Sustainability Tools for the Assessment of Construction Materials and Buildings

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The construction industry, contributing to about 9% of the European Union's GDP, has played a significant influential role in the development of the energy strategy of Europe and is also anticipated to be an important contributor in its successful implementation (EC, 2016). Holistic sustainability assessment tools that are able to evaluate and optimise the environmental performance of construction materials and buildings are considered a key for the development of advanced building designs and use of sustainable building materials and elements and green energy- efficient systems that will raise high the sustainability level of the European built environment. The aim of this work is the thorough explanation of the standardised LCA methodology, and the introduction of the approach of EcoHestia, a comprehensive building sustainability assessment tool. In view of that, the current legislation addressing the construction industry, as well as the state-of-the- art Life Cycle Assessment (LCA) tools that are used for the sustainability assessment and optimisation of construction materials and buildings are also presented. Furthermore, through the employment of EcoHestia, the environmental impact of a case study building is defined, also providing a detailed breakdown of the contribution of each construction material in the overall environmental performance of the building. The analysis of the results has not only determined on the construction materials of the building that are most harmful to the natural resources and the environment, but also showcased the effectiveness and added value of utilizing this approach in moving forward towards a more sustainable green building sector.

KEYWORDS: building material, EcoHestia, environmental performance, LCA, sustainability tool.

Introduction

With almost half of the energy and material consumption and a third of the waste generation and water consumption of the total European Union's figures, buildings are having a great weight on the energy strategy of Europe (COM(2007)860; COM(2011)571). Legislation is motivating research communities worldwide to develop more efficient and more transparent methodologies and tools for assessing the sustainability of buildings as a whole, as well as all the sustainability of the elements that make up a building. And there is a common consensus, among politicians, scientists and industry experts, which establishes Life Cycle Assessment (LCA) as the best framework for evaluating the performance of buildings and construction products currently available (Recommendation 2013/179/EU; Bernstein and Mandyyck, 2013). The sustainability performance of any

construction product or building is the sum of the energy and environmental benefits gained and energy consumption and environmental deterioration arising from the extraction of the raw materials, the manufacturing of the product or the construction of the building, the operation and maintenance phase, and the selected waste management route. Taking into consideration the impact from all of the phases of the investigated object's life cycle, it can be stated that decision- making is not anymore a point of perception or opinion, but is ought to be based on reliable and transparent evidence. Standardisation of the LCA methodology for having common grounds for measuring and communicating the life cycle environmental performance of products or systems has been established a decade ago (ISO 14040:2006), and it seems to make headway at a rapid pace.

Motivation for the development of sustainability tools

Legislation developed specifically for construction materials aspires the elimination of technical barriers that limit their trading within the market. The Construction Products Regulation establishes harmonised technical specifications on the assessment of the performance of construction products and on the use of CE marking on them (Regulation No 305/2011). Yet, a large part of the equation for the achievement of a nearly zero energy European building stock (Energy Performance of Buildings Directive (EPBD) 2010/31) and an Energy Efficient Europe (Energy Efficiency Directive 2012/27/EC) is the development and use of sustainable materials, green technologies and energy-efficient systems in both new and refurbished buildings. References to construction products are also indicated in the Ecodesign Directive (Directive 2009/125/EC), establishing a framework where the design of a number of energy- related products, also referring to construction such as windows, insulation materials, should be optimized for minimum environmental deterioration and maximum cost savings. Several additional European initiatives are found aligned and complement the existing policies with reference to the construction sector on resource efficiency and sustainability aspects. The key objective of the Roadmap to a Resource Efficient Europe (COM(2011)571) is to actively involve achieve the whole value chain of the sector in order to achieve significant improvements in the energy, material, and water consumption. The initiative also envisions the transformation of the building stock through the use of life cycle approaches for the development of advanced building designs, incorporation of improved sustainable construction materials and elements and sustainable reuse/ recycling of Construction Demolition Waste (CDW). Aligned with the Resource Efficient Europe goal is the strategy for the sustainable competitiveness of the construction sector and its enterprises, where the Union recognises the level of significance of construction SMEs on adopting resource efficient building methodologies and practices for tackling societal challenges and boosting the European construction sector globally (COM(2012) 433). The European initiative on resource efficiency opportunities in the building sector (COM(2014)445) highlights the importance of reducing the environmental burden of buildings throughout all the stages of its lifetime. The communication promotes, among others, the more resource efficient manufacturing of construction materials through the reuse of existing materials, the incorporation of recycled materials and the use of waste as fuel.

State-of-the-art sustainability tools

The collaboration between the construction industry and the relevant research community has led to the development of state-of-the-art sustainability assessment tools that are able to evaluate the life cycle environmental impact of building materials and buildings. A total of nineteen building environmental assessment tools, the majority of which are coming from European countries, have been reported to deploy LCA for their evaluation methodology (Castellano et al., 2014). Popular examples include the Green Guide of the Building Research Establishment Environmental Assessment Method (BREEAM) (UK), ATHENA (Canada), Eco Quantum (Netherlands), EcoEffect (Sweden), ENVEST (UK), and Comprehensive Assessment System for Built Environment Efficiency (CASBEE) (Japan). The Green Guide is part of the BREEAM, an accredited environmental rating

scheme for buildings, and contains more than 1500 specifications used in a variety of types of building. The underlying LCA methodology enables the rating of the environmental performance of buildings by separating the parts of buildings into elemental categories (BRE, 2015). The Athena Sustainable Materials Institute has developed two LCA tools; the Athena Impact Estimator for Buildings and the Athena EcoCalculator for Assemblies, where the latter allows for a more detailed and accurate assessment of the buildings' environmental impact. Their databases provide cradle-to-grave information for building materials and products, transportation, construction, as well as demolition processes (Athena Sustainable Materials Institute, 2016). It is also worth mentioning that one of the most popular sustainable building certification programs, Leadership in Energy and Environmental Design (LEED) (USA), has also incorporated LCA in its latest released rating system (USGBC, 2016). The most common cited LCA software tools in the construction industry, also employed for the majority of the forth mentioned state-of-the-art sustainability assessment tools include GaBi and SimaPro. The two represent the most well- established product sustainability solutions for LCA with over 25 years of experience and collaboration with leading LCA professionals and industry experts. Additionally, the reliability of results of both tools is further enhanced through the incorporation of the world's most consistent and transparent Life Cycle Inventory (LCI) database, Ecoinvent. However, regional legislation in combination with globalization has made the sharing of best practices and expertise much easier than ever. However, types of information or data that might be applicable for one country may not be suitable for another. Accordingly, there is the necessity for the introduction of a common framework for implementing LCA studies on assessing the sustainability of building materials, but at the same time in-depth development and understanding of specific country and local data is also needed on the subject (World Green Building Council, 2013; Kylili and Fokaides; 2016).

Life Cycle Assessment (LCA) methodology

Methods

The international standard on LCA is providing the methodology on implementing LCA for the evaluation and interpretation of the potential life cycle environmental impacts arising as a result of a product or system (ISO 14040:2006). The transparency of the methodology is attributed to a four-stage path; including the goal and scope definition, the inventory analysis, the impact assessment and the interpretation of the results stages.

The Goal and Scope Definition phase defines the object under investigation for the conduction of the LCA study, including its key objectives. In this phase, the functional unit, the system boundaries, the data requirements, the limitations and assumptions to be considered in the study are also presented in detail. Next is the LCI phase, which represents the data collection share of the study. The deliverable of the LCI phase is a list of all inputs and outputs, including raw materials, energy, and emissions and other waste released into the natural environment, in relation to the system under investigation throughout its whole life cycle. The Life Cycle Impact Assessment (LCIA) phase evaluates all inputs and outputs, as defined in the previous stage, into potential environmental impact into selected environmental impact categories. The list of environmental impact categories varies according to the evaluation method followed, however all LCIA methods should cover all certain impact categories according to the International Reference Life Cycle Data System (ILCD) handbook (Wolf et al., 2012). The ILCD handbook was developed and established by the Institute for Environment and Sustainability in the European Commission Joint Research Centre (JRC) and the Environment DG through a series of public and stakeholder consultations (JRC, 2014). LCIA results can support the definition of the main contributors of environmental benefits or deterioration at the selected impact categories that can be further exploited for the improvement/ optimisation of the system's under investigation environmental performance. The final Interpretation of the Results phase engages with the reporting of the findings and recommendations in relation to the initial objectives of the LCA study.

EcoHestia building sustainability assessment tool

EcoHestia is a comprehensive environmental impact LCA tool that integrates the most commonly- used building elements for Cyprus (SERG, 2016). EcoHestia performs 'cradle- to- gate' LCA of buildings based on inventory data of construction materials and building elements. This data is in fact based on the characteristics of Cyprus and primary sources from the local construction industry. Personal communications with local construction materials manufacturers have established the required amounts of raw materials and energy for the manufacturing of the final products. The fuels required for electricity generation, as well as transportation are also representative of the country's facts. Transportation distances have been calculated using map applications, while average emission factors for Cyprus' energy generation and transportation have been also been extracted from validated databases (GaBi database). The analysis of EcoHestia is according to the principles described in the ISO 14040 standard and employs the GaBi software and CML 2001 methodology. Accordingly, EcoHestia's LCIA generates the potential impact of the building, on the following environmental impact categories:

- _ Global warming potential (GWP 100 years) in [kg CO_2-Equiv.]
- _ Acidification potential (AP) in [kg SO_2-Equiv.]
- _ Eutrophication potential (EP) in [kg Phosphate-Equiv.]
- _ Ozone layer depletion potential (ODP, steady state) in [kg R11-Equiv.]
- _ Abiotic depletion potential of elements (ADP Elements) in [kg Sb-Equiv.
- _ Abiotic depletion potential of fossils (ADP Fossils) in [MJ]

- _ Freshwater aquatic ecotoxicity potential (FAETP) in [kg DCB-Equiv.]
- _ Human toxicity potential (HTP) in [kg DCB-Equiv.]
- _ Marine aquatic ecotoxicity potential (MAETP) in [kg DCB-Equiv.]
- _ Photochemical ozone creation potential (POCP) in [kg Ethene- Equiv.]
- _ Terrestric ecotoxicity potential (TETP) in [kg DCB-Equiv.]

Fig. 1

The approach adopted by EcoHestia, a comprehensive building sustainability assessment tool
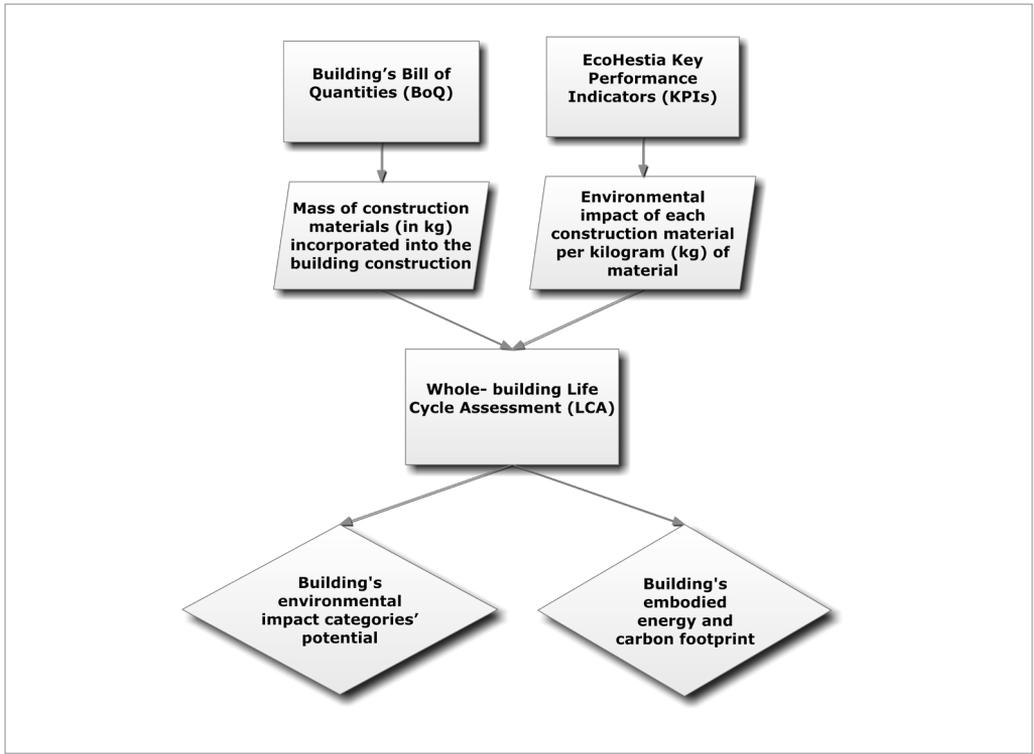
Additionally, ECOHESTIA also generates the building's carbon footprint (CF) in carbon dioxide-equivalent (CO_2- equiv.) and non- renewable embodied energy (NRE) in MegaJoules (MJ).

The approach employed by the building sustainability assessment tool is straightforward and friendly towards its users. Quantity data for each construction material incorporated into the building under investigation is extracted from its Bill of Quantities (BoQ). This data is used as an input in the EcoHestia tool. For the generation of the LCIA results, this data are evaluated against the Key Performance Indicators (KPIs) of the tool (Fig. 1). The EcoHestia KPIs represent the environmental impact of each construction material per kilogram (kg) of material, considering all the raw materials and energy requirements for its manufacturing at the plant and its transportation to the construction site. The final LCIA results are provided per construction material.

Case study building

EcoHestia has been used for the implementation of the LCA of a level- ground, two- storey residential building located in Nicosia, Cyprus. The building's total useful floor area, including covered and uncovered areas, is 315 m^2, while its total height is 11.5 m. The construction of the case study building is typical of the country's building stock. With reference to the building's BoQ, the masonry incorporates concrete, brickwork, and plasterboards. Expanded polystyrene was incorporated into the building envelope for insulation purposes, plasterboard used as a roof in all floors, and the building's doors and windows are made of aluminium.

The EcoHestia generated results for the case study building per construction material are presented in Table 1. The table indicates the life- cycle impact potential of each of the building's materials for the selected impact categories. For comparison purposes, the results are also illustrated in terms of the percentage contribution of each construction material in the overall environmental impact in Fig. 2.

Methods

It is evident that concrete, C20/C25 and C30/C37, are the greatest contributors across the majority of the impact categories. This is attributed to both the energy- consuming process of cement manufacturing and associated high carbon emissions, as well as the large quantities of materials that were required for the construction of the building (Pelisser et al., 2012; Chrysostomou et al., 2015; Teixeira et al., 2016; Vieira et al., 2016). In fact, the share of contribution of C30/C37 ranges between 42% and 46% except the ODP category which is 7%. Similarly, C20/C25 contribution ranges between 24% and 31% and only 1.6% in the ODP category.

Aluminium and steel also heavily burden the environmental impact of the building, as a result of their high non-renewable energy consumption for their manufacturing (EcoHestia database).

A/A	Construction material	Quantity	Unit
A	Concrete Works		
	C20/25	391200	kg
	C30/37	530400	kg
B	Steel	51000	kg
C	Brickwork		
	Thermal brick 30cm	17222	kg
	Thermal brick 25cm	24605	kg
	Thermal brick 20cm	46683	kg
D	Plasterboard	1456	kg
F	Insulation materials		
	EPS	340,5	kg
G	Plaster	5760	kg
H	Interior Paint	86,1	kg
I	Exterior Paint	65,475	kg
J	Aluminium	25760	kg
K	Glass	2300	kg
L	PVC	12,9	kg

Table 1

Summary of Bill of Quantities (BoQ) of case study building

A/A	Construction material	Quantity	Unit	GWP	AP	EP	ODP	ADP elements	ADP fossils	FAE TP	HTP	MAETP	POCP	TETP	CF	NRE
A	Concrete Works															
	C20/25	163	m³	5,0 E+05	4,13 E+03	1,51 E+02	2,38 E-07	9,42 E-02	6,24 E+06	4,61 E+04	5,17 E+07	2,34 E+02	2,12 E+02	1,15 E+03	4,9 3E+05	6,69 E+06
	C30/37	221	m³	7,18 E+05	6,03 E+03	2,21 E+02	1,04 E-06	1,63 E-01	9,12 E+06	6,74 E+03	7,58 E+04	3,45 E+07	3,15 E+02	1,71 E+03	7,00 E+05	9,81 E+06
B	Steel	51000	kg	1,36 E+05	7,97 E+02	4,49 E+01	2,03 E-07	7,94 E-03	2,30 E+06	6,87 E+02	9,93 E+03	6,10 E+06	4,62 E+01	1,92 E+02	1,30 E+05	2,43 E+06
C	Brickwork															
	Thermal brick 30cm	109	m²	1,37 E+04	1,15 E+02	4,23 E+00	1,69 E-08	6,82 E-04	1,74 E+05	1,29 E+02	1,44 E+03	6,54 E+05	5,96 E+00	3,29 E+01	1,33 E+04	1,88 E+05
	Thermal brick 25cm	133	m²	1,95 E+04	1,64 E+02	6,04 E+00	2,41 E-08	9,74 E-04	2,49 E+05	1,84 E+02	2,06 E+03	9,34 E+05	8,52 E+00	4,70 E+01	1,90 E+04	2,68 E+05
	Thermal brick 20cm	171	m²	3,70 E+04	3,11 E+02	1,15 E+01	4,57 E-08	1,85 E-03	4,71 E+05	3,49 E+02	3,91 E+03	1,77 E+06	1,62 E+01	8,92 E+01	3,61 E+04	5,09 E+05
D	Plaster-board	208	m²	2,20 E+04	1,42 E+02	6,53 E+00	1,76 E-08	1,37 E-03	2,52 E+05	1,20 E+02	1,86 E+03	1,22 E+06	7,68 E+00	3,59 E+01	2,10 E+04	2,68 E+05
F	Insulation materials															
	EPS	227	m²	8,36 E+02	2,10 E+00	1,87 E-01	5,21 E-08	2,32 E-04	2,60 E+04	7,33 E+00	4,04 E+01	2,60 E+04	3,00 E-01	5,03 E-01	7,63 E+02	2,87 E+04
G	Plaster	1920	m²	2,13 E+03	1,21 E+01	5,44 E-01	6,78 E-09	1,50 E-03	2,02 E+04	1,36 E+01	1,51 E+02	7,42 E+04	5,27 E-01	5,76 E+00	2,09 E+03	2,19 E+04
H	Interior Paint	615	m²	3,44 E+01	1,37 E-01	1,38 E-02	5,66 E-09	1,11 E-05	1,07 E+03	3,18 E-01	2,02 E+00	1,78 E+03	2,42 E-02	2,90 E-02	3,12 E+01	1,21 E+03
I	Exterior Paint	485	m²	4,41 E+01	1,74 E-01	1,81 E-02	7,57 E-09	1,35 E-05	1,43 E+03	4,20 E-01	2,57 E+00	2,20 E+03	3,23 E-02	3,35 E-02	3,99 E+01	1,62 E+03
J	Aluminium	92	m²	2,07 E+05	1,67 E+03	6,31 E+01	1,31 E-05	9,93 E-02	2,59 E+06	1,84 E+03	2,11 E+04	1,02 E+07	8,97 E+01	4,80 E+02	2,01 E+05	2,83 E+06
K	Glass	54	m²	5,33 E+03	4,21 E+01	2,05 E+00	3,60 E-08	1,33 E-02	6,74 E+04	4,41 E+01	4,94 E+02	2,37 E+05	2,33 E+00	1,15 E+01	5,18 E+03	7,29 E+04
L	PVC	87	m²	6,82 E+01	4,61 E-01	2,05 E-02	1,56 E-10	9,46 E-05	7,90 E+02	4,26 E-01	5,95 E+00	3,60 E+03	2,52 E-02	1,21 E-01	6,55 E+01	8,45 E+02
	TOTAL			1,67 E+06	1,34 E+04	5,11 E+02	1,48 E-05	3,85 E-01	2,15 E+07	1,47 E+04	1,68 E+05	7,91 E+07	7,05 E+02	3,59 E+03	1,62 E+06	2,31 E+07

Aluminium has the highest contribution in the ODP category, 88% of the total in particular, arising mainly from the alumina processing phase. The specific material that is used for the building's doors and windows has also the second highest in ADP category after C30/ C37. Its share for the rest of the categories is approximately 12% of the total impacts. Steel used for reinforcement, on the other hand is indicating a strong weight (10%) for the abiotic depletion of fossils.

Regardless of their low embodied energy and carbon footprint, when summed brickwork is attributed approximately the 4.5% of the overall environmental impact across all categories, except the ODP and ADP elements categories, where their share is insignificant. In fact, the most environmentally-destructive processes in brick manufacturing are mainly their final phase during
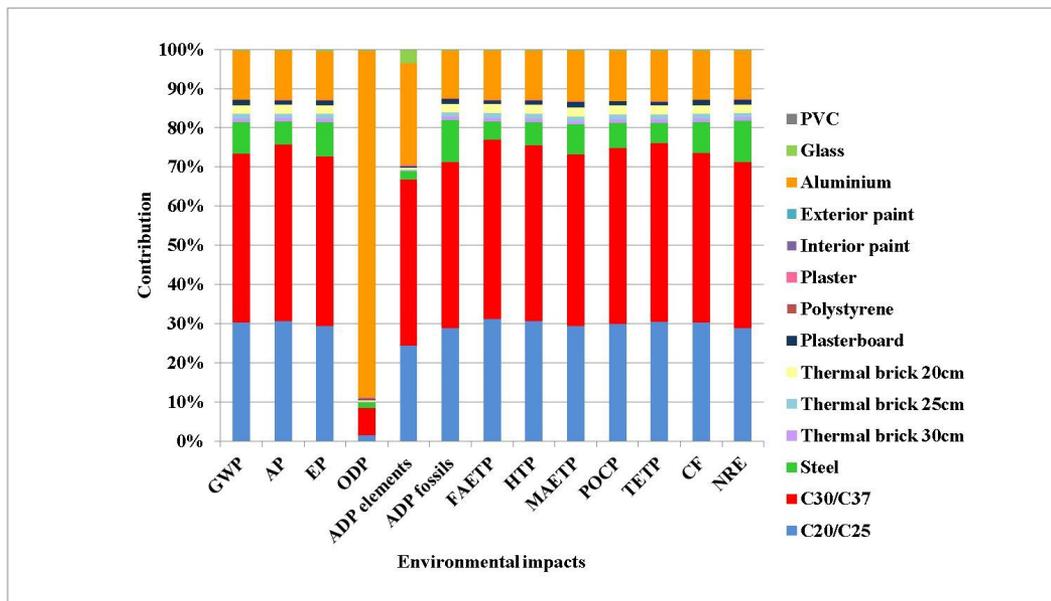
Fig. 2

Percentage contribution of construction materials in the overall performance of the case study building in selected environmental impacts

which brick are dried and fired, and the crushing and milling stage of the raw materials (EcoHestia database).

Notable is also the contribution of plasterboard, which accounts to around 1% to the majority of the selected categories, considering its small quantities used for the building's construction. Its low environmental performance is mainly the result of the calcine system, as well as the crushing and grinding preceding this stage.

Similarly despite the relatively high embodied energy and carbon footprint of PolyVinyl Chloride (PVC), its share of impact on the overall building's environmental performance is minor due to the low quantities of installation. Negligible is also the contribution of the exterior and interior paint in the overall impact of the case study building.

Conclusions

The existing energy policies and legislation are calling the construction industry for advanced building designs, use of sustainable building materials, green technologies and energy-efficient systems, and increased reuse and recycling rates of waste for improved energy efficiency and reduced energy consumption. The realization of these key goals is facilitated through the employment of holistic sustainability assessment tools that are able to evaluate and optimise the environmental performance of construction materials and buildings. Often enough, the coupling of these methodologies with design tools allow the optimisation even at an early design phase of new buildings or existing building that are planned to undergo renovation (Kylili et al., 2015). The effectiveness and added value of employing a LCA sustainability assessment tool has been presented in this work. EcoHestia, a comprehensive building environmental assessment tool for the case of Cyprus, has illustrated its potential in providing in detail the environmental contribution of each construction material in the overall environmental performance of the building. The LCIA results have indicated that concrete is the most environmentally destructive material in the construction, accounting for at least the 66% of the building's overall environmental impact, with an exception of the ozone depletion impact. Steel used for reinforcement and aluminium for doors and windows have also been shown to carry a significant share of the overall performance, and in particular in the abiotic depletion of fossils potential and the ozone depletion potential, respectively. By providing a breakdown of the construction materials' environmental impact, EcoHestia can assists the construction industry as well as the relevant scientific community in deciding which

route to follow and what should be the focus towards the greening of the built environment. It is a decision- making tool, which provides answers in the questions surrounding the improvement of the sustainability level of the building sector with reliable and transparent evidence. EcoHestia also promotes the in-depth development and employment of country- specific and local data for the implementation of LCA studies for the construction sector and beyond.

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