU policies while tackling global challenges much broader than just buildings.
- The Circular Economy Action Plan (N. EC 2020), a primary building block of the European Green Deal and the EU's 2050 climate neutrality targets with a focus on product and resource life cycles.
- The EU taxonomy (TEG, 2020), which defines requirements to establish a list of environmentally sustainable economic activities, including buildings, in order to scale up EU sustainable investments. Developers of properties larger than 5000 m^2 who wish to claim that their buildings are 'sustainable' must calculate and disclose the buildings' whole life cycle GHG emissions (TEG, 2020).

1.3. The integration of whole life cycle thinking within Level(s)

WLC thinking is an overarching theme within the Level(s) framework and is fully depicted in Indicator 1.2 on whole life cycle GWP (Dodd et al., 2020c), also commonly referred to as "carbon footprint". The background studies that supported the development of the Level(s) framework identified an increasing trade-off between GHG emissions related to energy consumption in the use of buildings and the construction and renovation of buildings (especially in terms of emissions embodied in construction materials and products). In this context, the IEA has highlighted the significant contribution of the steel and cement sectors (IEA 2019; IRP 2020; UN Environment 2019).

Therefore, Indicator 1.2 aims to broaden the focus of attention from energy consumption during the occupation of buildings (Indicator 1.1) to GHG emissions along the WLC of buildings. It enables reporting on the emissions of GHGs, measured as carbon dioxide equivalent per net floor area (kg CO_2eq/m^2), that occur along the different life cycle stages of buildings, i.e., from the cradle (raw material extraction) to the grave/cradle (deconstruction, reuse, recycling, recovery, or other forms of waste management), based on principles and requirements of LCA (CEN/TC 350 2019; CEN/TC 350 2011; ISO 2006a; ISO 2006b). To this end, it requires the availability and use of databases and software tools. The measurements of environmental impact in terms of GHG emissions are expressed in kg of CO_2 eq / m^2 in order to align with other widely accepted metrics such as Energy Use Intensity (EUI), measured per square metre of floor area. The unit kg CO_2 eq / m^2 was also defined as the focus of Macro-Objective 1.3 in Level(s). However, this could potentially wipe out improvements made by increasing the area per occupant, for example. Therefore, the absolute value (total emissions) should always be referenced, so that users can also normalize the results with other metrics (e.g., number of occupants in person-hours, life span of the building) which are available, such as kg CO_2 eq per occupant or per longevity of the building, etc.

1.4. Research gaps, needs, and objectives

As shown in the literature, there is a gap in terms of a limited focus on mainstream professional use cases and, linked to that, the need for a more sophisticated understanding and analysis of different end-user needs to mainstream the use of WLC assessment tools and data sources. To date, the focus of research has largely been on methodological development and the perfection of assessment from an academic perspective, but the need and drive to mainstream the technique requires a new focus on the steps that can be taken to make assessment more widely accessible as a practice. The literature shows in general that, except for some new tool developers, mainstream building professionals outside of the very niche market share of multi-criteria building assessment schemes have not been targeted for research on how to mainstream WLC assessment.

The first step is taken in this research: a filter of the information available about tools and databases on the market using carefully selected criteria. More focus is needed on the design and functionality of the tools themselves, the adaption and offer of relevant professional training, as well as their integration into professional workflows, including design optioneering and optimisation, structural engineering optimisation, Building Information Modeling (BIM), material selection, and design for adaptability/deconstruction assessments. Although WLC assessment is relatively complex, lessons can be learned from the widespread implementation experience of other complex environmental assessment methodologies, such as energy performance assessments.

Professionals in the building sector only use LCA tools and databases sporadically. It is crucial to evaluate their needs in order to accelerate the mainstream uptake of LCA. Therefore, we need to define the main criteria in designing an effective, decision-useful categorization of LCA tools and databases. The main end-user considerations for such a categorization need to be assessed. To do so, information is needed for potential external users. This paper follows a stepwise approach, which was developed so that the criteria can support decision-making for the use of whole LCA assessment tools and databases.

A first illustrative list of relevant LCA tools and databases for buildings was originally produced for the beta version of Level(s) in 2017 (Dodd et al., 2017), mainly based on the JRC's in-house knowledge. However, it was acknowledged by the JRC that this list was not sufficiently informative and supportive to users of Level(s) for the testing phase (2018–2020), which involved more than 130 building projects in 21 EU countries. To respond to the identified shortcoming, it was decided to prepare a list of criteria in 2019–2020 to characterise available tools and databases, thus providing end users with the information needed for adoption of the framework.

The need for listing and characterising such LCA databases and software tools was strongly identified during the process of designing Level(s) as an enabling factor for users of the framework. Uptake may be further mainstreamed by integrating digital tools, such as Computer Aided Design (CAD) and BIM, into LCA software used by design teams. It was also considered necessary to instigate a learning process about LCA data sources, with a focus on parameters of quality, such as EPDs. Guiding users towards suitable LCA tools and aiding their understanding of the background data sources is necessary to enhance the evaluation of GWP (as well as other environmental impacts) of buildings. This is particularly timely now that the EU taxonomy's first Climate Delegated Act includes disclosure of WLC GHG emissions for buildings in its Technical Screening Criteria for new construction and renovation (N. EC 2021). EU countries such as France, Belgium, the Netherlands, and Finland are also increasingly looking to incorporate requirements for this type of assessment into their national building regulations and public procurement requirements (BPIE 2021; Giddings and Bourgeon, 2021; Kuittinen and Häkkinen, 2020).

Objectives of this research were:

- to provide transparent reference information to users of Level(s) about what is on offer in different European countries in order to support users in following the appropriate instruction steps to perform the WLC environmental impact assessment of buildings necessary to quantify Indicator 1.2 (Dodd et al., 2020); and
- to compile transparent information on the features, characteristics, and capabilities of available tools and databases so that end users with differing levels of professional training, human and financial resources, as well as project needs are able to select appropriate tools and data.

It should be observed that the characterisation exercise was not aimed at delivering a ranking system. The feedback of users, experts, and providers was a fundamental step in refining the criteria for tools and databases. However, it was recognised that this feedback could be potentially biased due to the commercial interests of providers. Such risk was managed through public consultations organised by the EC and a cross-check by the JRC of the provided information.

1.5. Goals, scope, and problem statement

In the context presented so far, the aim of this paper is to develop a set of criteria to support user selection of tools and databases to perform whole LCA of buildings. There was a need for a listing of existing tools and initiatives in the EU for the integration of whole LCAs into building design and management processes, which was provided by the authors in the framework of this research. This paper offers a characterization of WLC GWP and LCA software tools and databases for buildings.

The research was developed during the period of 2017–2020 with the support of developers and users of such tools and databases. The results can be used in different EU countries to support the operationalisation of Level(s) and to encourage the assessment of GWP and other environmental impacts in the built environment. This work aims at informing a specific user selection process of WLC impact assessment tools and supporting databases for buildings, rather than comparing existing building environmental assessment tools.

The research questions this paper addresses are the following:

1. What are the building sector's professional needs in order to accelerate the mainstream use of LCA tools and databases?
2. What should be the main criteria in designing an effective, decision-useful categorization of LCA tools and databases?
3. What are the main end-user considerations in seeking to put together such a categorization?
4. Is the information needed to populate the criteria readily available and clear to potential external users?

This paper explains the exercise of populating the criteria and the survey of providers and experts, both on content and the criteria themselves. The main methods used were a review of existing literature, the Level(s) test process itself, the survey and detailed audits which followed this process, and the co-creation of a list of criteria to evaluate tools and databases.

The outcomes of the paper are used to provide user support so as to increase professional and scientific use of WLC GWP assessment. This paper can furthermore be used, for example, in the assessment of impacts associated with innovative construction materials and smart building designs, and for monitoring the convergence of the built environment towards net-zero CO_2 eq emissions, zero-waste and zero-pollution targets, as well as circularity and resource conservation.

2. Literature review

Following the list of EU initiatives for the integration of whole life cycle LCA into building design and management processes discussed in Section 1.3, the next sections review the current literature on the opportunities and challenges related to LCA software tools and databases and how to evaluate these tools and databases. The integration of LCA tools and linked databases into building design processes, as well as material and building product-selection decision-making, is an emerging area with a limited but increasing number of studies to date. The literature review shows a focus on integration with digital tools such as BIM, simplified LCA software tools, and building material and product databases linked to Environmental Product Declarations (EPDs). The potential for divergence amongst the results obtained from different combinations of methodologies, tools, and databases is also a topic that has drawn attention from researchers.

This literature review serves to identify the current situation in terms of the development and adoption of tools across the EU as well as some of the main challenges that arise from the patchwork of coverage/initiatives. Literature was identified that used various LCA tools and databases in comparison to identify existing differences between them and obstacles to adoption. To frame the research objectives, specific work focused on Level(s) and other EU initiatives for tracking or assessing building environmental impact. Additionally, search criteria for the literature review included focusing on schemas for assessment in addition to reviewing routes for tool and database adoption. Based on the literature found, we identified three general themes to present the findings: findings on stakeholder needs and current use, growing adoption through BIM, and lastly a review on characteristics of the current software.

2.1. Professional needs to support integration into design processes

To date, LCA tools and data for buildings have been satisfactorily used within the academic field or by experienced LCA experts (Guinee, 2002; Lasvaux et al., 2013; Malmqvist et al., 2011; Pomponi et al., 2018). However, a broader adoption of LCA in the analysis of buildings is hindered by challenges related to the inherent complexity of buildings and LCA itself, as well as the lack of comprehensive, robust, and harmonised tools and their operationalisation. There is no consensus on how to list what is important to consider when developing certification systems for addressing the environmental impact of buildings in urban planning (Lind et al., 2019). A review of municipal climate mitigation policies has been conducted to understand existing research on cities' experiences (Neij and Heiskanen, 2021). For example, the requirements set by Swedish municipalities to assess and lower the environmental impact of buildings have been studied (Francart et al., 2019). Building practitioners do not often have a clear overview of LCA data and tools that are available, and suitable, in their region (Francart et al., 2019). The International Energy Agency (IEA) also investigated how to reduce the embodied energy and greenhouse gas emissions of buildings through Annex 57 by analysing case studies from participating nations (Moncaster et al., 2019). The analysis of 80 case studies showed inconsistencies in how impact reduction strategies are approached methodologically, impeding meaningful comparisons (Birgisdottir et al., 2017). Annex 57 has reinterpreted the studies by looking at the methodological differences to propose embodied carbon reduction strategies.

Cambier et al. (2020) conducted interviews and focus groups with building designers to understand their needs in terms of circular building design support tools, identifying and categorising existing tools, including designating LCA as a circular building design method. The study concludes by identifying the need for more practical examples and best practices in circular building; workflow management and monitoring tools that enable fluid information transfer; greater integration of BIM in LCA; and more guidance on the use of design tools with an emphasis on *"user friendliness, prior knowledge and integral accessibility"*. The authors found that there was a general oversupply of tools which did not fit the needs of the user or that the tools were not found to be user-friendly and were difficult to adopt (Cambier et al., 2020). These results confirm previous research concluding that the many existing in-house embodied carbon calculation tools lack early design-stage efficiency and the flexibility to be adopted widely, while BIM plug-ins might offer potential (Ariyaratne and Moncaster, 2014).

Organisations such as the WGBC have already encouraged LCA adoption amongst building stakeholders and highlighted national efforts to utilize LCA and embodied carbon tools (WorldGBC and Ramboll 2019). Yet these efforts need to accelerate rapidly if many building design teams are to evaluate and lower environmental impact. The IEA's Energy in Buildings and Communities Programme (EBC) is developing Annex 72 – Assessing Life Cycle Related Environmental Impacts Caused by Buildings. This work focuses on harmonising methodology guidelines, building assessment workflows and tools, case studies, building sector LCA databases, and information dissemination (IEA 2021). Rasmussen, et al. (Rasmussen et al., 2020) aggregated responses from the web-based survey conducted as part of the IEA Annex 72 and analysed the results from Norway, Sweden, Finland, and Denmark. The primary barriers identified within this subset of countries were perceived lack of incentive and lack of sufficient data. There is an emphasis on the balance of needing to gather significant data to determine primary environmental drivers while readily communicating the results to the client (Rasmussen et al., 2020). Research has shown that practitioners need more knowledge on tools and methods they can use for the environmental impact assessment of buildings (Wallhagen et al., 2017).

Table 2 summarises what is needed for practitioners to adopt whole life cycle LCA tools and databases in their daily practice. While many tools exist, it is not always clear to practitioners which ones to use and how. There is a need for a user-friendly integration in BIM (Section 2.2), linking with circularity (Section 2.3), and evaluating the existing tools (section 2.4). The table gives a synthesis of the academic findings informing gaps and needs assessment.

A systematic literature review illustrates the nascency of the use of LCAs for buildings and the need for further work in unifying the approach (Sauer and Calmon, 2020). 143 papers on LCA tools, written between 2013 and 2018, were compared and the major gaps identified included: method, definition of scope and goal, inventory analysis, impact assessment, and interpretation (Sauer and Calmon, 2020). Ultimately, a need to standardise requirements, methodology, and data inventories.

Passer et al. (Passer et al., 2015) discussed methodologies and EPD programmes in Austria, Belgium, France, Germany, and Switzerland, and the differences in approaches between the EC PEF method and the EN 15,804:2012+A1:2013, stating that "harmonisation is needed on the impact categories and assessment models/indicators, on the system

Table 2
Non-exhaustive list of practitioners' needs identified in literature.

Need	Guinee, 2002; Lasvaux et al., 2013; Malmqvist et al., 2011; Pomponi et al., 2018	Cambier et al., 2020	Ariyaratne and Moncaster, 2014	WGBC and Ramboll, 2019, IEA, Ramussen et al., 2020	McManus and Taylor, 2015; Sauer and Calmon, 2020	Passer et al., 2015
Harmonisation	X		X		X	X
Comprehensive tools	X	X				
Robustness	X					
Practical examples / best practices		X				
Fluid information transfer		X				
Integration of BIM		X	X			
User friendliness, accessibility, guidance	X	X				
Incentive				X		
Sufficient data				X	X	X
Transparency			X		X	

boundaries and service life of products and buildings, on the definition of scenarios (transport, use phase and end-of-life), allocation rules, biogenic carbon emissions, end-of-life approach, data quality requirements". This demonstrates a need for the unification and streamlining of requirements and transparency of software capabilities for increased accessibility and effective communication to the industry.

2.2. BIM-LCA integration as a means to mainstream LCA

A literature review of BIM and parametric tools for LCA from 2013 to 2018 compared 25 papers in terms of their approach (BIM or parametric), design stage (early or detailed), Level of Detail (LOD), tools, impact indicators, functional unit, database, and lifecycle stages (Cavalliere et al., 2019). The paper neither develops criteria to analyse the included tools nor focuses on the tools and country of context. Rather, the primary focus is on data input approach.

To address the issues of BIM adoption, Arayici et al. (Arayici et al., 2011) noted the challenges and slow adoption rate of BIM by small and medium-sized enterprises for architectural design purposes. For many LCA tools, there is a requirement to integrate with a BIM model, not with CAD as many designers use (Arayici et al., 2011). The adoption of BIM within the industry has been slower than originally anticipated due to barriers including interoperability, matching the user's requirements, a change of working process, legal issues, and the training and creation of new roles and responsibilities (Walasek and Barszcz, 2017). Data is provided to prove the financial incentives of BIM adoption. The Level(s) test process revealed that in some countries, such as Finland, there is a high level of BIM adoption and thus a greater potential to promote more immediate integration of LCA with BIM as a means of streamlining analysis

An investigation of industry practice and the need for a BIM-based LCA was conducted by Zimmermann, et al. (Zimmermann et al., 2021) with eight companies in the Danish context. Most companies were using quantity take-offs and some were developing plug-ins, but the most valuable features extracted included visual interface, transparency of data, automation, design evaluation, and flexibility (Zimmermann et al., 2021). Potrč Obrecht et al. (Potrč Obrecht et al., 2020) conducted a systematic literature review on 60 case studies of integrating BIM and LCA tools, primarily across Europe. The study found that 16 cases still used Excel spreadsheets and only 16 applied LCA during the early design stage.

2.3. Characterisation of software tools and databases

2.3.1. Functional needs to support consistent assessments

Herrero-Garcia (Herrero-Garcia, 2020) compared available tools for whole building LCA, emphasizing the increasing impact of embodied carbon and the need for tools that look at the whole life cycle. Dalla Mora et al. (Dalla Mora et al., 2019) reviewed integrated LCA tools available for BIM platforms and discussed regenerative design applications through a case study using a masonry and timber building. The paper reviewed Tally and One Click LCA as plug-ins for Revit and showed that, on average, the environmental impact of materials varied by 22%, which was dependant on the software's database content and customizability (Dalla Mora et al., 2019). Emami et al. (Emami et al., 2019) compared the embodied environmental impact assessment of Ecoinvent, SimaPro, and GaBi on a concrete-element, multi-story residential building and a detached wooden house, both in Finland. Fifteen impact categories were compared and exhibited significant discrepancies between the programs. The whole building assessments yielded a 15% difference and most individual categories showed a difference of 40% or more, proving the need for transparency between tools (Emami et al., 2019).

Hallouin et al. (Hallouin et al., 2014) compared environmental impacts embodied in materials or associated with the operation stage by looking at two LCA databases used in France (Ecoinvent v2 and INIES). The building case study compares a concrete frame, timber frame, and steel frame building, showing a non-negligible deviation for some of the indicators from the EN 15978 standard. Results show discrepancies between generic databases and specific EPDs. Authors encourage combining different LCA and service life datasets to examine diverging assumptions (Hallouin et al., 2014). These papers show the need for comparing data within projects or countries in order to understand whether the data is accurate, and comparisons are consistent.

Frischnecht et al. (Frischknecht et al., 2020) compared 17 national assessment methods and LCA databases to quantify the greenhouse gas emissions of a high-rise residential building. The work examined differences in GHG allocation across the various available life cycle stages and, despite producing different outputs, highlighted the significance of region-specific approaches (Frischknecht et al., 2020).

Del Rosario et al. (Del Rosario et al., 2021) analysed how EPD data can fit for LCA in the German DGNB scheme and Level(s). The study looked at an office building envelope and found that the EPDs did not cover the minimum scopes, as there was not enough geographical context, and also proved inadequate for life-cycle stages beyond the product stage. Lasvaux et al. (Lasvaux et al., 2015) compared multiple generic and product-specific LCA databases for building materials and quantified deviations in their impact categories. They found that some indicators vary greatly (sometimes more than 100%) between EPD and generic data, which proves the need for further refining an LCA from generic to product- and country-specific.

These differences in whole life cycle LCA results encountered when comparing software tools and databases illustrate the need to evaluate them objectively.

2.3.2. Valuation criteria of tools and databases in literature

Rice et al. (Rice et al., 1997) analysed twelve European LCA software packages available in 1997 and discussed their performance for categories such as volume of data, impact assessment, graphical representation of inventory results, sensitivity analysis, units, cost, user support, burden allocation, transparency of data, input- and output-parameters, demo version, quality of data, etc. The suitable packages they identified at the time were The Boustead Model, The Ecobilan Group's TEAM™, PEMS 3.0, and SimaPro 3.1 (Rice et al., 1997).

A framework for evaluating Building Environmental Assessment Tools (BEATs) has been developed by Wallhagen, et al. (Wallhagen et al., 2013), splitting BEATs into parameters, issues, then categories. The categories assessed include energy & pollution, material & waste, indoor environment/health and wellbeing, domestic water, site & ecology, and management/procedures (Wallhagen et al., 2013). To test the framework, it was applied to EcoEffect, Code for Sustainable Homes (CSH), and LEED-NC v3. Though the framework is shown to be an effective method to compare assessment tools for building metrics, it does not assess the transparency, accessibility, and operability from the user's perspective. Additionally, the tool versions originally analysed have become superseded.

Olagunju and Olanrewaju (Olagunju and Olanrewaju, 2020) reviewed 45 LCA software tools in the context of the cement industry and determined their adherence to ISO 14040, use of database, data quality assessment evaluation, and impact assessment method, though more information on operability, covered life cycle stages, or adherence to European standards is not given. Hollerud et al. (Hollerud et al., 2017) provide information to new LCA practitioners for selecting data sources and LCA tools. The authors evaluate the credibility of information, ease of searching for data, understandability of datasets, and available breadth of processes from multiple sources, both public and private, from the United States and Europe (Hollerud et al., 2017). Table 3 gives a summary of the evaluation criteria encountered in the literature.

3. Methods & materials

In this section, the methodology used to evaluate the list of LCA tools

Table 3
Non-exhaustive list of evaluation criteria for LCA software and databases identified in the literature.

Evaluation criteria used in previous literature	Rice et al., 1997	Wallhagen et al., 2013	Olagunju an Olanrewaju, 2020	Cavalliere et al., 2019	Hollerud et al., 2017
Data volume, sources & quality	X		X	X	X
Impact assessment & methods (life cycle stages, indicators, etc.)	X	X	X	X	
Graphical representation of results	X		X		
Sensitivity analysis	X		X		
Cost	X				
User support	X				
Transparency of data	X				
Demo version	X				X
Adherence to standards (e.g., ISO)		X	X		X
BIM integration				X	
Credibility of information					X
Understandability					X

and databases is described, particularly the development of detailed characterisation criteria. The methodology consisted of several interlinked processes:

1 A detailed literature review set the general framework concerning ways to evaluate the existing whole LCAs of buildings. This review enabled a first iteration of the criteria to assess when looking at tools and databases for WLC environmental impact assessment.
2 A key part of the development of the full publication version of Level(s) in October of 2020 was the conclusion of a beta test involving potential users. This process yielded a range of feedback on the user-friendliness of the indicators, their methodologies, and the instructions on how to use them and report results. This feedback was provided via a number of routes, including helpdesk enquiries, a structured test survey, and interviews or conference breakout groups on specific indicators. The survey of Level(s) test users gathered user feedback obtained from the Level(s) test process. The survey results serve to cross-check and validate the literature review outcomes. The feedback obtained from the testing of the beta version of Level(s) was screened for relevant information on how the adoption of whole LCAs in buildings could be mainstreamed and what kind of information on supporting tools and databases would support this. Interviews were conducted to ask more specific questions regarding each indicator (and GWP assessment in particular).
3 The iterative development and co-creation process enabled the design and population of the listing of tools and databases, as well as the evaluation of the objective criteria. The list itself was created through an iterative consultation process during 2019 and 2020, involving stakeholders of Level(s) and building life cycle experts, as well as database and tool developers.

This process informed the definition of features and criteria that can be used to characterise the different tools and databases. Examples of survey and interview questions are illustrated in Table 4.

A first survey took place in the first quarter of 2019, addressing testers of Level(s) through the EC CIRCABC forum (CIRCABC 2021). This provided useful insights to refine the criteria used in the characterisation. A second survey took place in the second quarter of 2019, targeting experts and developers of LCA tools and databases, with the aim of revising both the criteria and lists of tools, and of obtaining initial information about the characteristics of such tools with respect to the defined criteria. This step allowed for the collection of more precise input. The verification of this information was then carried out while harmonising the received input.

A third and last survey took place in the second half of 2019, primarily to complement and refine the criteria for evaluating the tools and databases and populating them. A set of criteria were defined to give Level(s) test users guidance in terms of which tools or databases are available to them. The criteria are a categorisation of the level of sophistication of the tools and were developed to inform practitioners about decision-making, e.g., regarding the price of software and training requirements. The proposed set of criteria was sent to a selected group of LCA experts and tool/database developers to refine the criteria set and clarify the wording. The tools and databases were tested by the users, who were interviewed by the authors.

The final set of criteria and the characterisation of tools and databases resulting from the described process is presented in Section 4. This now provides Level(s) users with guidance about which tools or databases are available to them, and practical information such as geographical representativeness, level of detail, language(s), price, or availability of training. It should be noted that the list of tools and databases presented and discussed in the next section is non-exhaustive. In fact, there are a growing number of other LCA tools and databases available in Europe and throughout the world. However, the tools and databases discussed in this paper refer to the EU-wide consultation reported above, and the list is meant to be dynamic (i.e., new tools can be added and tools that are not used anymore can be deleted) to help the Level(s) users.

4. Results

The results from the survey and the consultation regarding draft criteria are brought into each criterion. Each criterion represents the results of the research, which includes the survey and verification steps from the test phase as well as the consultation process (N. Dodd et al., 2020) described in Section 3.

4.1. User support feedback on software tools and databases obtained from the testing of Level(s)

The findings from the helpdesk and survey (Table 4) were written up and published in the form of a detailed survey report (N. Dodd et al., 2020), a verification for a sample of projects (C. De Wolf et al., 2020), and a set of proposals and recommendations for improvement of the Level(s) framework (N. Dodd et al., 2020). The findings provide a range of feedback that is relevant to implementation by users of the Indicators 1.2 and 2.4 and are summarised in Appendix 1 and 2, respectively. The themes that arose informed the need for a listing of tools and databases. They included:

- the need to use third party software tools and databases, with a range of public and privately developed tools;
- the geographical disparity across Europe in terms of data coverage and software tools;
- the availability of these tools and data, their potential to simplify the calculation process, as well as their compatibility with the Level(s) methodology;

Table 4
Examples of survey and interview questions.

Survey Questions
Please provide the details of the building project.
What were the general expectations that motivated the use of Level(s)?
If your team has previous experience of making environmental or sustainability performance assessments, please identify the specific performance assessment schemes and methods you have used.
To what extent did Level(s) help you and your team to obtain practical information on the sustainability performance of the test building?
To what extent did use of Indicator 1.2 and/or 'life cycle tools' help provide a better understanding of the life cycle of the test building?
To what extent has use of Indicator 1.2 and/or the 'life cycle tools' has encouraged the team to analyse the life cycle of buildings in more depth?
If you made assessments of value and reliability for your test indicators and life cycle tools, to what extent did the assessments provide useful information?
Questions on the value of Level(s) to key stakeholders.
To what extent was Indicator 1.2 easy and logical to use?
If comparisons were made of different building design options, to what extent did the indicator or life cycle tool help to do this?
To what extent did you encounter any problems in obtaining a result?
When making the assessment, were there any other specific references, datasets, or tools you had used on other building assessments that proved useful?
To what extent did you already have access to the required results from other assessments of the building?
If you had to obtain the standards, data and/or tools to make the Level(s) assessment, how readily available were they?
If you had to purchase the standards, data and/or tools, to what extent was their cost a barrier to using them?
How would you describe the previous experience of the test team with similar indicators or life cycle tools?
Based on the previous experience of the test team, to what extent did using this indicator or life cycle tool require additional training and support?
If possible, please provide an estimate of the cost and/or time that were required to use this indicator or tool.
Now that you have tested the indicator/life cycle tool, please make any suggestions for improvements that would make it easier to use.
To what extent did Level 2 prove to be useful in making comparisons between buildings?
To what extent did Level 3 prove to be useful in making comparisons between buildings?
Follow-up Indicator-specific Interview Questions
Please describe the practical experience and the steps taken and tools employed to obtain the result for this indicator.
Was a result obtained? If not, what were the reasons?
Which were the main difficulties encountered and how have these been overcome?
Did you encounter any problems, either in the methodology or using the reporting excel?
If the interviewer identified any gaps or errors in the submitted results, these are to be checked and further discussed with the test team at this point.
To what extent did you make use of existing data/results, or had to do something new?
How did you use/follow the Level(s) guidance? Were you able to interpret and follow the guidance for your level? Did you have to make any short cuts/deviations from the guidance and why?
Were you missing anything that would have helped with the process?
Was it a useful exercise to calculate this indicator/life cycle tool? Were your expectations met? Did you learn anything from using the indicator/life cycle tool?
Do you have a sense of how reliable the information that you obtained is?
What modifications and supporting tools would you propose/recommend when revising the Level(s) beta guidance documentation?

- the inter-operability of these tools and data with other software commonly used by building designers and engineers, such as CAD and BIM;
- the need for training in the use of calculation and modelling tools, as well as access to and handling of datasets;
- the potential to establish minimum criteria for their functionality and alignment with core methodologies.

A significant number of testers were quoted as having requested better information about access to calculation tools and databases. This feedback emphasises the important role of third-party software tools in facilitating whole LCAs, as well as structured information on data sources and support in identifying and handling different sources such as EPDs. The subsequent revision of Level(s) in 2020 included instruction steps addressing the role of software tools as well as the separate listing of software tools and databases within the new Indicator 1.2 (Dodd et al., 2021a; Dodd et al., 2021b).

4.2. *Definition of the categories and criteria*

As a result of the two methodological processes described in Section 3, it was possible to define a set of criteria to characterise software tools and databases, subsequently used to populate the listing and further refine the criteria based on feedback from experts as well as developers and providers. As a result of the process, three main categories of criteria were identified:

- Comprehensiveness: This category addresses the extent of sector-specific coverage, including its relation to different life cycle stages, as well as methodological aspects of coverage, including the geographic, technical, and time representativeness of modelling capabilities and the data provided. The granularity and boundaries are also considered with respect to how they relate to a discrete building project. Both aspects were considered important by stakeholders and providers given the potential for variability across the tools made available.

Table 5
Criteria defined by the JRC to categorise the available LCA tools and databases in Europe.

Category	Criteria	Description
Comprehensiveness	Construction-specificity	Construction-specific or broader
	System boundaries & scope	Life cycle stages, databases, geographic information, languages
	Indicators	Full or partial coverage of impact indicators and LCC
	Modelling granularity	Parts or whole building
Robustness	Methodological adherence to Level(s) & EN standards	Alignment
	Data quality	Possibility for analysing reliability, sensitivity, uncertainty, and scenarios
	Transparency and verification	Traceability and documentation, third-party verification
Operability	Accessibility	Software format (web interface, spreadsheet, etc.)
	Data exchange & interoperability	Import and export possibilities
	Cost	Free or commercial price
	Training and support	Demo version, documentation, long-distance learning, sale support
Additional information	Maturity, development, management, and updates	

Table 6
System boundaries & scope.

Software tools	Databases
Allowing the assessment of the following EN 15,978 modules	Allowing the assessment of the following EN 15,804 modules
A0: 'Pre-construction stage'	A1-A3: 'Product stage' (material extraction and processing, transport, manufacturing)
A1-A3: 'Product stage' (material extraction and processing, transport, manufacturing)	A4-A5: 'Construction process stage' (transport to the building site and installation)
A4-A5: 'Construction process stage' (transport to the building site and installation)	B1-B5: 'Use stage – building fabric' (use or application, maintenance, repair, replacement, refurbishment)
B1-B5: 'Use stage – building fabric' (use or application, maintenance, repair, replacement, refurbishment)	B6-B7: 'Use stage – operation of the building' (operational energy and water use)
B6-B7: 'Use stage – operation of the building' (operational energy and water use)	B8: users' activities
B8: users' activities	C1-C4: 'End-of-life stage' (de-construction & demolition, transport, waste processing for reuse, recovery and/or recycling, disposal)
C1-C4: 'End-of-life stage' (de-construction & demolition, transport, waste processing for reuse, recovery and/or recycling, disposal)	D: 'Benefits and loads beyond the system boundary'
D: 'Benefits and loads beyond the system boundary'	
Extra: Separate reporting [Y/N]	Extra: Separate reporting [Y/N]
Databases used	End-of-Life scenario information (if applicable)
End-of-Life scenario information and modelling (if applicable)	Countries covered
Languages available	Languages available

- Robustness: This category reflects the extent of the methodological grounding of the software tool in the EN standard basis of Level(s). This was an important consideration given the objective of establishing a consistent and comparable basis for the calculations underpinning assessments. Data quality was a consideration arising from LCA methodological development in support of EU regulatory initiatives, but transparency regarding this aspect was also demanded by Level(s) stakeholders given the variability in quality across the EU.
- Operability: This category was considered critical to supporting professional implementation of Level(s). Factors influencing operability – such as accessibility of a tool, the level of training required, the associated costs of setting up and using a tool, as well as interoperability with other design software – appeared to be of high priority to address within such a listing.

A further category for general information on the tool or database seemed to be pertinent, given the need for the ongoing release of datasets to maintain representativeness as well as possible upgrades and improvements to software tools.

To then provide a detailed overview and characterisation of the software tools and databases available in Europe to perform LCAs of buildings, 11 criteria were defined, divided into the three categories (comprehensiveness, robustness, and operability). Table 5 gives an overview of the criteria defined in Level(s) to categorise the available LCA software tools and databases (Dodd et al., 2020). The final criteria, to classify the features of different whole life cycle impact tools and databases, have also been published in more detail by the JRC 2021 [84, p. 1].

Per category, we describe in detail the most requested criteria during the test feedback for the various LCA tools and databases analysed, as highlighted in Table 5. Some criteria had mutually exclusive options to choose from (only one option to be adopted), while others had multiple options (all the options that apply can be adopted), and still others required an analysis of sub-criteria through an answer to be provided for each bullet point. Extra information was also requested for some criteria.

4.2.1. Comprehensiveness

For the comprehensiveness category, the first criterion asks whether the software tool or database is construction-specific or has a broader range of applications. Table 6 gives an overview of how the second criterion of the comprehensiveness category, "system boundaries and scope", is analysed. It especially looks at the life cycle stages that are included in the software tools or databases.

A tool can use different databases. The database will dictate which modules can be reported or the level of alignment with EN 15804 and EN 15978 (more than the tool itself does). Users should therefore look at the databases used in each tool to make sure modules reported are available for all materials/components in the tool and to check their alignment with EN 15804 and EN 15978 (see also 4.1.2. Robustness).

Moreover, modules and impact factors considered in the EPDs of an EPD programme are not always the same. Users of the list should still be critical of the source of information when using the different tools and

Table 7
Methodological adherence to Level(s) & EN standards.

Software tools	Databases
I) Aligned with EN 15,978 with extension to fit with Level(s) (CIRCABC 2021) (part 3) II) Aligned with EN 15,978 – either based on self-declaration or external evaluation III) Not aligned for specific aspects	I) Aligned with EN 15,804 with extension to fit with Level(s) (part 1 and 2, part 3) II) Aligned with EN 15,804 III) Not aligned for specific aspects Extra: EN 15,804:2012+A1:2013 or EN 15,804:2012+A2:2019

databases. This is particularly relevant since results show that LCA tools and databases are not considering all modules (life cycle stages) similarly across Europe.

Coverage of indicators is the third criterion of this category. The European standard EN 15978:2011 states the indicators that should be assessed. The Product Environmental Footprint (PEF) also specifies a few additional indicators. Some tools and databases only focus on the 'carbon footprint' and only consider GHG emissions, while others include indicators of the European standards and/or PEF. An additional question asked within this criterion was whether LCC was included. Authors have found that, in most tools and databases, included indicators (EN/Level(s)) should be more transparent.

Finally, the fourth criterion is the modelling granularity (granularity in terms of stages is addressed in the criterion on system boundaries & scope). Some tools and databases are only looking at specific building materials or one or more construction products, while others look at the whole building, with the flexibility to adapt to specificities of the building. The granularity is important for users to understand when determining whether the tool or database is appropriate for the scale at which they want to conduct an LCA.

4.2.2. Robustness

In the robustness category, methodological adherence to Level(s) and EN standards, data quality, and transparency and verification are analysed. First, the general methodological adherence to Level(s) and EN 15804 / EN 15978 standards is analysed (Table 7), whereby a class I rating indicates optimal methodological adherence.

Moroever, the data quality is analysed by looking at whether the tool supports a reliability assessment of the quality of the data input, a sensitivity analysis (e.g., checking the influence of modelling assumptions, parameters, and datasets on the results), an uncertainty analysis (e.g., checking the variability of the results), and/or a scenario analysis (e.g., checking of alternative options). For databases, this criterion looks at the geographical representativeness (e.g., local versus EU/global average), the time-related representativeness (e.g., plausible until a certain year), the technological representativeness (e.g., material-specific versus generic), and/or the support of an uncertainty analysis (e.g., uncertainty distributions provided). In particular, during the development and testing of Level(s), it emerged that there was a need to determine and communicate the geographical representativeness of data and software tools.

Finally, transparency and verification are analysed. The sources of information, key data, and modelling assumptions are listed as 'not documented', 'reported', or 'trackable and verifiable'. The proportion of data that has been verified by a third party is also inquired about, as well as any national authority validation. This is a critical aspect since quality assessment, transparency, verification, and accessibility are not harmonised across European software tools and databases.

4.2.3. Operability

In the operability category, the tools and databases are assessed in terms of accessibility, data exchange & interoperability, cost, and training and support.

First, it is established whether the tool is a web interface, an Excel-based tool, or a piece of software to install on a computer or server, and whether the database contains datasets provided at the detail level of unit processes, through EPDs providing elementary flows and/or indicators, or information locked in a specific software. This criterion helps the user understand the accessibility of tools with their own installed software and access, as well as that of databases' data.

Second, the data exchange and interoperability criterion classifies the operability in terms of import and export options from one tool/database to another (Table 8). Class I is recommended: this is crucial in the integration of BIM into the workflow of Architecture, Engineering and Construction (AEC) actors. Authors have found that import and export of LCA and design information is often possible with the listed tools.

Third, a distinction is made between commercial and free tools and databases. For users of Level(s), it can make a difference whether licenses are needed for the use of the data or software. The 'cost' criterion indicates this aspect, although the pricing (possibly variable over time, geography, and type of licence) is not given in the listing.

The fourth criterion relates to the training and support options. It considers whether there is a demo version, documentation, and/or initial training available for free. It also asks about the possibility of supporting long-distance learning and an after-sale support system such as a helpdesk.

4.2.4. Additional information

All extra information can be covered in a fourth category, such as background information about maturity, development, management, and update/upgrade pathways for the tool or database, as well as the breadth of a database (number of materials, types of construction materials and equipment covered, level of detail, level of adaptation provided).

4.3. List of tools and databases

The full list of tools and databases classified according to the criteria discussed in 2021 in Sections 4.1 to 4.4 can be found on the JRC website (JRC 2021). The link to the table can be found in these documents under "Level(s). Indicator 1.2 (pdf) - Indicative list of LCA software and databases for use with Indicator 1.2″ (De Wolf et al., 2020). Table 9 shows an example of four entries in the non-exhaustive list of European LCA software tools and how each of the criteria is populated. The interactive link to the updated full list can be found at www.carbondeqo.com/lca.

The first example is OpenLCA, as this is an example of a generic and open-access tool used by LCA practitioners and researchers. The second example is OneClickLCA, a building-specific commercial tool that is widely used in several EU countries. The third and fourth examples are GaBi and SimaPro, generic LCA tools which are both widely used and recognized in different countries. GaBi was listed due to its large data coverage and its track record of application by research institutes in the sector.

Table 10 shows an example of four entries in the non-exhaustive list of European LCA databases and how each of the criteria is populated. The full list can be found in the same link. For similar reasons as mentioned above, the databases from OneClickLCA and GaBi were used as examples of LCA software tools that also embed their own database with good/dedicated data coverage for the building sector. SimaPro also

Table 8
Exchange & interoperability.

Software tools	Databases
I) Import/export of design and LCA information possible	I) Import/export of LCA information possible (e.g., import new material EPDs into the database)
II) Import/export of design information possible (e.g., BIM)	II) No import/export possible
III) Import/export of LCA information possible	
IV) No import/export possible	
Extra:	Extra:
Provision of conversion factors between measurement units [Y/N]	Provision of conversion factors between measurement units [Y/N]
Software-independence [Y/N]	Software-independence[Y/N]

Table 9
Non-exhaustive partial list of European LCA tools, analysed according to criteria from Table 6, Table 7, and Table 8.

Target Market	Tool	System boundaries & scope				Methodological adherence to Level(s) and EN standards adherence	Data exchange & interoperability		
		EN 15,978 modules covered	Separate reporting	Databases used	Languages	Alignment	Import/ Export	Conversion factors	Software-independence
DE & others	openLCA	A1-A3, A4-A5, B1-B5, B6-B7, C1-C4, D	Y	Not specified	English	II) Depending on used datasets	I)	Y, since version 1.9	Y
EU, US, others	One Click LCA	A1-A3, A4-A5, B1-B5, B6-B7, C1-C4, D	Y	Different tools with varying scopes	English	I) Third-party verified	I)		N
DE & others	GaBi	A1-A3, A4-A5, B1-B5, B6-B7, C1-C4, D	Y	GaBi	German, English	I)	I)	*Y* + flow mapping at import and export to / from ILCD/E F2.0 / import function	Y
NL & others	SimaPro	A1-A3 A4-A5 B1-B5 B6-B7 C1-C4 D	Y (several options)	Agri-footprint, Ecoinvent, EU and Danish Input Output Industry data 2.0, US Life Cycle Inventory database	English for online platform English, Chinese, Danish, Dutch, French, German, Italian, Japanese, Portuguese, Spanish, Swedish for SimaPro 9	I)	III)	Y	Y

Table 10
Non-exhaustive partial list of European LCA databases, evaluated according to criteria from Table 6, Table 7, and Table 8.

Target Market	Database	System boundaries & scope			Methodological adherence to Level (s) and EN standards	Data exchange & interoperability	
		EN 15,804 modules covered	Separate reporting	Language	B1) Methodological adherence to Level(s) and EN standards adherence	Import/ Export	Software-independent
EU, US, other	One Click LCA database	A1-A3 A4-A5 B1-B5 B6-B7 C1-C4 D	Y	English	I)	I)	Y
DE, Other (global coverage with focus on European countries)	GaBi Databases	A1-A3 A4-A5 B1 B2-B5 few data B6-B7 C1 few data C2-C4 D	Depends on data sets, typically A1-A3, in few cases A1-A5	English, German	III)	I)	Format GaBi tsx
CH	Ecoinvent	A1-A3, A4-A5, B1-B5, B6-B7, C1-C4, D	Y	English	II)	I)	Y, Exchange possible in Python
FR	INIES	A1-A3, A4-A5, B1-B5, C1-C4, D	Y	French, English	II)	I)	

offers the possibility of integrating databases, although these are generally developed by other providers. For instance, Ecoinvent is an example of an academia-led, not-for-profit organisation making environmental data available worldwide, while INIES is an example of a national database using EPDs. It should also be noted that the JRC has been working on the Life Cycle Data Network for the European Platform on LCA (LCDN 2021).

5. Discussion, conclusions, and future research

5.1. Discussion

The analysis of the non-exhaustive list of LCA software tools and databases used in EU countries, and the entire list in general, shows that a range of tools and databases are available in the EU market that provide a variety of features. In particular, the need for accurate and user-friendly LCA tools and databases is documented both in the Level(s) development process and in the literature. The need for more readily accessible tools and databases could facilitate their broader use. The listing entries give an overview of the status of different tools and databases across the EU. For example, there is a split between academic and professional target audiences, as well as a split between comprehensive LCA tools and streamlined building WLC GHG emissions tools.

Though there is a large range of tools and databases available in various EU countries, it is not yet sufficient to support mainstreaming of environmental impact assessment of buildings. The professional offer of user-friendly tools and databases is still limited, and some tools and databases still require a high level of expertise. This means that they are only accessible to large companies with the budget for specialised personnel or those that can sub-contract specialists.

Further support for mainstream application requires more LCA data, transparency, user-friendliness, education, third-party verification, and alignment or harmonisation of various efforts. Representative data coverage can be further supported across the EU through European research initiatives. The EC could promote demand and supply of LCA tools and data, explore opportunities offered by digitalization and cooperation (e.g., Eco Platform AISBL), and analyse data quality requirements. There is a role for national bodies to establish and work with research partners to set up and maintain national databases or reference EPD libraries (e.g., INIES in France for several years now). This would sidestep, to some extent, commercial interest on the data side, the quality and impartiality of which is critical. The central point can also screen and verify, as part of Product Category Rules, commercial data inputs from, for example, construction product manufacturers to the national dataset (e.g., BRE with Environmental Profiles and Green Guides for the UK government). Research institutes could work with the national Green Building Councils and the government to develop a database for public building assessment (e.g., ITeC in Spain). While the databases need more careful handling, the tools can be left more open for the market to respond.

The list published by the JRC of the EC (JRC 2021) is meant to be a dynamic list that will evolve over time. Therefore, software tools and databases that are not yet in the list can be added in future, or removed if not used anymore, whilst characteristics that change with updates can be adapted over time. In fact, the characteristics of some software tools and databases may change in response to evolving needs in the market (e.g., non-aligned tools might become Level(*s*)-aligned). Furthermore, while high-level information from providers helped with the review of tools and databases, their answers are still made available publicly in order to analyse and adapt results in a dynamic list.

The dynamic list can be used as a reference to find the appropriate LCA software tools and databases for a specific region and operability perspective. The indication of the geographical target market and language(s) can help users focus on tools and databases likely to be most suitable for specific geographical contexts (e.g., in terms of data quality and language used). It should be observed that the use of other tools and databases is not impeded, although this could result in the use and production of less accurate information and results.

The dynamic list also allows for the screening of key characteristics of tools and databases with respect to their comprehensiveness, robustness, and operability, as described in Section 4. Comprehensiveness covers the following aspects: construction-specificity, system boundaries and scope, indicators, modelling granularity. For example, Table 10 shows the building modules (according to EN 15804) covered in a selection of databases, generally showing a good level of granularity for the calculation and reporting of results. Robustness addresses methodological aspects relating to the adherence to Level(s), EN 15804 and EN 15978, as well as data quality, transparency, and verification issues. Relevant characteristics to enhance the operability of tools and databases are their accessibility, data exchange and interoperability, cost aspects, as well as the availability of training and support. For example, information in Table 10 indicates that selected databases allow for data exchange and interoperability, although this may sometimes depend on the use of specific software.

Costs associated with the use of LCA software tools and databases, as well as with the training needed to create an in-house capacity, can be a critical barrier limiting the spread of LCA in practice. However, these are difficult to evaluate. Costs of implementation per building project can fall as (a) personnel becomes more experienced, (b) more learning occurs, and (c) greater use of automated design process integrated tools occurs. The unit cost of software, tools, and databases can then be amortized across projects. Furthermore, in the future, the link with BIM and digitalization will become increasingly important and the interoperability of tools and databases will therefore be crucial.

A last aspect to highlight is that users of Level(s) are also interested in software tools and data that can help them in assessing LCC, as well as material stocks and flows that give them a sense of the circularity of a building project. In this respect, tools may support the modelling of future adaptability scenarios. New tools are also focusing solely on circularity assessment (e.g., Madaster in the Netherlands and a few other countries), but these are not reported in the dynamic list (which focuses on LCA).

5.2. Conclusion

In this paper, a list of LCA software tools and databases used for the analysis of building projects in EU countries is analysed and discussed. This list has been compiled in the context of development of the Level(s), the EU framework of environmental sustainability indicators for buildings which is based on existing standards and methods and provides a common EU approach to the assessment of the WLC performance of buildings, for both GWP and a broader set of impact categories informed by the standard EN 15978.

The four main research questions stated in Section 1.5 have been addressed in this paper. The building sector's practitioners (Question 1) need a clear idea of the comprehensiveness, robustness, and operability of LCA tools and databases in order to accelerate their mainstream use. The main criteria in designing an effective, decision-useful categorization of LCA tools and databases (Question 2) were therefore defined. This paper identified criteria to categorize LCA software tools and databases available in the EU market for buildings, in order to offer more transparency regarding their availability and specifications. The main end-user considerations in seeking to put together such a categorization (Question 3) include system boundaries such as life cycle stages, databases, geographic information, and languages; included impact indicators; alignment with Level(s) and standards; traceability and third-party verification; cost and training possibilities; etc. The resulting criteria show the end-user considerations. These considerations may depend on the professional profile and experience of the end user. For example, beginners may require more focus on operability, whereas experienced professionals may want information on comprehensiveness and the integration of other aspects such as LCC. The information needed to populate the criteria (Question 4) is not always readily available and clear to potential users. Indeed, an iterative process of surveying users, tool/database developers, and experts was needed to do so.

The resulting criteria focus on three main topics – comprehensiveness from the methodological point of view, robustness in terms of a grounding in standardisation, and operability from a professional software tool point of view. These three topics represent a response to the gaps and needs analysis carried out, with the aim of providing decision-useful information for professionals seeking to make assessments. The information itself was not necessarily easy to obtain in all cases – for example, in terms of some aspects of operability – as doing so may require trial versions of the tool itself. The developed criteria seek to answer the main questions we posed by starting to provide more structured, user-orientated information.

This paper provides a reference point for potential Level(s) users and building LCA practitioners and underlines the need for great transparency regarding the availability and features of software tools and databases, to ensure that they can fit with and respond to the purpose, context, resources, and expertise of users. Finally, the results of this paper illustrate the range of tools and databases available on the market.

5.3. Future research

Whilst a multi-stakeholder consultation on the criteria was carried out, there is still a need for further end-user views in order to validate the practical value of the criteria and listing. Moreover, there is a need for developing more accessible WLC assessment tools, which means that the research framework may have been constrained by both a current perspective on the problem (early adopters) and the limited offer on the market. A new perspective on tool and database development is needed, particularly in countries seeking to implement WLC assessment more widely.

Although the listing addresses buildings and construction products, the analysis can find practical usefulness in relation to the entire built environment. The analysis can also support the implementation of key EU policies integrating references to Level(s), such as the Renovation Wave and the EU taxonomy. In fact, the EC is ultimately aiming to achieve the broad application of LCA by built environment professionals through Level(s). Member States that are considering developing initiatives to push into the mainstream the whole LCA of buildings may also find the listing useful as a supporting implementation tool.

Maintenance of such a dynamic list of tools and databases in a rapidly developing field such as sustainable building assessment is a challenge that the JRC will have to manage. As the sector evolves in response to regulatory pressures, it could also be useful as a tool for the EC to monitor how the market is responding to the need to support the mainstreaming of life cycle assessment in the building sector, as well as to identify gaps in the market from a number of the different technical and market perspectives as captured in the categories and criteria. Potential technical developments of the listing could include the continuous updating of the list of LCA software tools and databases, including its potential extension to extra-EU countries, their characterization criteria, and the results of the classification itself.

Furthermore, a consideration of the factors that help support the adoption of a new design technique by built environment professionals, as well as the options for integration into existing processes, will be a crucial component of future work. The information provided in the list of LCA software tools and databases is supportive in driving mainstream adoption. Further research should analyse the costs of upscaling the use of these LCA software tools and databases and study comparative adoption paths for other building tools such as CAD and BIM. Costs, learning, automation, etc. are important criteria to consider. The tools' design and licensing should consider these aspects.

Finally, future research should, based on the given overview in this paper, further address the gaps and needs of these tools and databases to support their future updates.

CRediT authorship contribution statement

Catherine De Wolf: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft, Visualization. **Mauro Cordella:** Conceptualization, Methodology, Validation, Data curation, Writing – review & editing, Funding acquisition. **Nicholas Dodd:**

Conceptualization, Methodology, Validation, Writing – review & editing, Project administration, Funding acquisition. **Brandon Byers:** Writing – original draft. **Shane Donatello:** Data curation, Validation, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix 1. Key technical issues and proposed updates for Indicator 1.2: Life Cycle Global Warming Potential

Key technical issues to address	Main proposed technical updates and solutions
Floor area and unit of measurement	- Harmonise between the indicators and make reference to the correct unit of measure in the reporting tool (kg CO_2 eq per m^2 per year)
Definition of the scope of the analysis	- Provide a better description of how the scope of the analysis has to be defined for different Level(s) - Clarify the life cycle stages and sub-stages to cover in the analysis, differentiate between embodied and operational emissions
Lack of benchmarks	- Introduce guidance for setting benchmarks and targets in order to enable a comparative/improvement analysis between different building project options
Calculation methods and alignment with EN standards	- Simplify the description of the calculation methods, making a stronger link with revised EN 15804 and EN 15978 standards - Provide further clarification on carbonisation, biogenic, fossil and land-use emissions of CO_2 eq - Promote the use of BIM as a means of facilitating building data
Availability of LCA tools/data	- Provide a neutral description of tools and databases that are available for use - Explore the possibility of establishing minimum criteria for their functionality and alignment with EN 15804/15978
Difficulties in understanding how different Level (s) works	- Clarify how different Level(s) work, under which requirements, and provide further indications to make sense of the results
Duplication of results	- Avoid redundancy and overlap between 1.2 (GWP) and 2.4 (LCA)
Ease of reporting results	- Improve the layout and user-friendliness of the tool - Reporting unit to be aligned with the methodological guidance - Indications about other indicators, scenarios, data sources linked to different life cycle stages could be provided, as well as typical value ranges - A standard structure could be developed for the detailed insertion of supporting information

Appendix 2. Key technical issues and proposed updates for tool 2.4: Life Cycle Assessment

Key technical issues to address	Main proposed technical updates and solutions
Floor area and unit of measurement	- Harmonise indicators and refer to the correct unit of measure in the reporting tool (kg CO_2 eq per m^2 per year)
Definition of the scope of the analysis	- Provide better description of how the scope of the analysis must be defined for different Level(s) - Clarify the life cycle stages and sub-stages to cover in the analysis; differentiate between embodied and operational emissions - Set cut-off and normalisation rules based on the cost contribution of building elements - Provide clearer guidance for repair, refurbishment, maintenance and how to work with new and existing buildings
Lack of benchmarks and hot spot analysis	- Introduce guidance for setting benchmarks and targets to enable a comparative/improvement analysis - Introduce guidance on how to identify and analyse hot spots and options for improvement
Complexity of the calculation methods and alignment with EN standards	- Simplify and reduce the description of the calculation methods, building a stronger link with the revised versions of EN 15804 and EN 15978 standards - Promote the use of BIM
Availability of LCA tools/data	- Provide a neutral description of tools and databases that are available for use - Explore the possibility of establishing minimum criteria for their functionality and alignment with EN 15804/15978
Reliability of results	- Explore possibilities to simplify the data reliability - Strengthen the importance of reporting results transparently and interpreting them critically
Ease of reporting of results	- Improve the layout and user-friendliness of the tool - The reporting unit has to be aligned with the methodological guidance, and the service lifetime considered in the assessment has to be reported - Allow the possibility of avoiding reporting on GWP again if both Indicator 1.2 and tool 2.4 are used - Indications about the other indicators, scenarios, or data sources linked to different life cycle stages could be provided - Generate different results tables per scenario evaluated
Difficulties in understanding how different Level(s) works	- Clarify how different Level(s) work, under which requirements, and provide further indications to make sense of the results - For Level 2, refer to harmonised databases to avoid possible biases in the comparison between different building projects

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