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CRITICAL REVIEW

(Sprayed) concrete production in life cycle assessments: a systematic literature review

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Abstract

Purpose The carbon intensity that accompanies concrete manufacturing has been widely investigated. However, depending on the intended use, concrete's embedded materials' quantities can change significantly, affecting its environmental performance. Seldom investigated, sprayed concrete's impact differs from that of typical ready mixed concrete, which justifies a differentiated inspection. Our goals are (i) to prove that sprayed concrete's environmental impacts are under-investigated and (ii) to provide an overview on how concrete's components' production cycles are typically modelled in LCAs.

Methods We performed a systematic literature review (SLR) to gather the widest possible sample of papers in a replicable and transparent manner, aiming to answer two research questions: 'What is the life cycle performance of sprayed concrete?' and 'What are the most frequent methodological choices made to perform an LCA of concrete's constituents?'. We used eight different keyword strings for each of concrete's most used components and searched for documents in databases Springer and ScienceDirect. After 3 conservative filtering rounds, 282 papers were thoroughly and collectively assessed to feed the outcome herein documented.

Results and discussion The investigated literature not only showed a gap in sprayed concrete's environmental impacts documentation but also allowed us to build a literary dossier to ground researches aiming to calculate typical concrete mixes' impact through LCA, assuring comparability with the ecological status quo for that construction material. Practitioners' most frequent methodological choices were documented, along with common standard breaches and limitations in investigated studies.

Conclusions By systematically structuring our research protocol, we covered enough papers to provide a sound overview and to make collective conclusions regarding available literature. We make two main recommendations for LCA practitioners: non-carbon correlated impact categories ought to be investigated—especially as we move towards more carbon-friendly technologies in concrete/cement manufacturing. Second, practitioners should always comply with the transparency requirements of an LCA. Our outcome pointed to an alarming number of published papers that failed to declare basic methodological choices such as data sources, assessment methods used and impact distribution strategies in multifunctional processes' modelling.

Keywords Cement · Concrete · LCA · Life cycle assessment · Sprayed concrete · Systematic literature review

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1 Introduction

Mankind has benefitted from concrete's outstanding technical performance in terms of durability and strength for centuries now (Flower and Sanjayan 2007; Waters et al. 2016). Be it in the urban environment's infrastructure or in living or working spaces, one is constantly exposed to concrete structures. A more recent chapter in concrete's ancient history depicts, however, a less favourable profile: its significant environmental impacts. Society is now aware of the carbon/natural resource use intensity that accompanies the well-known construction material, and this acknowledgement arose from scientific researches performed throughout the world.

Even though abundant and (mostly) scientifically robust, concrete-related researches do not always cover all of its possible applications' peculiarities. Depending on the intended use, concrete's desired function and its embedded materials' quantities can change significantly. The use of sprayed concrete stands out as one of the latter cases. Seldom investigated, sprayed concrete's environmental performance can differ from that of typical ready mixed concrete (Saade et al. 2018a, b), which justifies a closer individual inspection.

Performing environmental evaluations of construction and building materials through life cycle assessment (LCA) is increasingly regarded as a sound and coherent scientific strategy (Passer et al. 2015). LCA widens the scope of typical environmental analyses to include all of a product's life cycle stages that might contribute to impact generation, thus providing a more complete assessment of potential ecological damages. Such a broad delineation and modelling of production processes, however, demands a number of methodological delimitations which affect obtained results.

This research's motivations are two-fold: (i) to prove our initial hypothesis that sprayed concrete's environmental impacts are under-investigated and (ii) to provide an overview on how concrete's components' production cycles are typically modelled in life cycle assessments. Results depicted here are part of a research project entitled 'Advanced and Sustainable Sprayed Concrete' (ASSpC), which aims to develop new sprayed concrete mix designs and technologies, to jointly improve the material's durability and environmental performance. The ultimate goal behind the performed review was to provide a methodological basis for a scientifically accurate environmental assessment of newly developed mixes and benchmarks to establish clear environmental and technical superiority.

2 Methodological approach

An inspection in published literature must be carefully planned to assure coverage of all important studies. We therefore chose to perform a systematic literature review (SLR) to try to gather the widest possible sample of papers in a replicable and transparent manner.

Following the typical protocol for SLRs, we initially defined two research questions that guided all subsequent steps: 'What is the life cycle performance of sprayed concrete?' and 'What are the most frequent methodological choices made to perform an LCA of (sprayed) concrete's constituents?'. We chose to search two databases: ScienceDirect and Springer. The former encompasses a number of journals assessing construction technologies while the latter was chosen especially because of the International Journal of Life Cycle Assessment, a publishing vehicle focused exclusively in LCA's methodology and its application. Journals Science and Nature were individually assessed, due to their scientific relevance. In addition, through the so-called snowball approach (Wohlin 2014), we checked for relevant papers that were not captured by our research strategy in citations within our paper sample.

We chose to exclude grey literature (i.e. papers that were not peer-reviewed) to assure coverage of only high-quality papers (except from when added through the snowball approach). No time boundaries were applied to our search, which was performed until January 2017.

The following keyword strings were structured based on (sprayed) concrete's composition and individually searched for across the previously mentioned databases:

- Sprayed concrete (OR shotcrete) AND LCA
- CEM AND LCA
- Admixtures AND concrete AND LCA
- Limestone AND concrete AND LCA
- Sand AND concrete AND LCA
- Gravel AND concrete AND LCA
- Fly ash AND concrete AND LCA
- Blast furnace slag AND concrete AND LCA

All papers that met the initial search criteria were transferred to a reference management software, where they went through three filtering rounds per keyword string: first a title analysis, then an abstract analysis and finally an in-depth full paper analysis. The remaining papers were listed in a data extraction form (built in .xls format, available as Electronic Supplementary Material; all assessed references are detailed in the further reading), where we documented all relevant information allowing for a joint assessment of each sample, namely (i) authors' name, country, paper title, journal and year; (ii) paper's goal; (iii) functional unit chosen; (iv) system boundaries adopted; (v) background data source; (vi) impact assessment method used; (vii) impact distribution criteria used (if any); and, finally, (viii) life cycle indicators' values for the assessed material (if present).

3 Results presentation and discussion

3.1 Research question 1: 'What is the life cycle performance of sprayed concrete?'

The search performed for sprayed concrete confirmed our hypothesis and clearly pointed to a gap: our final sample of papers was composed of only four studies (Huang et al. 2015; Pretot et al. 2014; Stripple et al. 2016; Amin Hosseini et al. 2016). Detailed information on the amount of papers remaining after each filtering phase can be found in Saade et al. (2018a, b). Due to the low sample of papers, no graphs were built, so a brief discussion on main methodological choices is herein presented.

Our scarce sample did not show results for sprayed concrete individually, which prevents the identification of the component's environmental performance. Amin Hosseini et al. (2016) actually cited the Inventory for Carbon and Energy values (Hammond and Jones 2011) as a source for concrete's impact, but since that inventory does not provide information on sprayed concrete, it is safe to assume that the authors considered typical ready mixed concrete as a proxy. Stripple et al. (2016) did not mention the background data source used, while Huang et al. (2015) and Pretot et al. (2014) used ecoinvent as the underlying data foundation for their LCAs. As for impact assessment methods used, only Huang et al. (2015) clearly declared their choice: authors used Recipe midpoint v.1.06, with the egalitarian perspective. Within system boundaries definition, cradle-to-grave predominated, except for Stripple et al. (2016), where the choice is not clearly stated. Finally, Pretot et al. (2014), Stripple et al. (2016) and Amin Hosseini et al. (2016) used m^2 of wall as a functional unit, while Huang et al. (2015) adopted road tunnel length (1 m) as chosen unit.

3.2 Research question 2: 'What are the most frequent methodological choices made to perform an LCA of concrete and its constituents?'

Due to the large number of keyword strings used, this section presents a joint meta-analysis performed for all papers found when using the different keywords. The figures detailing methodological choices show each time a specific method was used, even when a single paper adopted more than one method.

Figure 1 shows the temporal distribution of the assessed 282 published papers dealing with concrete components' LCA. The six papers published in early 2017, though part of our sample, are not plotted to avoid line distortions. One notices a discrete peak in 2010, followed by a much relevant increase rate as of 2014. Many scenarios might have contributed to the almost exponential growth after that year, but here we highlight the publication of the International Panel on Climate Change (IPCC) Fifth Assessment Report and the World Sustainable Building Conference in Barcelona, both events taking place in 2014. These two landmarks in regard to climate change (former) and the construction sector's sustainability (latter) highlighted the need for environmentally preferable alternatives to conventional building materials, paving the way for LCA practitioners focusing at this topic. The following subsections show the SLR outcome for the relevant methodological information extracted from sampled papers.

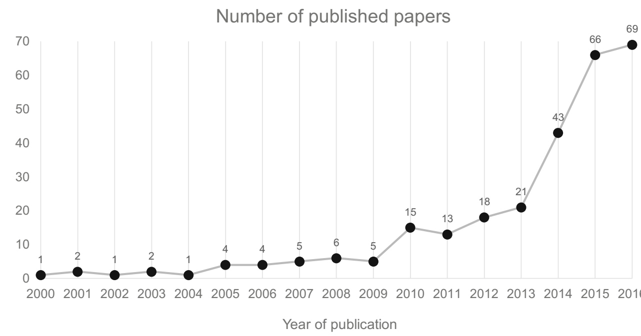

Fig. 1 Temporal distribution of papers in the final samples. Six papers, published in early 2017, are not plotted to avoid line distortions

3.2.1 Background data source

LCA's wide scope makes it a data-intensive methodology, in which the practitioner typically collects specific data related to his/her process of interest, but relies on background databases to provide environmental information on the processes that are up- or downstream on the investigated supply chain. There are idiosyncratic methodological procedures behind each available database and, therefore, the choice of one or the other potentially interferes with LCA results. Figure 2a plots the adoption frequency of the most well-known internationally used databases—namely ecoinvent and GaBi—in all assessed papers along with other less typical sources, while Fig. 2b shows how often the different versions of the most used database (ecoinvent) are chosen.

The less typical data sources dominate the sample, but closely followed by the ecoinvent database. The fact that varied sources (the 'other' category) grounded most of the assessed studies points to a difficulty in benchmarks definition, since comparability is hindered in those cases. The initially Switzerland-focused ecoinvent database stands out for its transparency and completeness, which might explain its relative preference in concrete's component's LCAs.

Considering its great use and the fact that there were significant methodological changes made to the database structure with time, acknowledging which version of ecoinvent is most adopted is also important. As expected, the first versions of the database—released from 1999 to 2007—(1.01, 1.1, 1.2 and 1.3 represented in Fig. 2b as '1.x') are the least adopted. Versions 2.0 and 2.1 (represented by '2.x') show an increase in use frequency, as does version 2.2, which is represented alone here due to its greater use. The 'ecoinvent 2' series

Fig. 2 **a** Background data source adopted in papers in the final samples. The 'other' category refers to alternative papers, environmental product declarations, industrial partners, sectorial reports and country-specific databases. Their individual frequency was low and did not justify a single category for each. **b** Database version in papers that adopted ecoinvent as a background data source

was released shortly after the publication of the revised ISO standards on LCA in 2006 (ISO 2006a), which stimulated a growth in publication of LCA papers in general, thus explaining its significantly larger adoption. Versions 3.0, 3.01, 3.1, 3.2 and 3.3 ('3.x' in Fig. 2b) were released from 2013 to 2016 and still have not shown a use as wide as the 2.x versions'. The changes made on the database methodological structure from version 2 to 3 were the largest so far, which might have inhibited its use (Saade et al. 2018a, b). Version 3.4 of the database was released on October of 2017, after our paper selection was finished, and is therefore out of our search's scope.

3.2.2 Impact assessment method

The life cycle impact assessment stage (LCIA) translates information on material and energy flows that happen throughout the product's life cycle into environmentally relevant indicators. Due to the great number of parameters to be translated into those indicators, practitioners typically rely on LCIA methods that, through the use of scientifically accepted conversion factors, calculate the overall contribution of each measured flow to an impact category. There are inherent differences between the available methods, which vary in terms of conversion factors used, which sets of flows contribute to which impact category and how far along the environmental cause and effect chain the results are. Unsurprisingly, once again, LCA results vary from one method to the other. Our SLR (Fig. 3) pointed that the most used LCIA method was the one developed by the Institute of Environmental Sciences of Leiden University, also known as CML or CML-IA, which is in line with the findings of Desideri et al. (2014) and Ferrández-García et al. (2016).

It is noteworthy that 31% of the sampled papers did not declare the impact assessment method used, which denotes a severe transparency issue—unacceptable if one aims for replicability.

3.2.3 Life cycle stages

Within the built environment and, more specifically, within the realm of construction products in general, the life cycle phases to be assessed are described in terms of different acronyms, following the guidelines published in the European Standard 15804:2012 (EN 2012). The so-called product stage encompasses raw material extraction (A1), transport to manufacturing (A2) and manufacturing per se (A3), and is considered mandatory for environmental product declarations (EPD). The following stages consider activities that are specific to the construction sector: A4 = transport of product to construction site, A5 = installation in building, B1–B7 refer to the product's use stage, while C1–C5 represent its end-of-life. An additional stage (D) is supposed to cover the potential recyclability of the assessed material. We adopted this nomenclature to identify which life cycle stages were mostly addressed in the specialized literature. The mandatory product stage (also called 'cradle-to-gate' or A1–A3) was the most adopted scope (Fig. 4), followed by a more complete A1–C5 scope, also referred to as 'cradle-to-grave'.

Almost 5% of our sample (13 papers) failed to declare the scope of the performed LCA which, as with the previous methodological choices assessed, renders unclear and incomparable results.

3.2.4 Functional unit

The functional unit plays one of the most important roles in LCAs. When performing comparisons between different products, one must always guarantee a functional equivalence among them, which needs to be translated into the unit for which the environmental flows are calculated. When performing an LCA for an isolated product, however, it is not uncommon to find what practitioners like to call a 'declared unit', since no functional equivalency is needed. Considering that our set of assessed materials are typically

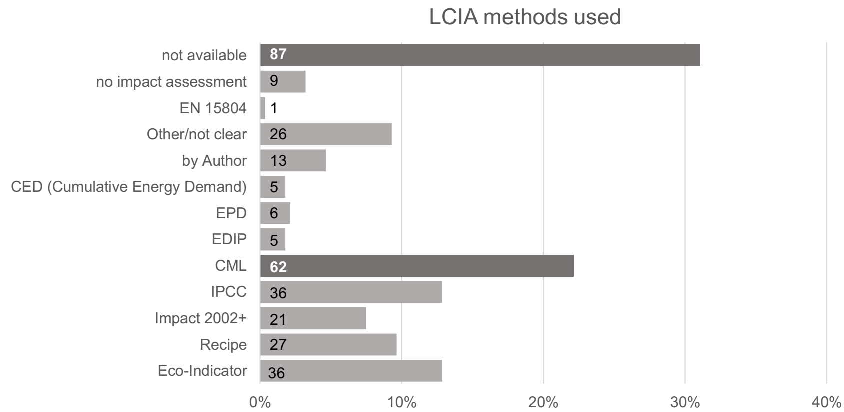

Fig. 3 Impact assessment methods adopted in papers in the final samples. Numbers within columns refer to the amount of times a method was used. Some papers adopted more than one method, which explains the total number depicted being larger than 282

sold and measured in terms of mass or volume and that most papers did not perform comparisons between different components, our SLR outcome does not come as a surprise (Fig. 5), showing that mass (kg or ton) and volume-related (m^3) were the most adopted functional units in cradle-to-gate LCAs. When all life cycle phases were considered, 'piece' stood out as a widely used functional unit, which can represent different construction systems as a whole, such as a concrete slab or column with specific dimensions, a whole house, a bridge or a defined highway section. Area units (m^2/km^2) were mostly related to LCAs in housing/residential sectors, where the net floor area is a typically adopted functional unit. The meter or kilometre functional units were mainly found in studies that referred to streets or pavements' LCAs.

3.2.5 Impact distribution method

In almost all product systems to be modelled in an LCA, one finds what practitioners call a 'multifunctionality problem'. Whenever a production process generates more than one product or has more than one function, the decision on how to distribute material and energy flows between the generated products/functions needs to be made. ISO 14044:2006 (ISO 2006b) provides a hierarchic stepwise procedure to solve multifunctionality problems: first, allocation, i.e. the distribution of impacts between a product and its co-product(s) based on specific criteria, should be avoided wherever possible, by either dividing multifunctional processes into sub-processes (sub-division) or by expanding the product system to include the co-products' additional functions (system expansion). When allocation cannot be avoided, system inputs and outputs should be divided based on the underlying physical relationships between them. If no physical criteria can easily enable partitioning, then the inputs and outputs should be attributed to reflect other relationships between the products and functions, such as their economic value.

Although not mentioned in ISO 14044, the 'avoided burden' approach is conceptually equivalent to the system expansion cited in it, and consists of subtracting the environmental loads prevented by co-product recycling from the multifunctional process' loads (Tillman et al. 1994; Heijungs and Guinée 2007). Also not explicitly mentioned in the international standard but widely adopted is the 'cut-off' approach—in which the

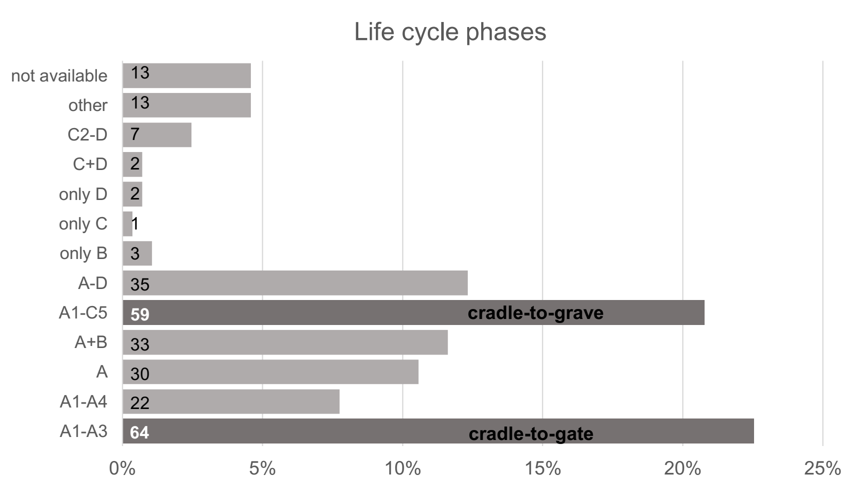

Fig. 4 Life cycle phases considered in papers in the final samples. Numbers within columns refer to the amount of times a scope was adopted. Shaded columns refer to most adopted scope, i.e. cradle-to-gate and cradle-to-grave. Two papers adopted more than one scope

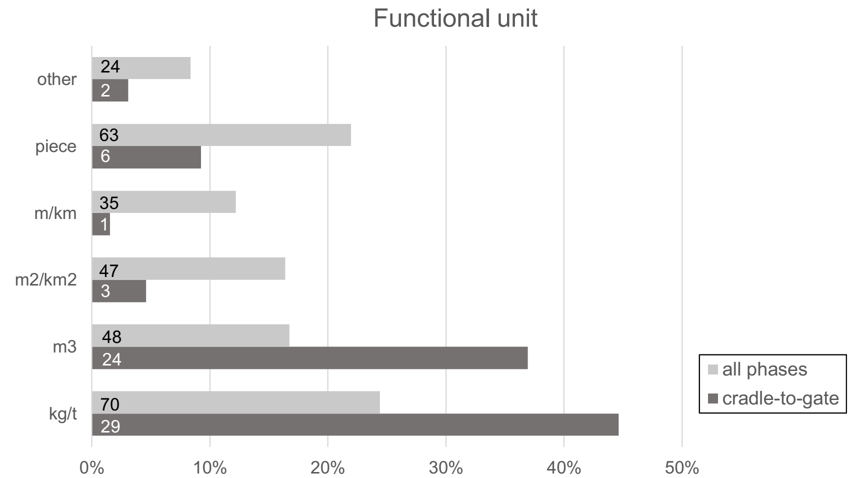

Fig. 5 Functional units adopted in papers in the final samples. Numbers within columns refer to the amount of times a functional unit was adopted. Five papers adopted two different functional units and were therefore double-counted

practitioner acknowledges the multifunctionality issue, but regards the co-product as a waste with null impact. Since distribution methods lead to significantly different outcomes, ISO requires that when modelling multifunctional processes, LCA practitioners perform a sensitivity analysis by using more than one method.

Due to high industrial co-product incorporation in building materials' manufacturing, the construction sector often faces impact distribution issues (Saade et al. 2015). The cement industry, for instance, is frequently confronted with this methodological conundrum mainly due to blast furnace slag (from steelmaking processes) and fly ash (from coal-based electricity generation) use as supplementary cementitious materials. Documenting how often each possible impact distribution method is used is paramount if one wishes to establish benchmarks or assure comparability with previously published researches.

Figure 6 shows the adoption frequency of each distribution method considering papers found when using the keyword strings for fly ash and blast furnace slag. The 'System expansion' column refers to papers that adopted either the avoided burden approach or actual system expansion as predicted by the standard.

Sixty percent of sampled papers (64 papers) failed to perform or acknowledge the need for impact distribution—a clear breach of ISO 14044's guidelines. Moreover, only 21% (23 papers) performed a sensitivity analysis as requested by the international standard. The cut-off approach was the most adopted method between ISO-compliant papers, typically accompanied by a sensitivity analysis using mass and/or economic value allocation.

3.2.6 Life cycle indicators

Albeit kept in our final samples for methodological aspects' identification, most evaluated papers (244) did not provide environmental indicators' values for concrete's components. This subsection provides an overview of those that did document their environmental performance, focusing on indicators that compose EN 15804's minimum impact category structure—namely acidification potential (AP), eutrophication potential (EP), global warming potential (GWP), ozone layer depletion potential (ODP), photochemical ozone creation potential (POCP) and abiotic depletion potential (ADP). Presented results refer to values per kg of material, considering a cradle-to-gate scope (A1–A3). A table with ranges found for each indicator and material is shown at the end of this section.

Cement As concrete's global warming potential's (GWP) greatest contributor, one does not struggle to find information on cement's greenhouse gas emissions as with most other components. Cement's carbon intensity has been widely investigated in the specialized literature (Flower and Sanjayan 2007; Chen et al. 2010; Van den Heede and De Belie 2012; Habert 2013), which explains the lowest standard deviation found when jointly plotting all GWP results for CEM I found in the SLR (Fig. 7). The 'n' acronym accompanying the indicator's name represents the number of values found—confirming the larger availability of information on GWP when compared to other impact categories.

ADP's variation assessment was hindered due to the low number or results found for that indicator (4). Nonetheless, it presented the highest results' range (from 1.98E-4 to 0.243 kg of antimony-equivalent per kg of cement), most likely due to its calculation's uncertainty, associated to each consumed mineral's availability, extraction rates and other possible parameters to which there is still no scientific consensus (Van Oers and Guinée 2016).

Few results (three papers) were found for average types of cement, considering the most consumed types in the country (García-Gusano et al. 2015a; García-Gusano et al. 2015b; Strazza et al. 2010). These were not plotted due to lack of confirmed functional equivalence with CEM I.

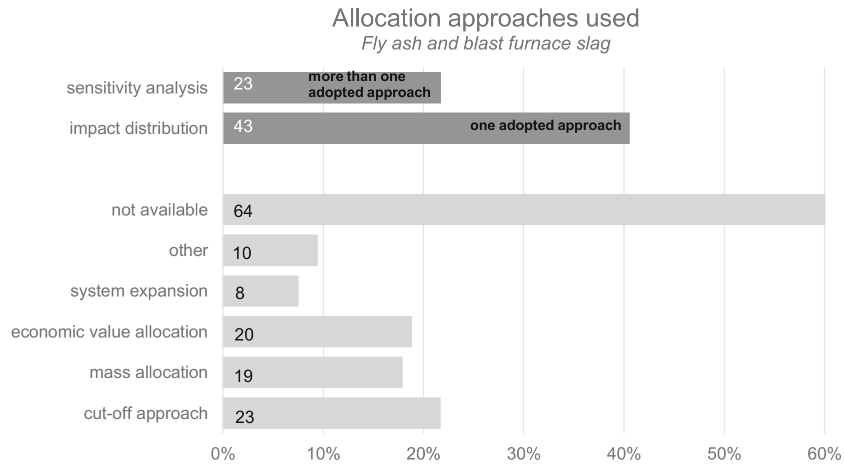

Fig. 6 Impact distribution methods used in papers addressing co-products fly ash and blast furnace slag. Numbers within columns refer to the amount of times a method was adopted. Dark grey columns show the 66 papers that performed some type of impact distribution, separating those that adopted only one method from those that performed a sensitivity analysis with more than one method. The 23 papers that performed the latter sensitivity analyses used more than one method and are therefore double-counted in the light grey columns

Sand and gravel Within our SLR strategy, sand and gravel's impact were searched for separately. Since some papers presented combined results for both fine and coarse aggregate, here we chose to jointly plot values to provide an overview of aggregates in general. Moreover, the main difference between sand and gravel is basically their grain size which, translated into environmental flows, means an additional energy for grinding consumption.

Again, ADP showed the highest variation, for the same reasons previously discussed—high calculation uncertainty coupled with lower number of values found. Apart from an isolated outlier, GWP has the least variation among found values, followed by the acidification potential. As expected, when comparing with figures obtained for cement, the much lower values of impact per kg of aggregate stand out.

Admixtures From the 26 papers that composed our final sample for chemical admixtures used in concrete, 11 provided information on those materials' environmental loads, with only 2 of them expanding the indicators' scope to include more than just GWP. Plasticizers and/or superplasticizers were the most addressed agents (eight papers). Table 1 shows GWP results found for the two latter chemical agents along with their data source. The European Federation for Concrete Admixtures' EPD (2006) data was adopted in two different papers.

GWP results range was wide, pointing to a lack of consensus in literature regarding this component's carbon intensity. The EFCA EPD was the most adopted data source, which also showed great variation depending on its year of publication. The current EPD for that organization (2015) shows an even

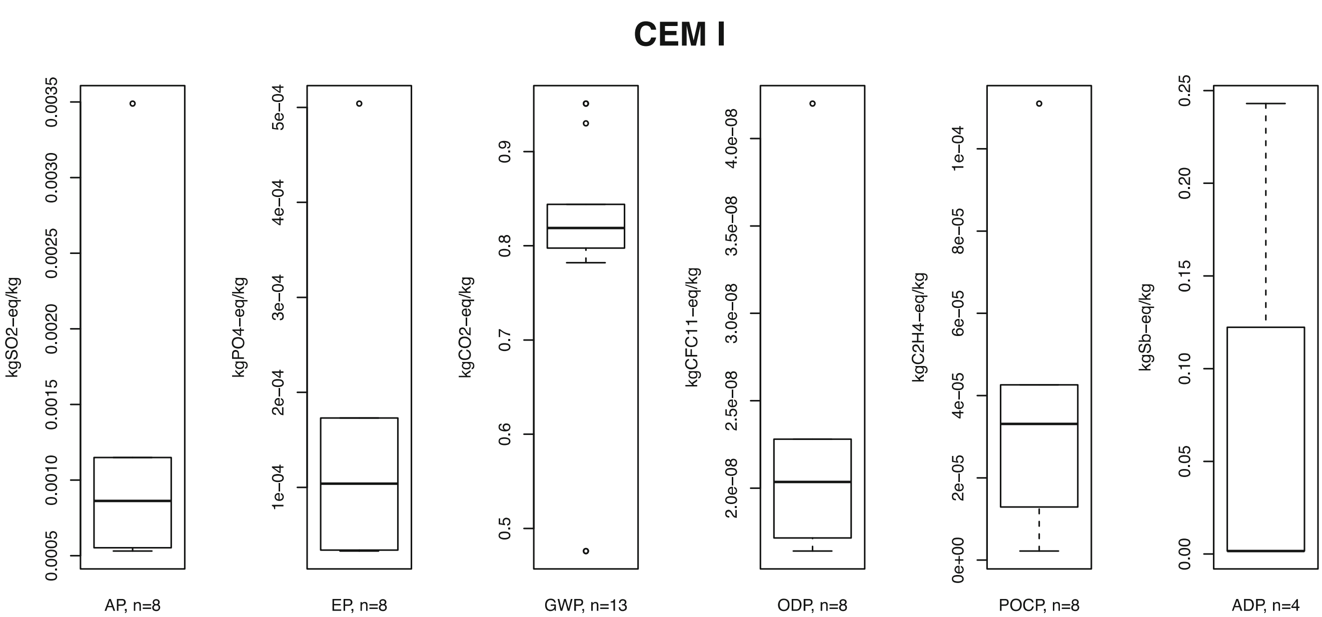

Fig. 7 Impacts of 1 kg of CEM I

Table 1 GWP values found for plasticizers and superplasticizers in sampled papers. Information in shaded cell is shown only for comparison purposes

Admixture type	GWP value (kg CO_{2eq}/kg)	Data source
Plasticiser	1.53	Ecoinvent
Plasticiser/Superplasticizer	0.22	EFCA EPD 2006
Plasticiser/Superplasticizer	0.72	EFCA EPD 2010
Plasticiser	0.944	German Association
Superplasticizer	0.739	German Association
Superplasticizer	0.0052	"Large manufacturer"
Plasticiser	0.75	unclear
Plasticiser/Superplasticizer	1.88	EFCA EPD 2015

higher GWP value, as listed for comparison purposes in Table 1's shaded cell. This variability points to a need of further investigation regarding chemical agents' contribution to concrete's loads. Typically disregarded due to its low consumption in ready mixed concrete (Van den Heede and De Belie 2012), admixtures are used in much larger quantities in sprayed concrete mixes, which most certainly interferes with the material's environmental attractiveness (Saade, Passer, and Mittermayr 2018b). In LCAs, when dealing with data uncertainty or unavailability, being conservative is usually the wisest approach. We therefore recommend using the latest data published by the EFCA whenever more specific and detailed inventory for an adapted LCA is unavailable. The referred EPDs also list GWP (and other indicators) values for hardening and set accelerators (2.28 kgCO_{2eq}/kg and 1.33 kgCO_{2eq}/kg, respectively) (used in typical sprayed concrete mixes), air entrainers (5.27E-1 kgCO_{2eq}/kg), water resisting admixtures (2.67 kgCO_{2eq}/kg) and retarders (1.31 kgCO_{2eq}/kg).

Limestone Our SLR pointed to a significant gap related to the presentation of limestone's life cycle impacts contribution in concrete-related researches. Even though 81 papers met our search criteria for this material (which means limestone is indeed considered in overall calculations), only 2 of them presented limestone's impact separately (Sagastume-Gutiérrez et al. 2012; Grist et al. 2015), but these referred to slaked lime production—not used as filler or aggregate in concrete. One safely assumes that limestone, aggregates and eventual supplementary cementitious materials (SCM) have lower environmental loads than cement's. Nonetheless, aggregates and other SCM's were far more individually investigated (Fig. 8). Limestone's lower content in concrete's composition might be the only explanation for such a pronounced overlook in our sampled papers. Present authors are currently collaborating in the development of a manuscript documenting limestone fillers environmental loads and investigating their optimal environmental/functional performance in pastes.

Fly ash As briefly discussed in the previous subsection, the cement (and concrete) industry has historically relied on industrial co-products use within its manufacturing processes. Incorporation typically happens in fuels' replacement (in what is called waste co-processing) or in clinker replacement, by using co-products that provide similar binding effect (calculated through the binding equivalency equation as listed in EN 206-1 (CEN 2004))—which is the case of SCMs like fly ash and ground granulated blast furnace slag. Regular materials (i.e. not co-products such as calcined clay, metakaolin and/or silica fume) also classify as SCMs, but are not part of our search's scope.

Allocation factors for co-products are calculated as a ratio between the co-product's property (be it mass or economic value) and the total figure of that property for the multifunctional processes (sum of mass figures or prices of product and co-product), as shown in Eq. 1; where Ap is the allocation factor based on a certain property, $p_{coproduct}$ is the co-product's value for that property and $p_{mainproduct}$ is the main product's value for that same property.

$$Ap = \frac{p_{\text{coproduct}}}{p_{\text{main product}} + p_{\text{coproduct}}}. \quad (1)$$

Being fly ash a widely used co-product, its impact values reflect differences related to the possible impact distribution methods adopted (Fig. 9).

When performing mass allocation for fly ash, authors typically consider the mass of hard coal necessary to generate a certain amount of electricity as the main product's property (as described by Chen et al. (2010)). Keeping that in mind, the far largest figures found for when mass allocation was adopted are expected, since fly ash's mass contribution to the process's total mass is always greater than its economic value contribution. The cut-off approach results—located in the lowest limits of the graph—only account for processing impacts (such as drying, storing and/or transporting). It becomes clear that fly ash's environmental attractiveness is greatly dependant on the impact distribution method used, adding relevance to the discussion presented in Subsection 3.2.5.

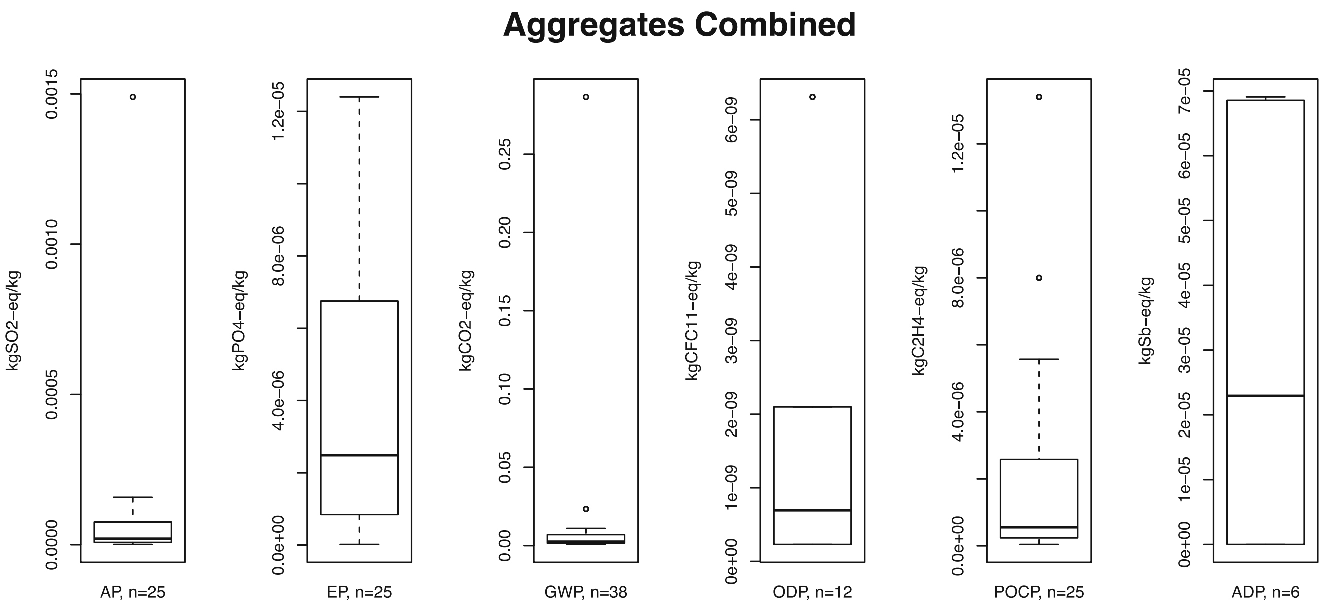

Fig. 8 Impact values for 1 kg of aggregates (fine + course)

Blast furnace slag Analogously to results presented for fly ash, blast furnace slag results are also inherently dependant on the distribution method adopted (Fig. 10). However, a few outliers stand out, in which economic allocation values surpass a few mass allocation values. Habert (2013) considers a range of economic-based allocation factors, from 0.6 to 12.6%, to more realistically depict price fluctuations, while Saade et al. (2015) present lower than average values for mass allocation due to state-of-the-art pig iron-making processes considered. Both papers' modelling peculiarities led to the mentioned differences.

For further reference, Table 2 summarizes the ranges of values found for each component, considering the six assessed environmental indicators.

3.2.7 Comparison between components

Results for concrete's components for which the largest number of papers were available are jointly plotted on Fig. 11, showing GWP values exclusively. We limit this comparison to the latter indicator due to the greatest number of results available for each component, which favours statistical

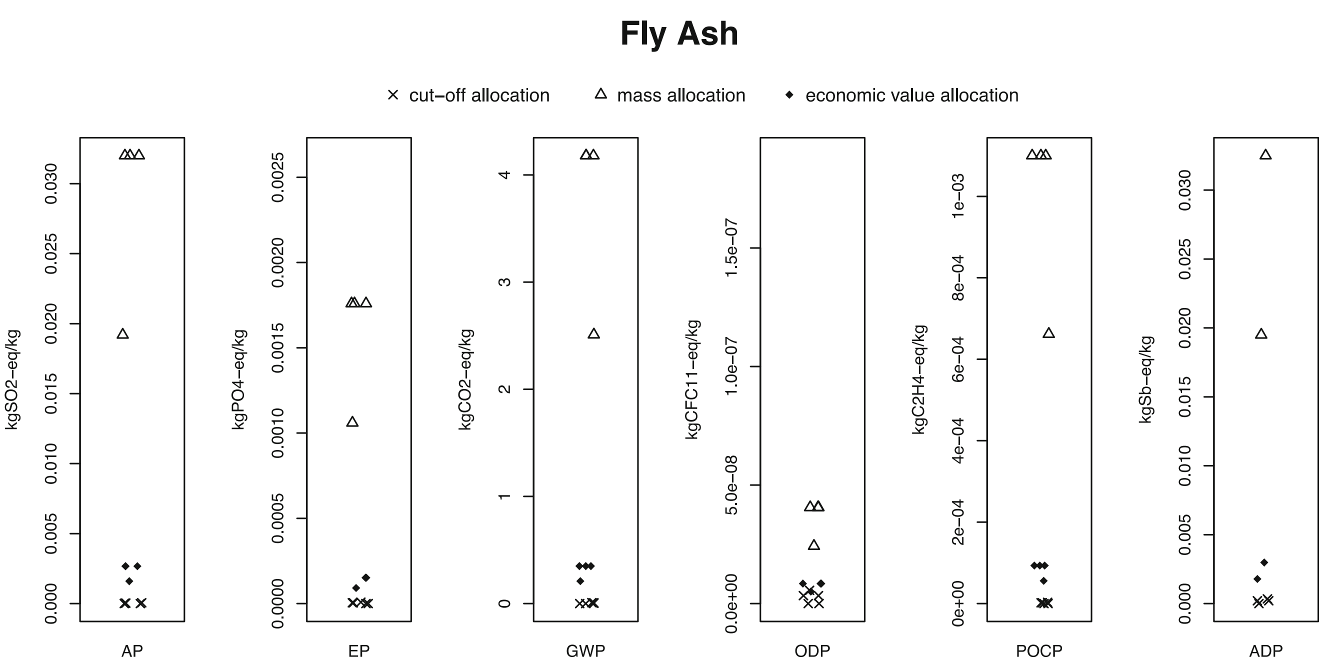

Fig. 9 Impact values for 1 kg of fly ash

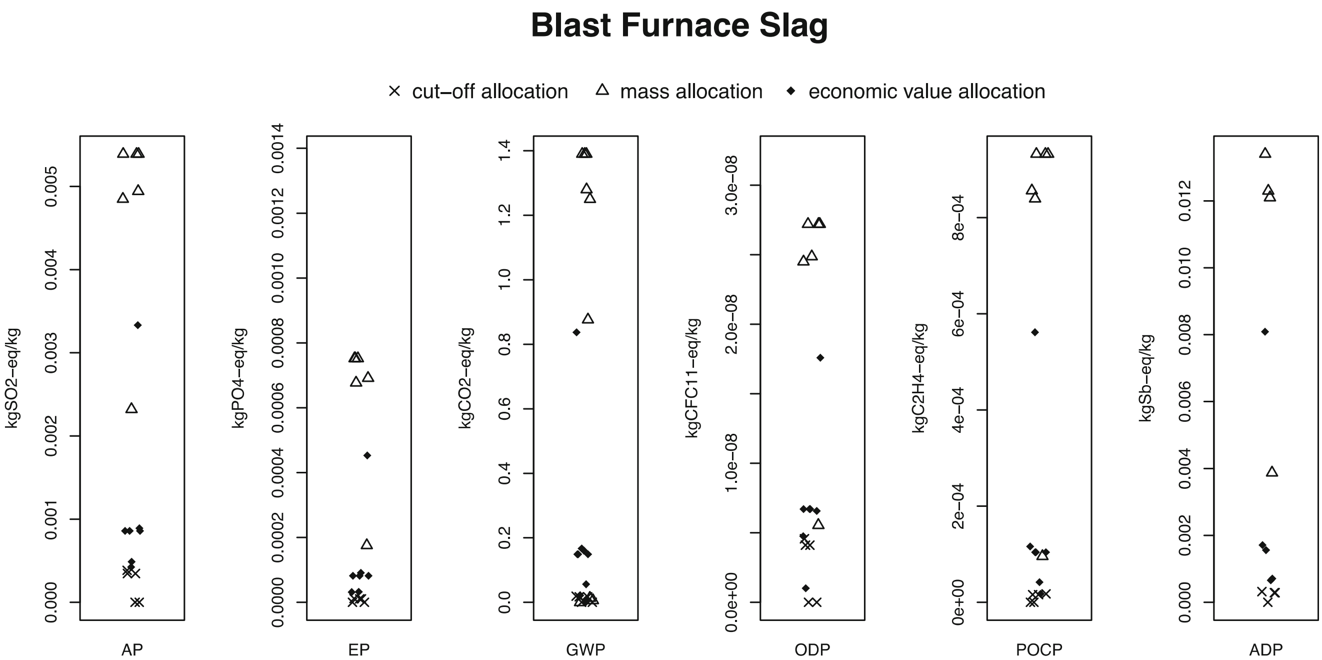

Fig. 10 Impact values for 1 kg of blast furnace slag

representation. Results are presented per equivalent binding capacity (BE) to assure a fair comparison (Chen et al. 2010). The assessed SCMs rank differently depending on critical choices made by the LCA practitioner.

As previously shown in Eq. (1), when one uses mass allocation in industrial processes that generate a great quantity of co-product, significant loads are assigned to the latter. For fly ash and blast furnace slag, it leads to an unattractive environmental profile for activities intending to recycle them, surpassing that of cement. The appropriateness of (and sensitivity to) different allocation criteria has been widely discussed in literature (Chen et al. 2010; Sayagh et al. 2010; Saade et al. 2015; Schrijvers Loubet and Sonnemann 2016a) but a consensus is far from being reached (Curran 2007; Schrijvers et al. 2016b). One could argue that the choice involves value judgement and therefore deliberating on the suitability of each approach would be a never-ending endeavour. Although we do agree that scientifically quarrelling over subjective matters might be a waste of time, here we present a more practical view of the issue: if an allocation criterion stimulates stakeholders to move away from a consolidated recycling practice which is in line with circular economy principles and knowingly avoids impact-intensive flows from and to nature (e.g. clinker manufacturing and waste disposal loads), while maintaining an overall net benefit (considering generated processing loads), then should not one consider it as inadequate for multifunctional modelling within one's own LCA? While for SCMs this perception is easier, we acknowledge that the identification of such situation in other cases might be tricky, and recommend caution whenever methodologically delineating a multifunctional process.

4 Final remarks

Our review's results provide a wide scientific panorama on how concrete (through its components) has been typically modelled in published LCA studies. The literary dossier that we have built not only aids in properly investigating sprayed concrete's loads within the ASSpC project, but it also has the potential to ground researches aiming to calculate typical concrete mixes' environmental profile through LCA, assuring

Table 2 Ranges of results found in the SLR. SCM's indicators values range from zero (cut-off approach) to the values obtained with mass allocation

	CEM I	Aggregates	Fly ash	Blast furnace slag
AP (kg SO_{2eq}/kg)	0.5E-3–3.49E-3	0.00087E-3–1.49E-3	0–0.032	0–0.00539
EP (kg PO_{4eq}/kg)	3.3E-4–5.04E-4	0.0018E-5–1.24E-5	0–0.00176	0–0.000752
GWP (kg CO_{2eq}/kg)	0.476–0.951	0.00106–0.287	0–4.18	0–1.39
ODP (kg $CFC11_{eq}$/kg)	1.64E-8–4.2E-8	0.23E-9–6.31E-9	0–4.06E-8	0–2.72E-8
POCP (kg C_2H_{4eq}/kg)	0.022E-4–1.11E-4	0.00416E-5–1.34E-5	0–0.0011	0–9.32E-4
ADP (kg Sb_{eq}/kg)	0.0159E-1–2.43E-1	1.6E-5–6.9E-5	0–0.0325	0–0.0134

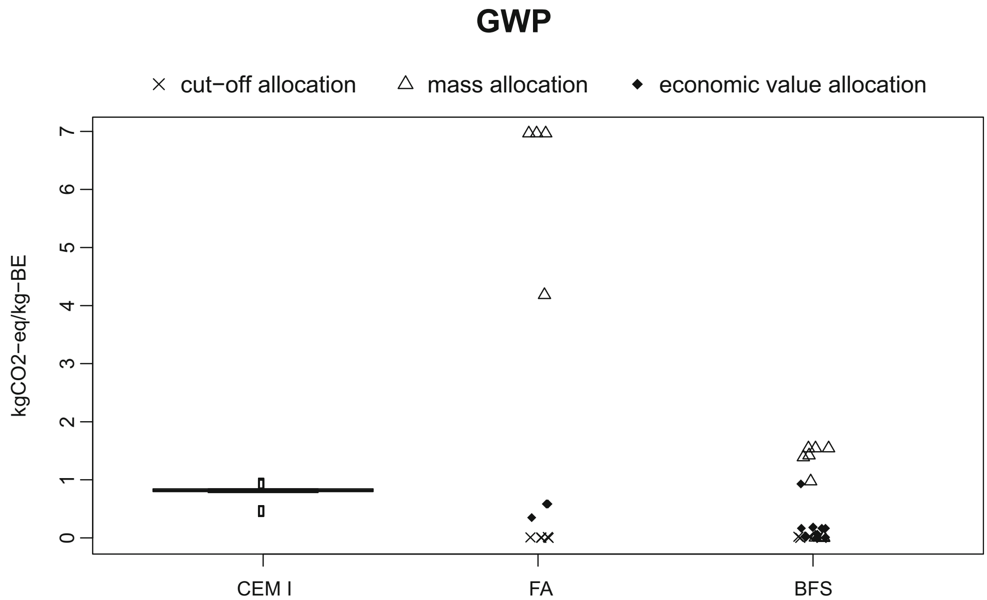

Fig. 11 GWP differences between 1 kg of cement, 1.11 kg of blast furnace slag and 1.67 kg of fly ash

comparability with the ecological status quo for that construction material.

As with any literature review, valid papers might have been left out because they fell out of our search criteria's scope. Still, by carefully structuring our research protocol and performing it systematically, we believe we have covered enough papers to provide a sound overview and to make collective conclusions regarding available literature.

We make two main recommendations for LCA practitioners assessing concrete's impacts: first, although knowingly carbon-intensive, concrete (and cement) do contribute to other impact categories which ought to be investigated—specially as we move towards more carbon-friendly technologies in their manufacturing. To restrict concrete's LCA focus to GWP is to risk overseeing equally important environmental issues or—worse—shifting the burden to other categories such as toxicity or depletion of non-renewable resources. LCA tools currently available are powerful enough to provide a range of impact results with almost no additional demand on the computational apparatus, so one should aim for seizing all of the method's potential.

Second, practitioners should always comply with the transparency requirements of an LCA. Our outcome pointed to an alarming number of published papers that failed to declare basic methodological choices such as data sources, impact assessment methods used and impact distribution strategies in multifunctional processes' modelling. Comparability is severely hindered in those cases. Journal reviewers and/or editors could be of help in assuring the proper declaration of calculation procedures taking place in published LCAs.

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Compliance with ethical standards

Conflict of interest The authors declare they have no conflict of interest.

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