

IMPACT DISTRIBUTION METHODS' USE IN MULTIFUNCTIONAL LIFE CYCLE ASSESSMENTS: A SYSTEMATIC LITERATURE REVIEW

O USO DE MÉTODOS DE DISTRIBUIÇÃO DE IMPACTOS EM ACVS DE PROCESSOS MULTIFUNCIONAIS: UMA REVISÃO SISTEMÁTICA DA LITERATURA

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Resumo

Partitioning loads related to multifunctional processes, which generate more than one product or service (*i.e.*, function), is a controversial issue within life cycle assessment (LCA). ISO 14044:2006 suggests avoiding allocation through a hierarchic stepwise procedure, through (i) subdividing the multifunctional process into unitary sub-processes with one specific function; or (ii) expanding the system boundaries to include the additional functions related to by-product(s). If the latter steps are not possible, the system's inputs and outputs must be allocated based on a fundamental physical relationship between products. When one is unable to identify such physical relationship, flows must be partitioned as to reflect other relations between products, such as their economic value. This paper aims to delineate a scientific overview of the impact distribution methods' use within LCA practice from 2006 to 2016. Authors performed a systematic literature review and documented methods' choice frequency within studies published in the considered time frame. Results revealed a lack of consensus among LCA practitioners. Most papers adopt the avoided burden approach (equivalent to system expansion), while the first step proposed in ISO 14044's hierarchy (subdivision) was the least used method. Our examination confirmed that the impact division problem is typically solved by substantially diverging from ISO's theoretical framework, which suggests both an opportunity for reflection and a reformulation need.

Keywords: LCA. Allocation. System expansion. Subdivision. Avoided burden. Systematic literature review.

Resumo

Uma questão controversa em ACV é a escolha do método de distribuição de impactos nos processos multifuncionais, isto é: que geram mais de um produto ou serviço. A ISO 14044:2006 sugere que se tente evitar a alocação, utilizando: (i) divisão do processo multifuncional em dois ou mais subprocessos unitários; ou (ii) expansão do sistema de produto para incluir as funções adicionais relativas aos co-produtos. Caso isto não seja possível, as entradas e saídas do sistema devem ser divididas com base em alguma relação física fundamental entre produtos. Caso a relação física não seja identificada, os fluxos devem ser divididos refletindo outras relações entre produtos, por exemplo, seu valor econômico. Este artigo visa delinear um panorama científico do uso de métodos de distribuição de 2006 a 2016. Para tanto, realizou-se uma revisão sistemática de literatura e documentou-se a frequência de escolha dos métodos nos estudos realizados no período considerado. Os resultados revelaram uma falta de consenso entre praticantes de ACV. A maioria dos estudos adota a abordagem do impacto evitado (equivalente à expansão do sistema), enquanto o primeiro passo proposto pela ISO 14044 (subdivisão) foi o método menos usado. Nossa avaliação confirmou que o problema de distribuição de impactos é tipicamente solucionado de forma contrária ao encaminhamento teórico proposto na norma, sugerindo uma oportunidade de reflexão e reformulação.

Palavras-chaves: ACV. Alocação. Expansão de sistema. Subdivisão. Revisão sistemática da literatura.

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Introduction

A multifunctionality problem in LCA arises when a process fulfills one or more function(s) for the investigated product's life cycle, and a different function (or functions) for other product(s) (EKVALL; FINNVEDEN, 2001). Cases like a production process generating multiple products, a waste management process comprising various waste flows, or a recycling process which combines waste management and material production, challenge sharing and distributing material and energy flows across multiple functions.

Due to high co-product incorporation in building materials' manufacturing, the construction sector often faces impact distribution issues. For example, sustainability strategies devised for the cement industry worldwide have been mostly based on clinker substitution to mitigate global warming. LCA provides a robust analysis framework, which enlightens the embedded risks and limitations of single impact-driven policies. Still, multifunctional processes modeling - i.e. impact distribution within them - remains as a highly controversial issue in LCA for its significant influence on studies outcomes (FRISCHKNECHT, 2000; WEIDEMA, 2001; EKVALL; FINNVEDEN, 2001; REAP et al., 2008; SAYAGH et al., 2010). Incomplete impact consideration and contradictory results from varied impact distribution strategies cloud decision-making capacity of affected industries and stakeholders.

ISO 14044 (ISO, 2006a) provides the guideline for performing LCAs. Regarding multifunctionality problem-solving, the standard suggests a stepwise procedure. First, allocation, i.e. the distribution of impacts between a product and co-products 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.

Mass-based allocation is quite straightforward, depending on easily calculated and constant values. However, in many industrial processes, co-product mass generation is significantly high, and mass allocation tends to favor the waste generator, since a large part of the environmental loads is transferred to the activity that uses the co-product.

Economic value-based allocation advocates argue that all industrial activities are guided by economic principles, and to follow that approach for impact distribution would

therefore make sense. The most common criticism of using this partitioning criterion refers to its sensitivity to market fluctuations, which hinders results reliability over long periods.

System expansion, as defined by ISO 14044 (2006a), suits best for consequential LCAs (PELLETIER et al., 2015), which consider how to obtain information on changes and environmental impact due to a decision or a change in demand for a product (SCHRIJVERS et al., 2016).

Although not mentioned in ISO 14044 (ISO, 2006a), 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; GUINÉE, 2007). This approach improves processes modelling, but still fails to distribute prevented environmental loads across the expanded system components (CHEN et al., 2010), requiring further modeling adjustments (SAADE; SILVA; GOMES, 2015).

At the theoretical level, Weidema and Schmidt (2010), for example, defend that system expansion always respects mass and energy conservation laws, while allocation nearly always fails to do so. According with these authors, as allocation splits the original system into two or more artificial systems, based on the allocation criterion adopted, the only remaining balance would be defined by the given criterion, i.e. when mass regulates allocation, only mass conservation is respected. Conversely, Chen et al (2010) affirmed that system expansion (through the avoided impact approach) does not respect mass conservation laws when the product and co-product are considered together, and chose mass and economic value allocation criteria to assess mineral additions use in concrete manufacturing impacts. Both papers sustain their arguments by using either case-specific (WEIDEMA; SCHMIDT, 2010) or author-defined hypothetical example and equations (CHEN et al., 2010). Both explanations can be contested in different contexts and perspectives.

Methodological approach

Systematic literature reviews (SLR), widely used in the medical sciences, stand out as a way of synthesizing evidence and allowing researchers to really grasp the status of a research area (WOHLIN, 2014). Systematic reviews consist of an exhaustive summary of the high-quality literature on a particular topic. They usually also adopt an additional technique called meta-analysis, which pools together results from a number of different studies (GLASS, 1976), to provide a quantitative (and many times statistical) evaluation of published researches.

In this paper, following the typical protocol for systematic reviews, the designed research question is: 'How often have the different impact distribution methods been used in multifunctional processes' LCA over the past 10 years?'. We selected Springer database as a search source, for hosting volumes of the 'International Journal of Life Cycle Assessment', the only LCA-specialist international journal available. The time boundary's initial limit refers to the date in which the international LCA standard was last updated (2006). The review ended in the first semester of 2016.

Search keyword string used was: LCA AND allocation OR multifunction* OR avoided burden OR system expansion. Over 1,000 results matched the initial search criteria. The final sample of papers was selected through three exclusion rounds: a title analysis, an abstract analysis and a full paper analysis. Our sample included papers covering attributional and consequential LCAs carried out in any industrial sector. We disregarded grey literature, yet using the 'snowball' approach (LITTEL et al., 2008) to expand the original sample. 147 papers remained, which complied with the predetermined requirements. Then, a data extraction form was built containing all relevant information documented in each paper, to feed the meta-analysis: authors' names and affiliation, date, publishing journal and the method(s) used for impact distribution.

Results presentation and discussion

Although not described in the international standard, there is, in practice, a distinction between two types of LCA: attributional and consequential. The first is used to learn about the impacts associated to a specific process, to identify improvement opportunities and/or to provide market information (e.g. communicate a product's impact to potential users) (TILLMAN, 2000). The latter is used to obtain information about direct or indirect changes in environmental impacts due to decisions or a change in demand for a product or process (SCHRIJVERS et al., 2016).

From the 147 studies that composed the final sample, only 17 papers worked with consequential LCA. All of them adopted system expansion (SE) and/or the avoided burden approach (AB). These two methods seem to represent the only proper approach to solve impact distribution problems in this type of LCA (Pelletier et al., 2015). As to the remaining literature referring to attributional LCA, we identified not only the methods proposed by ISO 14044 (ISO, 2006a) – subdivision (SD), system expansion, physical causality (PC) and economic value-based

allocation (EV) - but also papers that proposed new methods (PM) or ignored impact distribution (NA). As many studies did not follow Heijungs (2014) recommendation to explicitly distinguish 'system expansion' from the 'avoided impact approach', we assessed if (a) the defined functional unit encompassed the co-product(s) function, or (b) avoided impact subtraction occurred; which respectively characterize 'system expansion' and 'avoided burden' approaches. Whenever a paper used multiple, complementary methods, we registered occurrence of all methods.

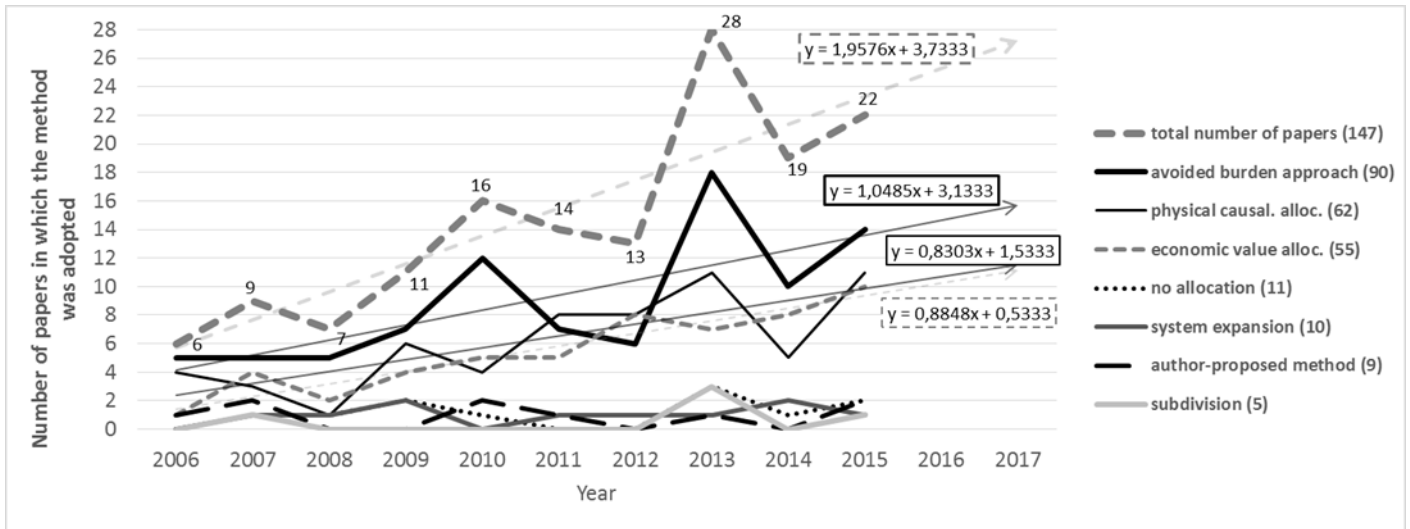
The number of different approaches registered in the SLR reflects vagueness of ISO 14040 (ISO, 2006b) proposed guidelines. In fact, LCA practice captured in our review (Figure 1)⁽¹⁾ frontally opposes ISO's recommended hierarchy. On one hand, the first alternatives to be tried according to the standardized hierarchy - 'subdivision' (5 papers) and 'system expansion' (10 papers) – showed a discrete and stable use profile. On the other hand, our final sample was dominated by the 'avoided burden approach' (90 papers, derived function $\partial y/\partial x=1,0485$ in Figure 1), which is not listed in the standard, followed by physical (62 papers) and economic value (55 papers) allocation, despite the latter being the least recommended approach by ISO. The two allocation approaches present similar trend lines.

Seventy six (76) papers adopted one exclusive impact distribution method. Figure 2 shows that the avoided burden approach's choice dominance still stands out, while subdivision was never individually used. The fact that more than half of the assessed paper sample adopted a single method indicates a breach in ISO compliance in published literature. The international standard clearly states that, when facing a multifunctionality issue, LCA practitioners must perform a sensitivity analysis with more than one distribution method.

Seventeen (17) papers documented construction sector-related researches. Their method's choice frequency is depicted in Figure 3⁽²⁾. Although the total number of papers presented a discrete peak in 2013 (analogously to the curves plotted in Figure 1), any trend observation is hindered by the sample's limited size. Still, the top three most used methods' ranking (Figure 1) was maintained in this construction-related excerpt.

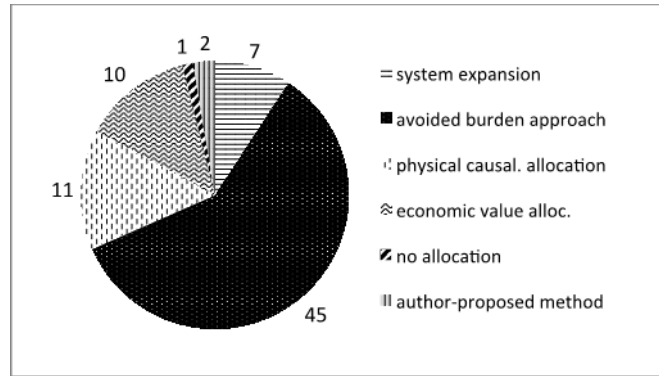
Table 1 summarizes our findings, listing each paper and the respective adopted method(s).

Figure 1 - Multifunctionality modelling solution occurrence since 2006 (occurrence of each method is shown between brackets)



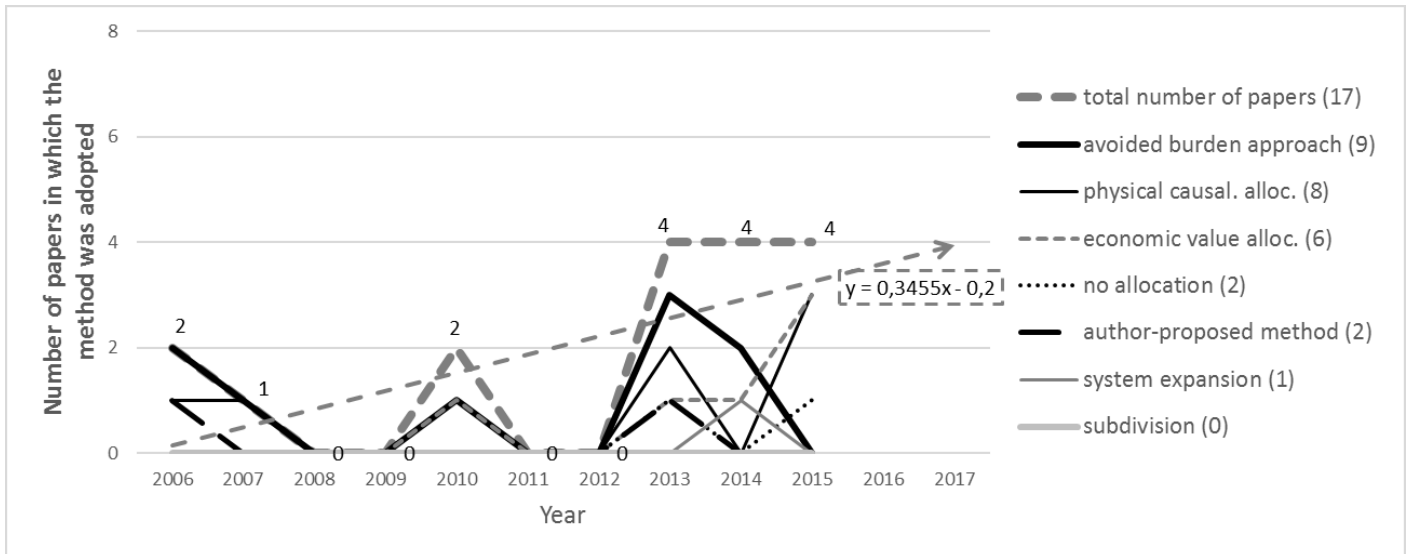
Source: Authors

Figure 2 - Multifunctionality modelling solution occurrence in papers that adopted one method solely since ISO 14040 update in 2006



Source: Authors

Figure 3 - Multifunctionality modelling solution occurrence in construction sector-related papers since ISO 14040 update in 2006. Occurrence of each method is shown between brackets



Source: Authors

Table 1 - Impact distribution methods chosen in each paper

(continues)

Author(s)	SD	PC	EV	SE	AB	PM	NA
Adom <i>et al.</i> (2012)		X	X				
Aguilera, Guzmán and Alonso (2015)			X		X		
Almeida <i>et al.</i> (2014)		X					
Amores <i>et al.</i> (2013)		X	X				
Anastasiou, Liapis and Papayianni (2015)			X				
Andreola <i>et al.</i> (2007)		X			X		
Astudillo, Thalwitz and Vollrath (2015)		X	X		X		
Bier, Verbeek and Lay (2012)		X	X		X		
Boldrin, Balzan and Astrup (2013)		X			X		
Cai <i>et al.</i> (2013)		X			X		
Chen <i>et al.</i> (2010)		X	X				
Choo <i>et al.</i> (2011)		X			X		
Cleary (2010)					X		
Cleary (2014)					X		
Cottle and Cowie (2016)		X	X		X		
Dalgaard <i>et al.</i> (2008)					X		
Dhaliwal <i>et al.</i> (2014)					X		X
Dias, Arroja and Capela (2007)	X	X			X		
Dressler, Loewen and Nelles (2012)		X			X		
Du <i>et al.</i> (2014)					X		
Eckelman and Chertow (2013)				X			
Ferreira <i>et al.</i> (2015)		X	X				
Fiksel <i>et al.</i> (2011)		X					
Flysjö <i>et al.</i> (2011)		X	X		X		
Gala, Raugei and Fullana-I-Palmer (2015)					X		
Galatioto <i>et al.</i> (2015)		X	X				X
Babarenda Gamage <i>et al.</i> (2008)					X		X
Gaudreault, Samson and Stuart (2010)		X			X		X
Gazulla, Raugei and Fullana-I-Palmer (2010)			X		X		
Gomes <i>et al.</i> (2013)		X			X		X
González-García <i>et al.</i> (2011)		X					
Groot and Borén (2010)			X		X		
Gruber <i>et al.</i> (2015)		X					
Guinée and Heijungs (2007)		X	X				
Guinée, Heijungs and Voet (2009)		X	X		X		
Guo and Murphy (2012)			X		X		
Habert (2013)					X	X	
Herrmann <i>et al.</i> (2012)					X		
Höglmeier, Weber-Blaschke and Richter (2014)				X			
Hossain <i>et al.</i> (2015)		X					
Huang, Spray and Parry (2013)		X	X				
Humbert <i>et al.</i> (2009)					X		
Jung, Von Der Assen and Bardow (2013)		X			X		
Karlsdóttir <i>et al.</i> (2015)	X	X					
Kendall, Yuan and Brodt (2013)	X		X				
Kim and Dale (2006)					X		
Kim, Dale and Jenkins (2009)		X			X		
Kim and Dale (2009)		X			X		
Knoeri, Sanyé-Mengual and Althaus (2013)					X		
Kuczenski and Geyer (2013)					X		
Escobar Lanzuela <i>et al.</i> (2015)					X		
Lesage <i>et al.</i> (2007)			X		X		
Lundie <i>et al.</i> (2007)						X	
Luo <i>et al.</i> (2009)		X	X	X			
Margallo, Aldaco and Irabien (2014)					X		
Mestre and Vogtlander (2013)							X
Moon, Eun and Chung (2006)					X	X	
Mora <i>et al.</i> (2014)					X		
Mu <i>et al.</i> (2010)					X		
Muñoz <i>et al.</i> (2006)		X			X		

Source: The authors.

Table 1 - Impact distribution methods chosen in each paper

(conclusion)

Author(s)	SD	PC	EV	SE	AB	PM	NA
Muñoz <i>et al.</i> (2009)					X		X
Muñoz <i>et al.</i> (2014)			X				
Murphy and Kendall (2013)	X	X	X				
Napolano <i>et al.</i> (2014)					X		
Nebel, Zimmer and Wegener (2006)		X			X		
Nguyen and Hermansen (2012)		X	X	X			
Nielsen and Høier (2009)				X			
Panichelli, Dauriat and Gnansounou (2009)		X	X				
Peters, Iribarren and Dufour (2015)					X		
Pires, Chang and Martinho (2011)					X		
Pires and Martinho (2013)					X		
Prasara-A and Grant (2011)					X		
Ridoutt <i>et al.</i> (2012)			X				
Saft (2007)					X		
Samuel-Fitwi <i>et al.</i> (2013)		X			X		
Sandin <i>et al.</i> (2015)		X	X		X	X	X
Scharnhorst <i>et al.</i> (2006)		X					
Schmidt and Weidema (2007)				X			
Schmidt (2010)			X		X		
Shonnard <i>et al.</i> (2015)		X			X		
Siegl, Laaber and Holubar (2011)					X		
Siegl, Laaber and Holubar (2012)					X		
Silva <i>et al.</i> (2014)			X				
Slade, Bauen and Shah (2009)		X			X		X
Spugnoli and Dainelli (2013)	X				X		
Sreejith, Muraleedharan and Arun (2013)					X		
Svanes, Vold and Hanssen (2011a)		X	X			X	
Svanes, Vold and Hanssen (2011b)		X	X				
Svanes and Aronsson (2013)		X	X				
Thomassen <i>et al.</i> (2008)		X	X		X		
Thrane (2006)		X	X		X		
Toniolo <i>et al.</i> (2013)					X		X
Tsiropoulos <i>et al.</i> (2014)			X		X		
Van Der Werf and Nguyen (2015)		X	X			X	
Vázquez-Rowe <i>et al.</i> (2014)				X			
Wardenaar <i>et al.</i> (2012)		X	X		X		
Werner <i>et al.</i> (2007)			X		X		X
Wiedemann <i>et al.</i> (2015)		X	X		X		
Wiloso, Bessou and Heijungs (2015)			X	X	X		
Xie <i>et al.</i> (2013)					X		
Zaimes and Khanna (2014)		X	X		X		
Zaman (2010)					X		
Zampori and Dotelli (2014)					X		
Zimmermann <i>et al.</i> (2011)			X				

Source: The authors

Poor adherence between ISO's preferred method hierarchy and practice trends is probably related to implementation difficulty. The fact that not all multifunctional processes can be easily split up into unit sub-processes greatly hinders subdivision application. System expansion, on its turn, requires redefinition of system boundaries and functional unit, which might affect the original goal and elongate data collection. Though the scientific robustness of the avoided burden approach is intensively discussed (CHEN *et al.*, 2010; SCHRIJVERS *et al.*, 2016), its dominance suggests that LCA practitioners ultimately value easiness of understanding and use over conceptual superiority.

Final remarks

The controversy involving multifunctional processes' modeling is extensively documented and discussed in the specialized literature, however, until the finalization of this paper, no research documenting impact distribution methods' choice frequency was identified. This research did not intend to question the appropriateness or superiority of a method, but to outline the scientific overview behind the extensive discussion on multifunctionality within LCA, and to serve as a background or starting point for future discussions on the matter.

Results illustrate LCA practitioners' preferences to model multifunctional processes. The choice variability detected in the review strengthens the perception of a lack of consensus between researchers and scientists, all the while questioning the appropriateness of the international standard's proposed hierarchy.

Wide and less restrictive guidelines are not uncommon in international standards, which are calibrated to encompass idiosyncratic practices, especially related to impact

distribution choices – that predict a certain level of value judgment. However, impact allocation, highlighted in ISO 14044 (ISO, 2006a) as a problem to be avoided, stands out as the second most used method to model multifunctionality in LCA. A decade's worth of application confirmed that the impact division problem is typically solved by substantially diverging from ISO's theoretical framework, which suggests both an opportunity for reflection and a reformulation need.

Acknowledgments

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Notes

- (1) Since the review ended in the first semester of 2016, the number of papers found for that year was smaller than for the previous two years. To better illustrate the trendline, those values were not plotted in Figures 1 and 3. Those researches and their respective chosen methods can be found in Table 1.
- (2) In another systematic literature review, carried out by one of the authors for the Austrian *Advanced and Sustainable Sprayed Concrete* (ASSpC) project, it became noticeable that, actually, most LCA papers applied to building materials consider co-products as waste. The SLR performed for the present paper was unable to capture that type of LCA due to the keywords' selection, all referring to impact distribution – typically not mentioned in the papers that disregard co-products' impacts.

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