

Review

A Systematic Review of the Discrepancies in Life Cycle Assessments of Green Concrete

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Abstract: It is challenging to measure the environmental impact of concrete with the absence of a consensus on a standardized methodology for life cycle assessment (LCA). Consequently, the values communicated in the literature for “green” concrete alternatives vary widely between 84 and 612 kg eq CO₂/m³. This does not provide enough evidence regarding the acclaimed environmental benefits compared to ordinary Portland cement concrete knowing that the average for the latter was concluded in this study to be around 370 kg eq CO₂/m³. Thus, the purpose of this study was to survey the literature on concrete LCAs in an attempt to identify the potential sources of discrepancies and propose a potential solution. This was done through examining 146 papers systematically and attributing the sources of error to the four stages of an LCA: scope definition, inventory data, impact assessment and results interpretations. The main findings showed that there are 13 main sources of discrepancies in a concrete LCA that contribute to the incompatibility between the results. These sources varied between (i) user-based choices such as depending on a cradle-to-gate scope, selecting a basic volume-based functional unit and ignoring the impact allocation and (ii) intrinsic uncertainty in some of the elements, such as the means of transportation, the expected service life and fluctuations in market prices. The former affects the reliability of a study, and hence, a concrete LCA methodology should not allow for any of the uncertainties. On the other hand, the latter affects the degree of uncertainty of the final outcome, and hence, we recommended conducting scenario analyses and communicating the aggregated uncertainty through the selected indicators.

Keywords: green concrete; life cycle assessment; environmental impact assessment; inventory data; allocation; functional unit; service life

1. Introduction

For every living individual, around 4 tonnes of conventional concrete, comprised primarily of ordinary Portland cement (OPC) and naturally sourced aggregates (NA), were produced in 2015 [1]. Due to its inherent strength and durability properties, concrete is the second most used substance on Earth after water [2]. Unfortunately, the use of concrete is associated with immense negative environmental impacts. The current production rate of more than 4 billion tonnes of OPC annually is responsible for 7% of the global CO₂ emissions [3]. It also risks depleting natural resources, since more than 50 billion tonnes of aggregates are being extracted annually [4]. Concrete has an environmental impact of 320 kg eq CO₂/m³ on average as will be concluded in the next section of this paper, of which

90% is attributable to OPC [5]. Although this is less than that of steel and most polymers per unit mass [6], the intensive use of OPC concrete results in alarming environmental hazards. In China for example, the over-reliance on concrete alone resulted in approximately 1.5 billion tonnes of greenhouse gases (GHG) emissions in 2014 [7], which represents around 20% of the total produced in the same year [8]. Nevertheless, projections indicate that the growing global urbanization will double the demand on concrete by 2050 [9].

Hence, recent research has been directed to meet the “2015 Paris climate conference” guidelines of enhancing the sustainability of concrete [10]. As seen in Figure 1, there are five main families of concrete types found in the literature that are considered more eco-friendly [11–49]. Those are the types that were chosen to be studied in this paper as a sample for green concrete. First, there is the use of natural materials, such as bacteria, and agricultural waste, such as hemp [11], in order to create natural biological concrete (BioC) with reduced environmental impact. Second, there is recycling aggregate concrete (RAC), where construction and demolition wastes (CDWs) are used as aggregates in concrete. This reduces the landfill potential of concrete by 50–75% and its embodied carbon by 10–30% [12,13]. Blended cement concrete (BCC), where OPC in the binder, is partially replaced with various pozzolanic materials called supplementary cementitious materials (SCM), and is considered the third family. Examples of these are secondary materials such as fly ash (FA), which is a by-product of coal combustion; ground granulated blastfurnace slag (GGBS) which is a by-product of steel manufacturing; and silica fume (SF), which is generated from glass manufacturing. Additionally, some primary materials that are manufactured with lower energy demands than OPC can be used to partially replace it, such as calcined clay (CC) and lime. The mechanical and durability properties of the resulting concretes vary significantly between the different types of materials and the percentages by which OPC is being replaced, and similarly, the environmental impact varies [50]. For example, the embodied emissions of concrete could decrease by up to 30% and 60% with the incorporation of 35% and 70% of FA and GGBS, respectively [51]. In order to totally replace OPC, alkali activated concretes (AAC), are made with precursors of 100% FA, (CC) or GGBS that are activated using an alkaline solution from usually sodium hydroxide or sodium silicate. This is the fourth concrete type selected in this study. AAC causes 70–75% less GHG emissions compared to OPC concrete [52]. The fifth family is high performance concrete (HPA), which is recognized as a concrete type with enhanced mechanical and durability properties compared to OPC concrete (OPCC). This allows for a reduction in the required volume of concrete in certain applications. Additionally, the concrete mixes are prepared with fillers such as lime powder to increase the particle packing of the mixing components, which minimizes the required amount of binder [15]. This potentially yields a binder with less environmental impact than OPCC.

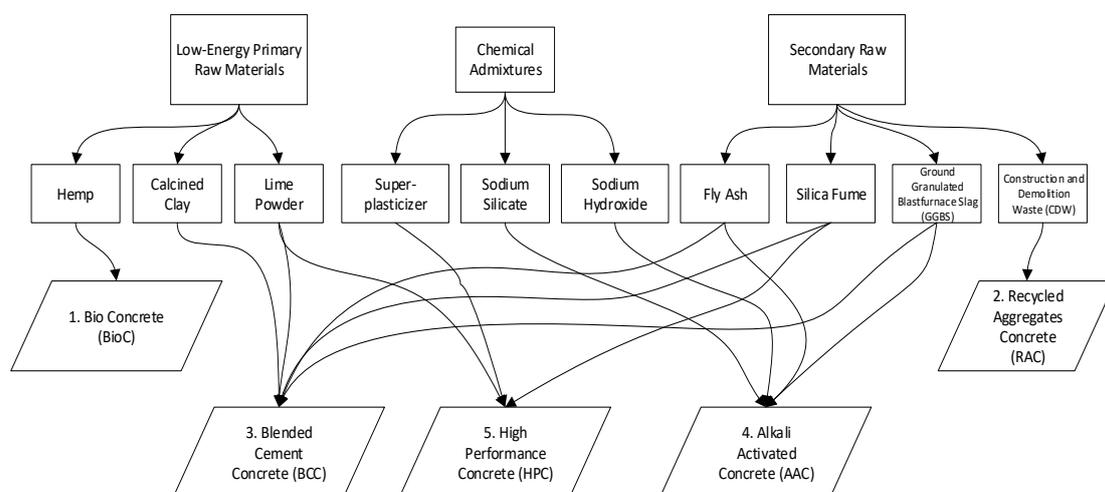


Figure 1. Green concrete strategies and types.

Therefore, the starting point of studying a green concrete type is to create alternative concrete types that reduce the environmental impact of OPCC [52]. Life cycle assessment (LCA) is the most widely-accepted tool to assess and compare these acclaimed environmental benefits [53]. According to ISO 14040:2006, LCA is defined as “the compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle.” An LCA study is divided into four main stages: (i) Scope and goal definition. (ii) Defining the inventory for the life cycle processes. (iii) Characterizing and measuring the life cycle impact. (iv) Interpretation of the results [54]. First, goal and scope definition involves outlining the system boundary, the functional unit (FU) selection and any assumptions and/or limitations that need to be considered. A system boundary of a concrete product could be cradle-to-gate, which means including all processes and emissions until the production of its different constituents, or cradle-to-grave which includes the “Use” and “End-of-Life” phases as per Figure 2 [55]. A Cradle-to-Cradle LCA scope is that which assumes that all waste generated will be recycled in the future [23].

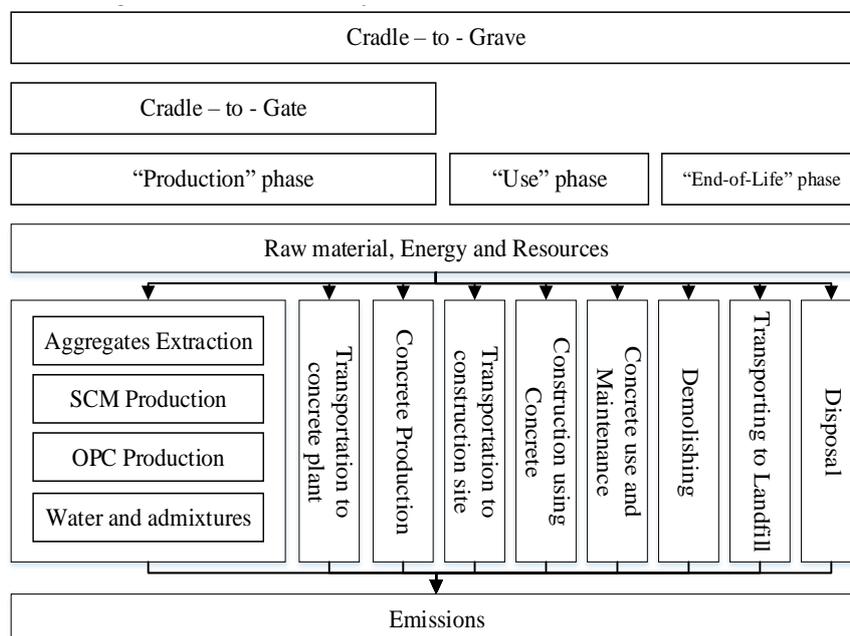


Figure 2. Different system boundaries of green concrete life cycle assessment (LCA) [21].

A FU is the basis for quantifying the inputs and outputs between alternatives. Hence, its selection needs to be reflective of the nature of the LCA subjects [56]. The second LCA stage includes collecting the data of energy and emissions associated with the aforementioned scope. The data needed for standard processes can mostly be obtained from primary sources or found in databases such as Ecoinvent and European reference Life Cycle Database (ELCD) [57]. A further source of inventory data is the environmental product declarations (EPD) of the concrete’s raw materials, which are produced by the local manufacturers according to a local binding legal framework [16]. At this stage, it is also important to decide on allocation, which is basically portioning the environmental burden of the original process to the product under study [17]. The third and final stage of an LCA is to calculate the environmental impact of the product being studied. This is performed by adding up the individual impacts of all the associated processes as per ISO 14040:2006 to calculate an environmental impact indicator, a number that makes the output of the impact assessment study more understandable to the user [58]. According to Menoufi [59], there are two main types of indicators: mid-point indicators, which correlate with the estimated impact of a specific change in the environment, such as global warming potential, and end-point indicators, which correlate that same impact to damages via cause–effect changes, such as human health.

As explained before, the LCA of green concrete cannot be easily assessed. In fact, there are a lot of uncertainties in the assessment process due to lack of a standardized methodology. To highlight this issue, an attempt was made by this study to compare the absolute values for the environmental impacts of the aforementioned green concrete types to that of OPCC, by considering around 300 different mixes from 39 journal papers [11–49]. Using the most predominant environmental impact indicator, global warming potential (GWP), the impact per unit volume of the concrete mixes varied between 110 and 600 kg eq CO₂/m³, as shown in Figure 3. Assuming the results from these values have a normal distribution, the mean value would be around 320 kg eq CO₂/m³ while the standard deviation would be around 90 kg eq CO₂/m³. This is indicative of large discrepancies that could challenge the original argument that these concrete mixes cause less environmental impact compared to OPCC. Nonetheless, the absolute values communicated for the OPCC using the same indicator (GWP) were found to also vary widely. Upon reviewing 80 mixes from 20 papers, the mean value was found to be around 370 kg eq CO₂/m³ with a standard deviation of around 110 kg eq CO₂/m³, as shown in Figure 3. Therefore, this systematic review paper was presented in order to critically examine each stage of the LCA studies carried out by researchers in the domain of green concrete in order to identify the sources of the discrepancies. Huijbregts [60] attributes these large discrepancies to the uncertainties involved in the current use of LCA methodology. Hafliker [61] claim that the source of these uncertainties are modelling choices by the user of the system boundary, FU and source of data. On the other hand, Menoufi [27] differentiates between the uncertainties due to the nature of the inventory data used and those from choices such as the impact allocation and FU. The first affects the precision of the results due to the fact that the elements included in the study include a percentage of uncertainty, while the latter affects the reliability of the study. Hence, in this paper, which is the first of its kind to systematically tackle the sources of discrepancies in concrete LCA studies, the same categorization will be followed. Hence, the objective of this review was to provide the concrete LCA user with a coherent, state-of-the-art guide to avoid the sources of reliability error and to solve the issues caused by the sources of uncertainty.

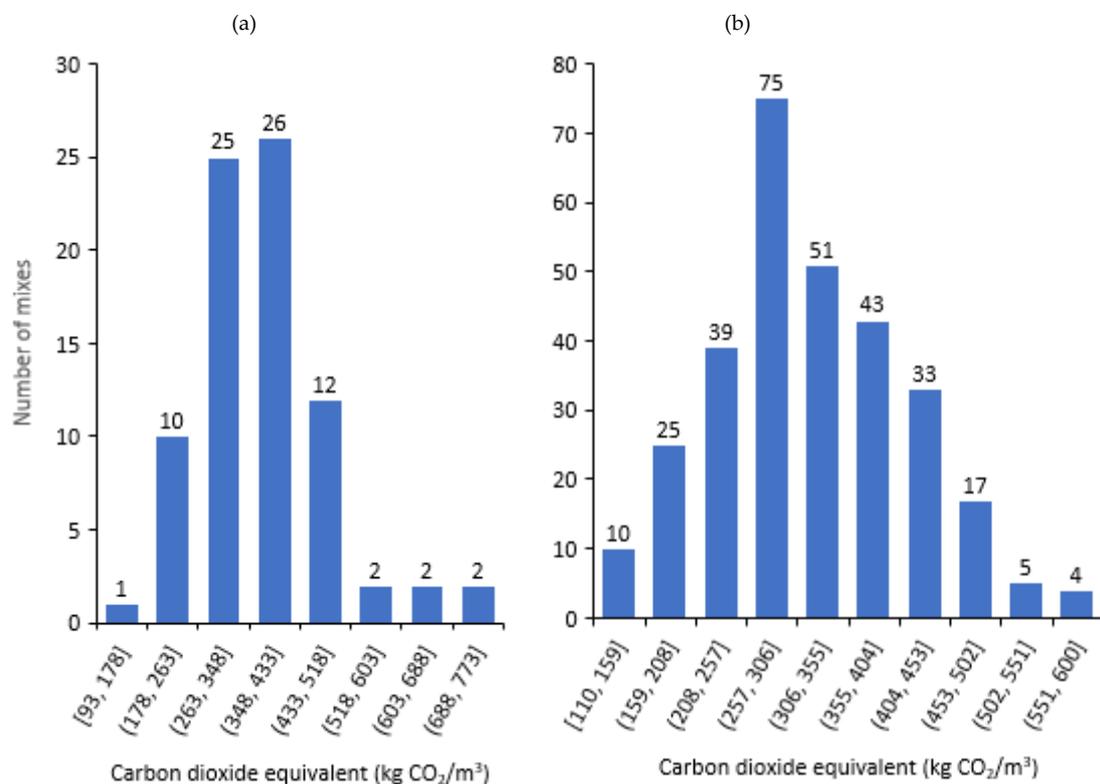


Figure 3. A review of the values for the equivalent kg CO₂/m³ of: (a) 80 Ordinary Portland Cement Concrete (OPCC) mixes and (b) 300 mixes of all 5 concrete types studied from the literature.

2. Methodology of the Systematic Review

The scope of the systematic review was to examine the methodology of LCA studies performed on green concrete, along with OPCC, in order to track down the sources of discrepancies. A total of 11,000 references were found after searching online databases such as Science Direct, Taylor and Francis and Scopus using a combination of the following keywords:

- LCA;
- Concrete;
- Cement;
- SCM;
- Sustainable;
- Methodology.

First, the references were filtered based on their titles, then on their abstracts, and finally, on full paper analysis. The point of preference was that the study included either an LCA study on an OPCC or any of the green concrete types in the scope (exploratory) or a review of the environmental impact of any of these types; or it could be a paper that studies the methodology of a concrete LCA. The 146 references [14–159] selected were divided into categories: 107 “exploratory” articles, 23 “methodology” articles, and 16 reviews. The distribution of the exploratory LCA references between the six concrete types studied was found to be almost 50% BCC, as shown in Figure 4a. In addition, most of the references were published during the last 10 years (2009–2019) as seen in Figure 4b. The countries of origin of the publications are shown in Figure 4c. The method followed in order to come up with the sources of discrepancies was examining the methodology of each of the 107 “exploratory” studies and pointing out anomalies across the four LCA stages. Hence, the review is divided into four subsections, for each of the sources found in the corresponding LCA stages as follows.

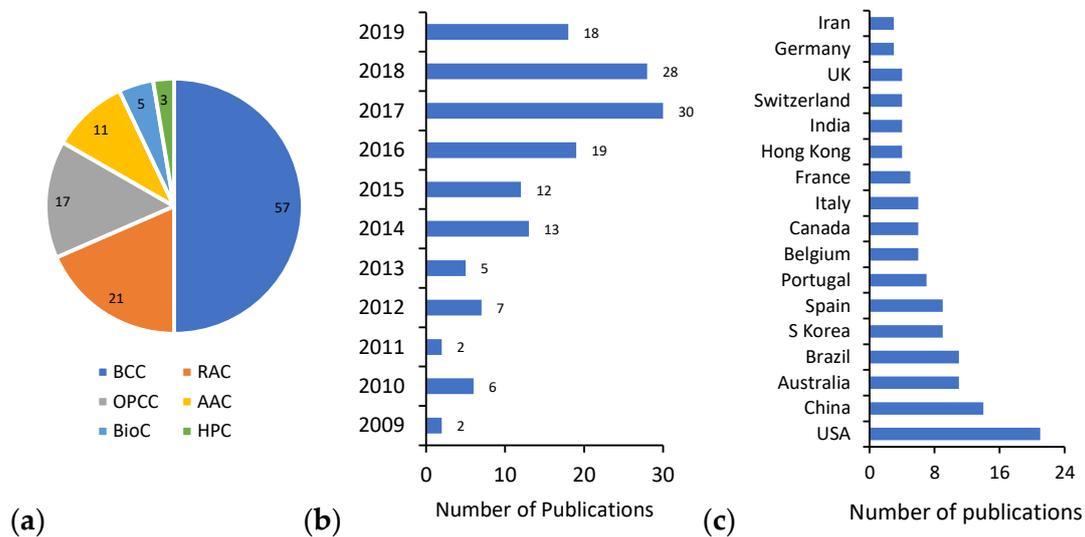


Figure 4. Number of LCA studies per (a) type of concrete, (b) published year and (c) country.

3. Sources of Discrepancies in LCA Stages

3.1. Stage 1: LCA Scope

3.1.1. System Boundary

More than 75% of the studies (107) we reviewed, in which an LCA study was actually conducted, used a cradle-to-gate system boundary, as shown in Figure 5. A cradle-to-gate system boundary would limit the scope of the processes and resulting emissions and energy studied in the LCA up until the

production stage, excluding the use and end-of-life stages. As stated by Wu et al. [24] the ISO 24067, released in 2013 to provide a benchmark for the LCA methodology, specifies that for a user to exclude the use and end-of-life stages while conducting an LCA, there needs to be enough evidence that the results will not be affected by this. Hence, it would not be acceptable to cut-off the use and end-of-life phases from the scope due to the following reasons (i–iii):

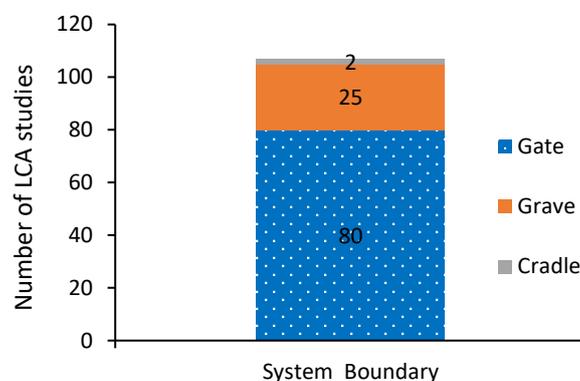


Figure 5. Meta-analysis of the selected system boundary for each of the LCA studies reviewed in this paper.

(i) Throughout its “use” phase, concrete exhibits carbonation, a process by which carbon dioxide is absorbed by the concrete from the exposed environment reacting with the calcium compounds in its matrix, forming carbonates [62]. A justifiable cut-off percentage is when the processes affects less than 1% of the total environmental impact according to Wu et al. [16] and 5% according to Gursel et al. [63]. However, through the carbonation process, concrete can absorb, throughout its whole service life, 13–48% of the carbon dioxide it emitted during the production phase [62]. This value of the captured carbon dioxide, denoted as carbon sequestered, varies depending on the concrete type, exposure conditions and geometry [44]. Out of the 107 references, only seven included the sequestered carbon in the LCA study, with varying values, as seen in Table 1. OPCC can capture up to 47% of its embodied carbon during use and end-of-life phases, while BCC can capture only up to 22% [39]. In all cases, it is apparent that the sequestered carbon ought to be included in an LCA study to allow for its value to be deducted from the carbon emissions in the remaining processes.

Table 1. The different values for carbon sequestration from the papers reviewed.

References	First Author’s Last Name	Year	Kg CO ₂ /m ³
[62]	Collins	2010	5
[29]	Garcia-Segura	2013	61
[64]	Kim and Chae	2016	172
[65]	Lee	2013	10
[46]	Panesar and Churchill	2010	30 *
[66]	Zhang	2019	39 *
[44]	Souto-Matrinez	2017	60

* Calculated based on a percentage of the 320 eq CO₂/m³ average value.

(ii) By omitting the use phase, the user is also assuming that all concrete mixes being compared will sustain the required service life. However, the findings in Table 2 show proof from the literature that this assumption is not true. Depending on the exposure conditions, concrete cover and the concrete mix, there is a high probability that a reinforced green concrete mix is unable to fulfil its required service life, especially one above 60 years [61]. Hence, according to Panesar et al. [56], there should be at least a 20% increase in the environmental impact of concrete to account for the potential maintenance

that allows it to fulfil its service life requirements. Nevertheless, Tae et al. [15] set the expected CO₂ emissions for concrete at 0.60 eq kg CO₂/m³/year in service. Additionally, it was also proposed that a replacement factor N, which is a ratio between the reference service life of the concrete member studied and its predicted service life, needs to be included as a multiplying factor to the environmental impact of the concrete under study to make the calculation more relative, and therefore, reliable [61]. That, then, shows that there is a major underestimation of the environmental impact—the relative and absolute environmental impacts—of concrete if the maintenance/replacement impact is not considered as a part of the “use” phase of the LCA.

Table 2. Service life predictions for different concrete types from the literature.

Reference	[36]			[46]			
	Concrete Type	OPCC	25%GGBS	50%GGBS	15% FA	35%FA	50%FA
	Cover (mm)			Service Life (Years)			
Carbonation	65	62	124	200	-	-	-
	50	124	200	200	-	-	-
	35	200	200	200	-	100	100
Chloride Penetration	65	33	68	114	-	-	-
	50	67	138	200	51	-	60
	35	91	186	200	-	-	-

(iii) Having an end-of-life phase (which could be achieved by considering a cradle-to-grave boundary or a cradle-to-cradle one) included in the LCA system boundary is a prerequisite to studying RAC. De Schepper et al. [23] assumed that the aggregates used in a concrete mix were fully recyclable. By selecting a cradle-to-cradle system boundary, it was calculated that avoiding the landfilling of concrete reduces the environmental impact compared to OPCC by 4%–15%. Ding et al. [34], they included the avoided-landfilling potential for recycled CDW in the LCA and the result was that the environmental indicator CMR, consumption of natural resources, decreased by 46%. Apart from that, when the service life of a concrete product ends, the demolition process requires energy. Whether the waste will be re-used or not is an unknown at the LCA study stage. However, as seen in Table 3, the energy and impact required for the demolition of concrete constitutes 2%–10% of an average 320 kg eq CO₂/m³ of concrete, which means that it should not be ignored.

Table 3. Some values for the environmental impact of demolishing concrete from the literature reviewed.

References	First Author's Last Name	Year	kg CO ₂ /m ³
[28]	Garcez	2017	25
[29]	Garcia-Segura	2013	5
[67]	Lopez-Gayyare	2015	13
[62]	Collins	2010	5

3.1.2. Functional Unit Selection

The second part of the LCA scope that the user selects is the FU. According Panesar et al. [56], a functional unit is the element that dictates how the inputs and outputs of the LCA are quantified. There are four main levels for functional units of concrete: a whole structure or a building, which was selected by around 6% of the 107 studies reviewed, as seen in Figure 6; or a component of a structure such as a beam, column or a bridge girder, and only 16% of the studies opted for that. The most famous level of detail (LOD) studied in concrete LCA is the material unit for concrete, which was selected by around 70% of the references. A unit-based FU for concrete is divided into: volume-based, volume-based while considering the strength of concrete and volume-based while considering both

the strength and service life of concrete. Panesar et al. [56] claims that it is not accurate to call a unit volume a FU since it is not indicative of enough comparable functional properties. It should be called a declared unit instead. However, as seen in Figure 6, 65% of the references reviewed in this paper where a unit-based FU was selected did not consider strength nor durability; 25% considered strength and only 10% considered both. According to Zhang et al. [68], depending on the type of unit-based FU selected, the results for the LCA study might vary up to 30%. In order to further investigate this through our systematic review, the following examples were prepared.

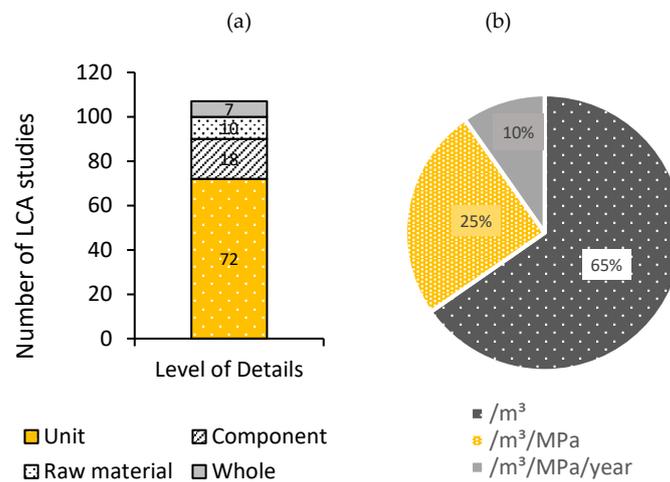


Figure 6. The division of the FU in the LCA studies reviewed based on (a) Level of Detail and (b) type of unit volume.

In terms of the difference in strength between the concrete alternatives in question, for RAC, maintaining the same binder, replacing fresh aggregates with coarse and/or fine recycled aggregates from CDW, will decrease the strength of the resulting mix (coarse aggregate (RC) and fine aggregate (RF) respectively) [58]. This decrease in strength of the concrete incorporating the recycled aggregates can sometimes be larger than the associated decrease in environmental impact. Hence, as shown in Figure 7, it is clear that when a FU of kg eq CO₂/MPa was used instead of just kg eq CO₂, the environmental impact of the mixes with the recycled aggregates turned out to be larger than that of OPCC, not less [69].

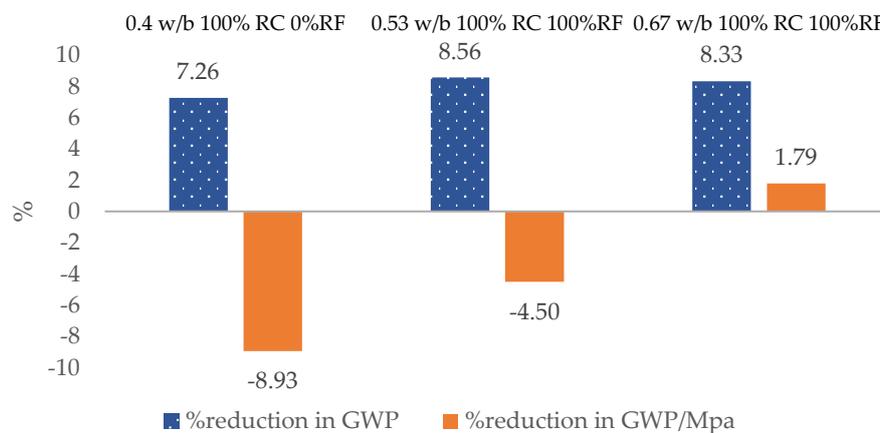


Figure 7. A comparison between the impact of a recycling aggregate concrete (RAC) using volume-based FU and a FU normalized to strength [69].

For BCC types, the results from Celik et al. [21] suggested that the optimum replacement of OPC with FA in terms of minimizing environmental impact in a BCC mix is 70%. However, adding FA

beyond a certain threshold would significantly decrease the compressive strength of concrete [35]. As seen in Figure 8, when the same GWP results were modelled using a FU of kg eq CO₂/m³/MPa instead of a volume-based kg eq CO₂/m³, the optimum replacement percentage dropped to only 40%. Smaller gaps between both FU results were found when examining the results for GGBS from Bilim et al. [19], as seen in Figure 8. This could be due to the fact that the results for the compressive strength were tested after 90 days of curing instead of the common 28, at which the pozzolanic reaction would mature and most BCC mixes would achieve comparable strength to that of OPCC [70].

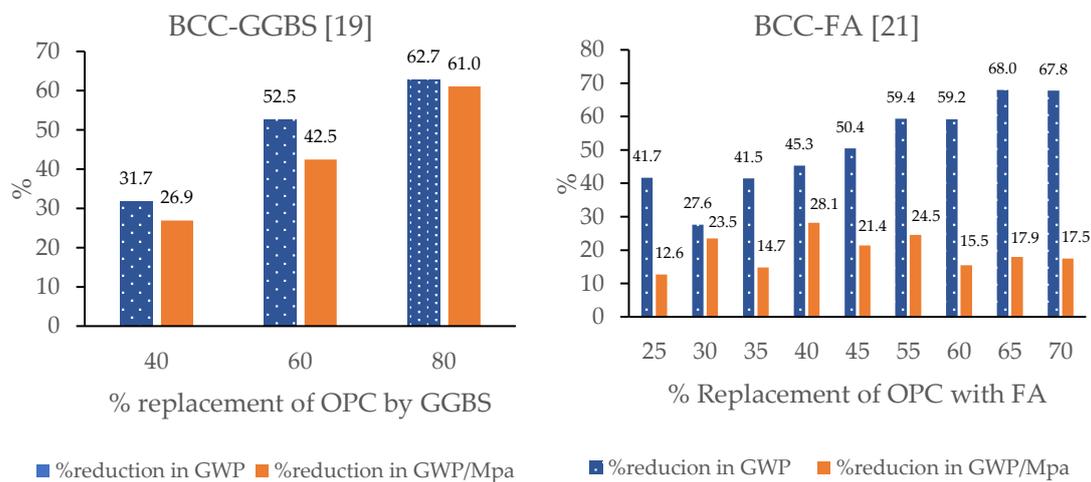


Figure 8. A comparison between the impact of blended cement concrete (BCC) using a volume-based FU and a FU normalized to strength.

According to Mahima et al. [71], premature concrete deterioration, due to carbonation and chloride penetration, is responsible for a loss of 2.2 trillion USD, which is equivalent to 3% of the world’s gross domestic product (GDP). This means that durability is a more detrimental factor to the performance of concrete than that of the compressive strength. Thus, the durability of concrete is an essential factor that needs to be included when the LCA of reinforced BC concrete is compared to reinforced OPC concrete. Panesar et al. [56] defined a FU where the volume of the BC concrete is multiplied by its compressive strength and the chloride ion penetration resistance, and is compared to the FU of an equivalent OPC concrete. Similarly, Celik et al. [21] and Kurda et al. [69] used experimental data of the different BCC mixes in terms of compressive strength and chloride penetration to compare the performance of BCC with OPCC. However, for the absolute environmental impact values to be credible, these durability properties need to be translated into the service life to describe a performance parameter of concrete [59]. Heede and De Belie [47] accounted for a 100 year timeframe as the service life of concrete, but only carbonation was used to determine the service life. Sagastume-Gutierrez et al. [57] devised a FU that divides the volume of cement by the number of years of durability from both chloride penetration and carbonation. Furthermore, an accurate methodology was proposed by Gettu et al. [30], where the test results of thirty different BC concrete mixes were incorporated into a FU (A-indices) that converts carbonation and chloride penetration parameters into expected service-life predictions. However, in all of the aforementioned, concretes with more than 100 years of durability will have a better environmental impact using both indices, while the specified service life for the mix is only 100 years. The same applies to compressive strength. Not capping the performance nor the durability of the concrete being studied, though it maximizes the sustainability potential according to Muller et al. [72], impinges upon the performance base specifications of the concrete. Instead, performance-based specifications similar to those in the framework proposed by Hafez et al. [55] should be adopted. Finally, according to Sagastume-Gutiérrez et al. [57], the comparison between the environmental impacts of two construction materials can be reliable, only after considering the combined effects of mechanical and durability characteristics.

The user's choice for a unit-based LOD could be based on a personal preference or absence of the necessary details about the project, such as the quantity of concrete per member or per a whole structure. However, the benefit of studying the member or a whole structure in which the concrete mix would be a part adds is that it another important factor to the equation, which is the optimization of the total volume. For example, increasing the prescribed strength requirement for concrete from 25 MPa to 50 MPa in a solid slab building would decrease the volume of concrete needed by around 15%, especially with columns [28]. It is recommended, therefore, to run a parametric analysis on the concrete under study based on compressive strength, strength, service life and the resulting volume, and hence, the combined environmental impact.

3.2. Stage 2: Inventory Data

The second source of uncertainties and unreliability in LCA results after the scope definition is LCA inventory (LCI). This is the data collection stage, in which the input and output factors, including energy, raw materials, products and waste, are analysed for the LCA of concrete. The LCI for a concrete mix mainly include: (a) upstream processes: those involved in the production of each of the constituents and its transportation to the concrete production plant; (b) core processes which involve the energy and emissions required for mixing concrete and transportation to site; and (c) downstream processes needed for the demolition or any other end-of-life scenario [24]. Out of all the inputs/outputs data from these processes, it is primarily important to quantify the emissions and energy-use rather than the oil use, waste generated and the rest [63]. Upon reviewing the necessary literature, it shows that LCI data is a major contributor to the uncertainty in a concrete LCA study due to the following reasons (i–iv):

(i) The LCI source has no standards as to where and how to get LCI data for a LCA of concrete. Anand and Amor [73] stated that concrete inventory data should come from primary sources for reliability purposes or secondary sources if the former is not available. Primary data could be lab results, governmental reports or EPDs from the building industry to which the user has access. EPDs are standardized documents to communicate the environmental performance of a product that are accredited by local authorities [74]. On the other hand, secondary data could be from accredited environmental databases, such as EcoInvent, GaBi and ELCD database or just using previously published data from the literature. By examining the 107 papers that actually included an LCA study, it was found that more than half, as seen in Figure 9, opted for the use of secondary sources for inventory data, which could not be reliable enough to describe the special scenarios being modelled in the concrete LCA. Although EcoInvent (which was developed by the Ecoinvent Centre, a competence centre of the Swiss Federal Institutes) and GaBi (which was created by Thinkstep Inc.) are updated annually to reflect any changes in the inventory data included, the environmental impact of concrete when modelled using the Ecoinvent database and EPDs has a variability of up to 20% [61]. Hence, it is suggested that the priority in the source of upstream processes of a concrete mix is for EPDs and in the case of several EPDs, an average should be taken. The reason is that EPDs are done in accordance with the same process, an LCA, under the guidance and supervision of local authorities such as the Green Building Council of Australia's concrete [75]. This would contribute to standardized processes and more efficient error tracking of concrete LCAs.

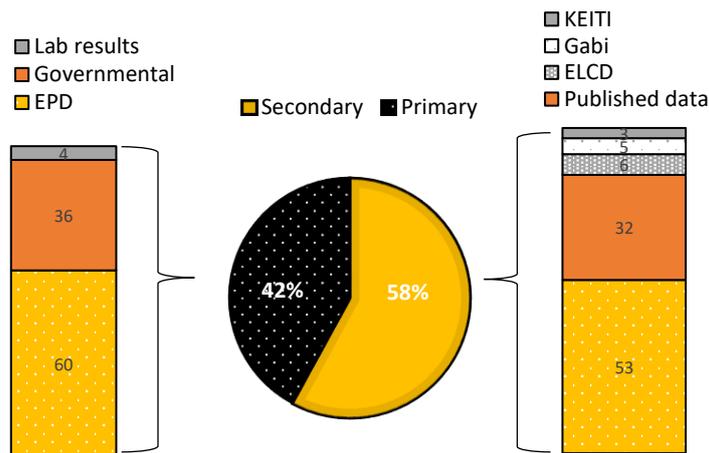


Figure 9. The meta data for the primary versus secondary sources for LCA studies reviewed and the databases used.

(ii) Apart from the reliability issue of the choice of the suitable LCI for the data, the existing data in each of the LCI sources contain large uncertainties. Looking into 25 papers, the inventory impact for OPC was found to vary between 691 kg eq CO₂/tonne and 1452 eq kg CO₂/tonne as shown in Figure 10. The reason could be that the OPC production process is different in efficiency between one producer and the other [76]. Additionally, the upstream process for OPC production depends on the electricity mix of the country of origin. For example, in the U.S. about 8% of the OPC used is imported and the upstream inventories of the imported clinker specific to the country of origin, as well as the energy consumed in transporting the OPC to the US, would increase the resulting impact of the OPC over the local alternatives [63]. The electricity mix in China almost has twice the environmental impact as that of Malaysia, Indonesia and Thailand due to, for example, the higher dependency on fossil fuel in electricity generation [31]. In all cases, the discrepancy in the impact of cement attributed has a great impact on the final environmental impact calculated through an LCA for a concrete alternative.

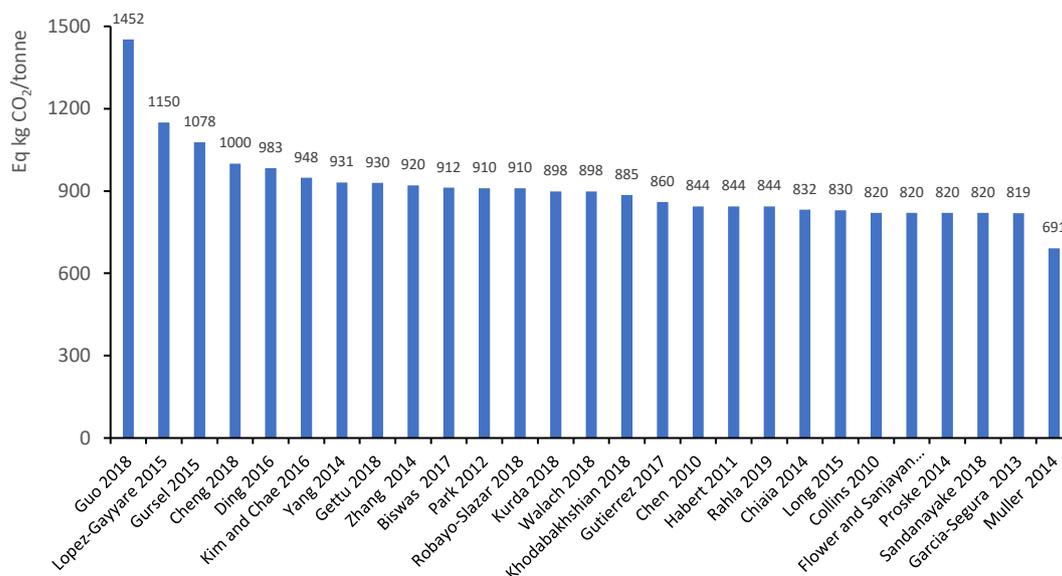


Figure 10. A review of the global warming potential (GWP) of a tonne of ordinary Portland cement (OPC) reported in 25 papers.

(iii) The variability in inventory data is not only in the OPC, but as seen in Table 4, it is the same with the rest of the concrete mix components. The most variable components found were the supplementary cementitious materials, such as FA, GGBS and SF whether in BCC or AAC mixes. The reason behind

this could be attributed to the case of environmental impact allocation. Impact allocation is the process of portioning the environmental burden of the original process to the waste material being recycled in the product under study [17]. According to the EU directive 2008, waste can be considered to be a by-product when its further use is certain, it is produced as an integral part of a production process, it can be used without any further processing other than normal industrial practice and its further use is lawful [77]. All four points apply to FA, GGBS and SF; hence, they ought to be considered by-products, not waste. This means that they ought to be allocated a percentage of the environmental burden of their original production processes, which are coal combustion, steel production and glass manufacturing, respectively [19]. The first impact allocation scenario is “mass allocation” where the percentage allocation is based on the relative mass between the waste material as a by-product and the total mass (the effective mass of electricity + the mass of FA) as shown in Equation (1). The second scenario is “economic allocation” in which the percentage allocated is based on the relative market value between the final product, which is FA, and electricity, as per Equation (2) [77].

Table 4. Inventory data for different concrete components from the literature we reviewed.

Ref.	1st Author's Name	Year	eq kg CO ₂ /Tonne												
			Steel	Coarse NA	Fine NA	FA	SF	GGBS	Lime	SH	SS	SP			
[78]	Yang	2014		3.2	2.3				27						
[30]	Gettu	2018				265			144	516					
[79]	Zhang	2014		14	41	27								720	
[20]	Biswas	2017	1470	5	2.4			72	156					1130	
[37]	Park	2012		4	1	20			27					250	
[39]	Robayo-Slazar	2018		1.1	0.5	9			277		1359	793			
[69]	Kurda	2018		29	2	4									
[80]	Walach	2018		3	13			4						1840	
[77]	Chen	2010				350			19						
[5]	Habert	2011		4.3	2.4	5			17	35			1140	749	
[81]	Rahla	2019				210		1580	134						
[82]	Chiaia	2014	150	2.5	2.5					19				720	
[83]	Long	2015		6	1	9			19	17				720	
[62]	Collins	2010		46	14	27			143						
[84]	Flower and Sanjayan	2007		36	14	27			143						
[85]	Proske	2014	874	7	2.3	11				29				772	
[52]	Sandanayake	2018		40	14						1425	780			
[29]	Garcia-Segura	2013	920	4	4	4			52					220	
[18]	Al-Ayish	2018	370	2.4	1.7				88						
	Mean		694.8	11.547368	6.44737	74.46	552	95.85	105.5	1392	904.3	833.2			
	St dev		486.2	14.489436	9.75525	118.2	890.9	78.61	201.2	46.7	204.2	441.7			
	St. dev (% of mean)		69.98	125.47825	151.306	158.7	161.4	82.01	190.7	3.35	22.58	53.01			

$$\text{Mass Allocation} = \frac{(m)_{\text{by-product}}}{(m)_{\text{main product}} + (m)_{\text{by-product}}} \tag{1}$$

$$\text{Economic Allocation} = \frac{(\text{€} \cdot m)_{\text{by-product}}}{(\text{€} \cdot m)_{\text{main product}} + (\text{€} \cdot m)_{\text{by-product}}} \tag{2}$$

Hence, it is seen as a reliability requirement for LCA studies, including SCMs, to include an impact allocation scenario. However, upon reviewing the literature, it was found that out of 59 exploratory LCA studies of green concrete involving SCMs, only 14 (25%) of the LCA studies included an allocation scenario. Eight papers included economic allocation scenarios while six included both of them. According to Marinkovic et al., in case the difference between the price of main and secondary process generating the SCM product is more than 25%, economic allocation should be

applied. However, the fact that the fluctuation in market prices of the raw materials should now be a part of the environmental impact assessment of concrete through the economic allocation, creates room for further discrepancies in the results, as seen in Table 5. It is recommended to keep the LCA results of concrete limited to the time frame for which the prices of the raw materials still stand unchanged.

Table 5. Market prices of different concrete components from the literature.

Ref.	1st Author's Name	Year	Country	FA (£/Tonne)	GGBS (£/Tonne)	SF (£/Tonne)	Electricity (£/kWh)
[53]	Anastasiou	2015	Greece		3.50		
[86]	Chen	2019	France	35	23		0.12
[77]	Chen	2010	France	20	40		0.1
[75]	Crossin	2012	Australia		100		
[87]	Gursel	2015	USA			890	
[5]	Habert	2011	Switzerland	25	45		0.12
[51]	Jiang	2014	USA		74		
[88]	Khodabakhshian	2018	Iran			500	
[89]	Li	2015	China		20		
[17]	Marinkovic	2017	Serbia	3.5			0.05
[34]	Igancio	2018	Spain	38		1140	
[56]	Panesar	2019	Canada	135			
[37]	Park	2012	South Korea	33	41		
[81]	Rahla	2019	Portugal	28	37	430	
[90]	Seto	2017	Canada	107			0.07
[45]	Teixeira	2015	Portugal	21			0.22
[91]	Tucker	2017	USA				0.09
[92]	Wang	2017	China	10			0.11
[93]	Yuan	2017	China				0.11
[59]	Zhang	2014	China	9			
	Mean			38.7	42.6	740.0	0.11
	St dev			40.3	29.0	334.8	0.05
	St. dev (% of mean)			104.2	68.2	45.2	43.1

(iv) Another source of discrepancy in LCAs of concrete with regard to inventory data is the impact attributed to the transportation of raw materials to the concrete manufacturing plant. It could vary between 5% and 20% depending on the location of the raw materials relative to the concrete batch plant [94]. While examining a sample of the papers being reviewed, it was apparent, as seen in Table 6, that the transportation distances vary widely between the different studies. A study by Panesar et al. [95] concluded that the critical distance for importing FA that would still yield a BCC mix with a positive overall environmental impact profile compared to OPCC is around 900 km as opposed to the 3000 km proposed by Hafez et al. [160] and 5700 km by O'Brien et al. [96]. Additionally, Turk et al. [13] argue that if the recycled aggregates are sourced from a landfill that is more than 230 km from the concrete batch plant, the RAC produced would have a higher environmental impact compared to OPCC, which is a larger figure than the 145 km concluded by Anastasiou et al. [53]. In all cases, it is recommended to perform a scenario analysis in each LCA study for concrete in case the sources for the raw materials are not exact, to determine the sensitivity of the output relative to the change in distances.

Table 6. A sample of the inventory data for the transportation distances of concrete raw materials in km.

Ref.	Author	Year	Kilometres						
			OPC	Aggregates	FA	GGBS	SP	SH	SS
[53]	Anastasiou	2015	50	50	50				
[20]	Biwas	2017	25	1		0.01			
[93]	Chrysostomou	2017	45	36			39		
[75]	Crossin	2012	90	30	945	9317			
[98]	Maria	2018	50	50		10			
[24]	Ding	2016		100					
[29]	Garcia-Segura	2013	32	12	180	1640	724		
[64]	Kim and Chae	2016	106	32			77		
[69]	Kurda	2018	60	65	160		15		
[89]	Li	2015				177			
[17]	Marinkovic	2017	100	100	50			50	20
[39]	Robayo-Slazar	2018	6	10	10	493		53	192
[41]	Salas	2018	5	5				12	64
[13]	Turk	2015	50	1					
[46]	Van den Heede and De Belie	2010	113	193	38		118		
[78]	Yang	2014	277	43	322	339	70		
	mean		72.1	48.5	195.9	1498.0	173.8	38.3	92.0
	St dev		68.5	51.0	299.2	3205.7	271.8	22.9	89.4
	St. dev (% of mean)		95.0	105.2	152.7	214.0	156.4	59.6	97.1

3.3. Stage 3: Impact Assessment

The third stage of an LCA is the assessment of the impact of the concrete mix by simply multiplying the functional unit by the aggregates impact of the concrete from the three life phases. As seen in Equations (3) and (4), the emissions and energy use are calculated by adding up all the emissions and energy uses of the products and processes involved in the production, use and end-of life stages.

$$\text{Total emissions for mix (x)} = \text{FU}_x \times \sum_{n=1}^3 \text{emissions of all products and processes of stage n} \quad (3)$$

$$\text{Total energy use for mix (x)} = \text{FU}_x \times \sum_{n=1}^3 \text{energy use of all products and processes of stage n} \quad (4)$$

In order to contextualize the information about the concrete mix being studied, an environmental impact indicator is needed. An impact assessment method is vital to producing judgements on the severity of the impact of concrete on the three main areas of protection: (i) ecosystem quality, (ii) human health and (iii) natural resources [59]. This is done through three steps: characterization of the impact, which is a must-do; then, normalization and weighing, which are both optional [49]. According to Sayagh et al. [99], there are two main types of indicators: mid-point indicators, which correlate the calculated impact to a specific change in the environment, such as global warming potential, and end-point indicators which correlate the same increase to damage occurring later-on in the cause-effect chain, such as human health. The significance of this differentiation is that the same comparison between products or processes could result in different scores if looked upon by a mid-point or an end-point indicator, due to the exaggeration of damage that happens to reach the latter [100]. By examining the references reviewed, it was noticed that out of 107 papers, as seen in Figure 11 only six chose to rely on end-point indicators to present the concrete LCA findings.

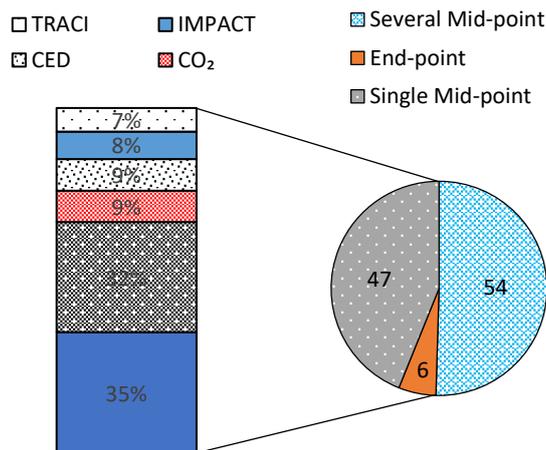


Figure 11. Meta-data for the indicators used in the concrete LCA studies reviewed.

In terms of relying on mid-point indicators to represent the environmental profile of concrete, the majority of the papers only selected global warming potential. The first reliability issue is that 10% of the papers opted to use the carbon dioxide emissions value as equivalent to the global warming potential [37,64,78,79,101,102]. In fact, according to the two most established midpoint environmental methodologies: CML and the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI), GWP is based on the aggregation of carbon dioxide emissions, methane and nitrogen dioxide. CML was developed in 1992 by the Institute of Environmental Sciences of the University of Leiden, and TRACI was prepared by the US Environmental Protection Agency’s (US EPA’s) National Risk Management Research Laboratory in 2003.

The second reliability issue with this choice is that GWP is not the only significant environmental impact indicator. As seen in Figure 11, more than 10% of the authors opted to use, along with GWP, the cumulative energy demand (CED). More than half of the authors opted to present several midpoints, according to the following methodologies: CML (32%), Integrated Material Profile And Costing Tool (IMPACT) (10%) and TRACI (7%). These midpoint indicators include, besides GWP, ozone depletion potential (ODP), acidification potential (AP), eutrophication potential (EP), and abiotic depletion potential (ADPE), among others. Considering these indicators would include emissions such as carbon monoxide, sulphates and ammonia [67]. This concludes that in order to provide a reliable assessment of the environmental impact of a concrete alternative, it is advisable to calculate it using several midpoint indicators. However, it remains up to the user to remove any that are deemed irrelevant. For example, Passuelo et al. [103] argue that since the ODP potential of 1 tonne of geopolymers concrete is almost equal to 1.34×10^{-5} , equivalent to operating a household lamp for 2.5 years, this is not a significant indicator to consider.

3.4. Stage 4: Interpretation of Results

The fourth and final stage of an LCA is that when the user analyses the assessed outcome from stage 3 to judge the environmental impact of the concrete alternative studied. In this stage, two main problems were observed. It was noticed that almost 90% of the papers reviewed opted to produce deterministic results for the environmental impact of concrete. Regardless of the indicator chosen, even if the user avoids all the systematic errors explained earlier to make the study reliable, it has been established that some of the most significant elements of a concrete LCA are intrinsically uncertain, such as (i) predicting the expected service life of a mix based on the exposure conditions and mixing proportions; (ii) uncertainty in upstream data regarding some raw materials, depending on the source or database used; (iii) the forecasted energy use in futuristic activities, such as demolition and/or maintenance of the concrete alternative; (iv) predicting the amount of carbon the concrete mix is able to sequester depending on the surface area and atmospheric conditions; and (v) the characterization factors

for the mid-point indicators selected. Hence, the results of a concrete LCA should be communicated in a probabilistic fashion. In order to quantify these uncertainties, scenario analysis should be performed on each of the individual elements. Upon quantifying the aforementioned uncertainties, the user could then model the impact assessment indicators using Monte Carlo simulation, and through running the model repeatedly, that would generate a probabilistic aggregated indicator. The model would also allow the user to choose the uncertainty distribution and define the confidence level over the model output accordingly.

4. Conclusions

This review paper aimed at analysing the process of preparing a LCA for concrete and identifying potential sources of discrepancies. The purpose was to standardize the concrete LCA methodology in order to be able to judge the environmental impact in absolute terms across industries, which is a prerequisite for the rising demands to cut down the environmental impact of concrete to combat the rising global warming issues. As seen in Table 7 upon reviewing 146 references, it is apparent that there are 13 most-common sources of discrepancies that spread across the four stages of an LCA study. More than half of these sources are user-based choices, such as depending on a cradle-to-gate scope, selecting a basic volume-based functional unit, ignoring the impact allocation and relying on a single indicator. Throughout the paper, it was shown that based on these choices, the results of the concrete LCA study are not deemed reliable and are not comparable either to other concrete studies, nor in absolute terms to other products and services. Hence, it was concluded that the errors need to be addressed by following an inclusive methodology. In order to cater for the intrinsic uncertainty in some of the elements of the methodology proposed, such as the means of transportation, the expected service life and fluctuations in market prices, it is advised to perform scenario analyses on each of these elements and run a Monte Carlo simulation to aggregate the uncertainty in the final presented LCA outcome.

Table 7. Summary of the sources of error from the review.

#	LCA Stage	Source of Discrepancy	Description	Outcome	Frequency	Category	Impact on LCA Outcome	Potential Solution
1	Stage 1: LCA Scope	System Boundaries		Ignoring potential carbon sequestration by concrete	90%	Reliability	2–20% overestimation	Deduct the sequestered carbon by predicting the carbonation potential of concrete throughout its expected service life
2			Disregarding the “use” phase	Assuming same service life for concrete alternatives	75%	Reliability	Underestimation (variable)	Include maintenance and/or replacement impact depending on the difference between the required and expected service life of concrete
3				Ignoring the operational energy consumed by concrete	75%	Precision	1–10% underestimation	Add an estimate of the operational energy consumed by concrete throughout its service life
4		Disregarding the “end-of-life” phase	Ignoring the impact of demolishing concrete	75%	Precision	1–10% underestimation	Add an estimate of the emissions and energy required to demolish the concrete alternative at the end of its service life	
5			Ignores the avoided landfill impact for CDW waste	95%	Precision	1–10% overestimation	Deduct the impact from avoiding landfilling the waste that is being recycled as aggregates in the concrete mix	
6		Functional Unit	Selecting a volume based FU	Ignores the functional properties of concrete	65%	Reliability	Variable	Select a functional unit that reflects performance based specifications such as strength and predicted service life
7			Selecting a unit level of details	Missing out on the potential of optimizing the total volume required	70%	Precision	Variable	If possible, select a “whole structure” LoD to run different scenarios optimizing the impact based on strength and volume of concrete

Table 7. Cont.

#	LCA Stage	Source of Discrepancy	Description	Outcome	Frequency	Category	Impact on LCA Outcome	Potential Solution
8	Stage 2: Inventory Data	Data source	Relying on secondary sources	Not reliable and sometimes irrelevant data	45%	Reliability	Variable	Whenever possible, rely on primary sources such as EPDs and certified lab results
9		Data variability	Variability in upstream data	Higher uncertainty in the values for impact and cost of transportation and raw materials	NA	Precision	Variable	Whenever needed, perform scenario analyses to measure the sensitivity of the outcome to the potential variability in upstream data
10		Impact allocation	Impact allocation for SCM	Ignoring the impact allocation for SCMs recycled in concrete	75%	Reliability	Variable	If the difference between the price of main and secondary process generating the SCM product is > 25%; economic allocation should be applied
11	Stage 3: Impact Assessment	Indicators	Using end-point indicators	Carries large uncertainties in correlating cause-effect environmental impact relationships	5%	Reliability	Variable	Use a combination of mid-point indicators to calculate the impact for concrete such as GWP, EP, ODP, AP, CED
12			Using CO ₂ as GWP	It ignores the impact associated with methane and nitrogen dioxide as GHG emissions	10%	Reliability	10–30% underestimation	Use a standard methodology such as CML or TRACI that characterizes the different GHG emissions contributing to the GWP indicator
13	Stage4: Interpretation of results	Absolute judgements	Deterministic LCA outcome	Ignores the uncertainties aforementioned in the nature of the upstream data	90%	Reliability	NA	Perform scenario analyses, quantify the uncertainties in each of the elements then do a Monte Carlo simulation to aggregate the uncertainties of the indicators

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