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Relevance of including capital goods in the life cycle assessment of construction products

Relevância da inclusão dos bens de capital na avaliação do ciclo de vida de produtos de construção

Relevancia de la inclusión de los bienes de capital en la análisis del ciclo de vida de productos de construcción

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Abstract

The development of representative Life Cycle Inventories (LCI) is fundamental to enable the use of Life Cycle Assessment (LCA) as a decision tool. Capital goods, such as buildings and machinery (infrastructure), are particularly difficult to determine and are therefore commonly based on rough estimates, even in international databases. The aim of this work is to explore the effects of considering capital goods on the Life Cycle Impact Assessment (LCIA) results of six construction products: sand, gravel, clinker, cement, concrete and concrete block. LCI are based on ecoinvent version 3.4 and impact assessment was done using the CML 1A baseline method. We compare the LCIA results with and without infrastructure by using the Monte Carlo analysis to account for the increase in total uncertainty caused by the inclusion of the highly uncertain capital goods flows. The difference between LCIA results with and without infrastructure is not significant for global warming, acidification, eutrophication, ozone depletion, photochemical oxidation and fossil fuels depletion; and is considered high for toxicity impact categories and abiotic elements depletion. However, these impact categories influenced by infrastructure have limited applicability for decision making in construction. Furthermore, changing capital goods is difficult due to required investments and therefore, unlikely to be a strategy for improving the environmental performance of construction products. Thus, we consider that the added value to LCA by the inclusion of capital goods is low, since uncertainty *remains high, while the efforts to collect them are significant, thus questioning its inclusion in LCA studies and databases by default.*

Keywords: *Life cycle assessment. Capital goods. Infrastructure. Construction products. Uncertainty.*

Resumo

O desenvolvimento de inventários de ciclo de vida (ICV) representativos é fundamental para o uso da Avaliação do Ciclo de Vida (ACV) como ferramenta de decisão. Bens de capital, como construções e maquinário (infraestrutura), são difíceis de serem inventariados e, por isso, baseiam-se normalmente em estimativas grosseiras, mesmo em bases de dados internacionais. O objetivo deste trabalho é explorar os efeitos de considerar os bens de capital nos resultados de Avaliação de Impacto do Ciclo de Vida (AICV) de seis produtos de construção: areia, brita, clínquer, cimento, concreto e bloco de concreto. Os ICVs são baseados no ecoinvent versão 3.4 e a avaliação de impacto utiliza o método CML 1A baseline. Compararam-se os resultados de AICV com e sem a infraestrutura, utilizando a análise de Monte Carlo para contabilizar o aumento na incerteza causado pelos fluxos de bens de capital, que possuem incerteza alta. A diferença entre os resultados de AICV com e sem infraestrutura não é significativa para aquecimento global, acidificação, eutrofização, depleção de ozônio, oxidação fotoquímica e depleção de recursos fósseis; e é alta para categorias de impacto relacionadas à toxicidade e depleção de recursos abióticos. Entretanto, estas categorias de impacto influenciadas pela infraestrutura têm aplicabilidade limitada na construção. Além disso, alterar os bens de capital é difícil, devido aos investimentos requeridos e, portanto, pouco provável como estratégia de melhoria do desempenho ambiental de produtos de construção. Portanto, considera-se que o valor agregado à ACV pela inclusão dos bens de capital é baixo, pois a incerteza permanece alta, enquanto o esforço para coleta de dados destes fluxos é significativo, questionando-se a inclusão dos bens de capital em estudos e bases de dados de ACV como padrão.

Palavras chave: *Avaliação do ciclo de vida. Bens de capital. Infraestrutura. Produtos de construção. Incerteza.*

Resumen

El desarrollo de inventarios de ciclo de vida representativos es fundamental para el uso de la Evaluación del Ciclo de Vida como herramienta de decisión. Los bienes de capital, como las construcciones y la maquinaria (infraestructura), son difíciles de inventariar y se basan normalmente en estimaciones groseras, incluso en bases de *datos internacionales. El objetivo de este trabajo es explorar los efectos de considerar los bienes de capital en los resultados de Evaluación de Impacto del Ciclo de Vida de seis productos de construcción: arena, gravas, clinquer, cemento, hormigón y bloque de hormigón. Los inventarios se basan en ecoinvent versión 3.4 y la evaluación de impacto utiliza el método CML 1A baseline. Se compararon los resultados de impacto con y sin la infraestructura, utilizando el análisis de Monte Carlo para contabilizar el aumento en la incertidumbre causada por los flujos de bienes de capital, que tienen incertidumbre alta. La diferencia entre los resultados de AICV con y sin infraestructura no es significativa para el calentamiento global, acidificación, eutrofización, depleción de ozono, oxidación fotoquímica y depleción de recursos fósiles; y es alta para las categorías de impacto relacionadas con la toxicidad y la depleción de recursos abióticos. Sin embargo, estas categorías de impacto influenciadas por la infraestructura tienen una aplicabilidad limitada en la construcciónn. Además, alterar los bienes de capital es difícil, debido a las inversiones requeridas y, por lo tanto, poco probable como estrategia para mejorar el desempeño ambiental. Por lo tanto, se considera que el valor agregado a la ACV por la inclusión de los bienes de capital es bajo, pues la incertidumbre permanece alta, mientras que el esfuerzo para recolectar datos de estos flujos es significativo, cuestionándose la inclusión de los bienes de capital en estudios y bases de datos de ACV como estándar.*

Palabras clave: *Evaluación del ciclo de vida. Bienes de capital. Infraestructura. Productos de construcción. Incertidumbre.*

1. Introduction

A key issue to enhance the application of Life Cycle Assessment (LCA) is the availability of local, representative Life Cycle Inventories (LCI). The authors of this paper were involved in the development of LCI for cement-based construction products in Brazil, to be submitted both to ecoinvent and to SICV (Brazilian LCI database), within the Sustainable Recycling Industries (SRI) project coordinated by ecoinvent. Our aim in that project was to develop high-quality datasets representative of the national technology, based on primary operational data for all flows considered relevant. To facilitate data collection, we relied on flows already controlled by the manufacturers.

Ecoinvent requires the datasets to be "as complete as the knowledge of the data providers allows" and does not apply any systematic cut-off rules (WEIDEMA et al., 2013). Therefore, we were asked to report the consumption

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of capital goods for all datasets (buildings and machinery, amortized by the production during their service life). SICV, on the other hand, only requires to inform if capital goods have been included in the dataset (IBICT, 2016). ISO 14040 and the ILCD Handbook recommend by default including capital goods in the system boundary of the LCA study, applying the usual cut-off rules regardless of activity type (ABNT, 2009; EUROPEAN COMMISSION, 2010), while Environmental Product Declaration (EPD) standards for construction products do not explicitly require the inclusion of capital goods (DIN, 2014; ISO, 2007).

Some studies investigated the importance of capital goods in LCA. Eickelkamp (2015), using a hybrid input-output and life cycle approach covering all economic sectors, assessed an average increase of 20% in energetic resource depletion and climate change results by the inclusion of infrastructure – for the basic manufacturing industry the increase is only of 5% though. Frischknecht et al. (2007) analyzed about 700 ecoinvent datasets and concluded that, for construction products, the influence of infrastructure is more relevant (more than 30% difference in LCIA results) for human- and eco-toxicity, mineral resource depletion and land use, while impact categories like global warming and acidification are less changed (less than 10% difference). Studies using primary data to model the infrastructure, such as Brogaard and Christensen (2016) for waste management systems and Igos et al. (2014) for water treatment plants, came to similar conclusion in terms of infrastructure effect on the different impact categories.

The main contribution to capital goods' environmental impacts comes from the steel used in machinery and buildings and its life cycle, i.e. mining and steel manufacturing activities (FRISCHKNECHT et al., 2007; IGOS et al., 2014; LIU et al., 2016), except for land use, for which the area occupied by buildings is more relevant (FRISCHKNECHT et al., 2007). The sensitivity analysis carried out by Igos et al. (2014) shows that the service life of concrete and steel used in capital goods is also an important parameter, as infrastructure impact is amortized over its service life and the corresponding production volume.

However, getting good quality primary data to model the inventory flows for capital goods can be a difficult task, especially if one is expected to develop an LCI that can be used for many purposes and with various LCIA methods, like in the ecoinvent database, which requires a high level of detail. The manufacturer of the product being inventoried can only deliver part of the information (e.g. specification of machinery), and most data must be provided by other agents in the supply chain (e.g. machinery producers). The availability of specific inventories is still limited, which leads to an additional data collection effort, often more complex than the product inventory itself. Moreover, some data are difficult to retrieve or estimate, such as factory buildings' specifications and infrastructure lifetime. Therefore, capital goods are commonly based on rough estimates with high uncertainty (WEIDEMA et al., 2013), often not considered in the calculation of impact results – sensitivity analysis shows that variations in the amounts or specifications of capital goods, especially for steel, can significantly influence final indicators (BROGAARD; CHRISTENSEN, 2016). One may argue that "a rough estimate is better than nothing" but depending on the study (such as comparative assessments), unprecise infrastructure estimates may be misleading. It also implies a dilemma: if capital goods are important, shouldn't they be properly modelled? And if they are not important, couldn't they be excluded from the scope?

This works aims at analyzing the relevance of capital goods for the environmental performance of six construction products addressed in the SRI Project – sand, gravel, clinker, Portland cement, concrete and concrete block – considering both the increase in environmental impact results and in uncertainty, in order to assess not only the relative difference between LCIA results with and without infrastructure, but also its significance.

2. Method

The following ecoinvent version 3.3 datasets are used: gravel and sand quarry operation; gravel production, crushed; clinker production; cement production, Portland; concrete block production; unreinforced concrete production, with CEM II/A; with geographical scope "Rest-of-the-World" (RoW) and allocation system "cut-off by classification". Standard deviation values for all inventory flows (including infrastructure) are also taken from ecoinvent, which considers the lognormal probability distribution function by default.

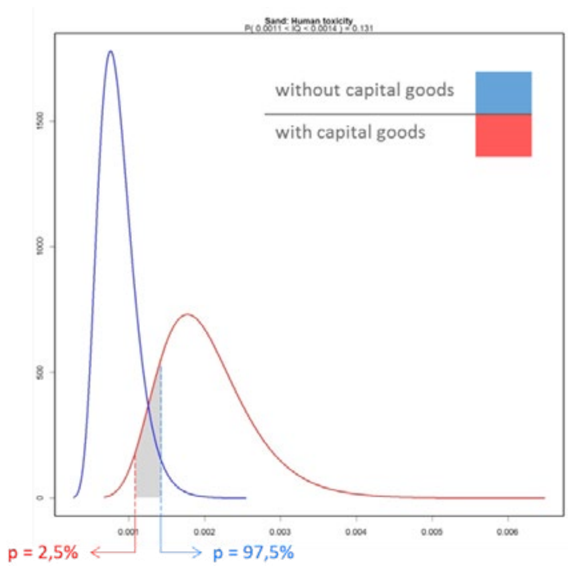
It is worth mentioning that even in ecoinvent, infrastructure is modelled based mostly on rough estimates, despite the request for completeness: for instance, the rotary kiln for clinker manufacturing is modelled by approximation as a 300 t "generic heavy industrial machine" (with an estimated service life of 25 years), which in turn is based on the specifications of a rock crusher (KELLENBERGER et al., 2007).

Impact assessment results are calculated using the CML 1-A baseline (version 3.04) method, recommended by EN 15804 (DIN, 2014), and running Monte Carlo sampling with 10.000 iterations, with and without infrastructure, using the Simapro function "exclude infrastructure processes" for the latter (inventory flows for replacement of wearing parts, such as steel and rubber inputs, were not excluded as they are modelled as direct inputs in each product inventory). The following parameters are extracted from the resulting probability curves (which also have a lognormal shape) from Monte Carlo sampling: mean LCIA result, lower and upper limits of the 95% confidence interval (with and without infrastructure).

For each product and impact category, the probability of coincidence of LCIA results with and without infrastructure was calculated, i.e. the probability of the results without infrastructure being contained in the probability distribution of the results with infrastructure. As the results with infrastructure will always be higher than the ones without it, this interval is defined by the following limits: minimum LCIA value with infrastructure (2,5% cumulated probability) and maximum LCIA value without infrastructure

(97,5% cumulated probability) – considering the probability distribution of the results with infrastructure (Figure 1).

Figure 1 - Probability of values without infrastructure (blue curve) occurring in the interval of results with infrastructure (red curve), defined in the gray area (sand, human toxicity).



The following acronyms will be used to refer to impact categories: AD-E - abiotic depletion, elements; AD-F - abiotic depletion, fossil fuels; AP - acidification; EP - eutrophication; FAET - freshwater aquatic ecotoxicity; GWP - global warming; HT - human toxicity; MAET - marine aquatic ecotoxicity; ODP - ozone layer depletion; PO - photochemical oxidation; and TET - terrestrial ecotoxicity.

3. Results and discussion

Table 1 shows the detailed LCIA results. Figure 2 and Figure 3 show, respectively, the increase in LCIA results and standard deviation values by the inclusion of infrastructure.

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Table 1 – LCIA results with and without infrastructure (average values) and corresponding coefficients of variation.

Product		Sand				Gravel			
Impact category	Unit	without infra		with infra		without infra		with infra	
		Result	C.V. (%)	Result	C.V. (%)	Result	C.V. (%)	Result	C.V. (%)
AD-E	kg Sb eq.	4,9E-10	23	2,2E-08	72	1,6E-09	27	8,8E-08	89
AD-F	MJ	4,5E-02	20	5,2E-02	19	1,0E-01	20	1,2E-01	20
AP	kg SO2 eq.	2,2E-05	19	2,6E-05	18	4,7E-05	20	6,0E-05	20
EP	kg PO43- eq.	6,6E-06	38	8,4E-06	35	1,6E-05	47	2,1E-05	41
FAET	kg 1,4-DB eq.	6,7E-04	45	1,5E-03	46	2,1E-03	64	4,2E-03	35
GWP	kg CO2 eq.	3,7E-03	16	4,3E-03	15	8,9E-03	19	1,1E-02	18
HT	kg 1,4-DB eq.	7,6E-04	36	1,9E-03	38	2,4E-03	43	5,0E-03	31
MAET	kg 1,4-DB eq.	3,0E+00	28	4,8E+00	28	9,5E+00	32	1,4E+01	28
ODP	kg CFC-11 eq.	3,4E-10	49	3,9E-10	51	5,6E-10	38	7,0E-10	38
PO	kg C2H4 eq.	1,3E-06	41	1,6E-06	38	3,0E-06	41	3,8E-06	34
TET	kg 1,4-DB eq.	2,7E-06	22	9,6E-06	36	8,5E-06	25	2,7E-05	33
Product		Clinker				Cement			
Impact category	Unit	without infra		with infra		without infra		with infra	
		Result	C.V. (%)	Result	C.V. (%)	Result	C.V. (%)	Result	C.V. (%)
AD-E	kg Sb eq.	1,4E-08	25	8,7E-08	24	1,7E-08	26	2,1E-07	57
AD-F	MJ	3,3E+00	13	3,4E+00	13	3,3E+00	23	3,5E+00	23
AP	kg SO2 eq.	1,8E-03	13	1,8E-03	13	1,8E-03	23	1,8E-03	22
EP	kg PO43- eq.	4,1E-04	30	4,3E-04	31	4,3E-04	36	4,6E-04	36
FAET	kg 1,4-DB eq.	3,9E-02	44	4,6E-02	37	4,4E-02	158	5,6E-02	53
GWP	kg CO2 eq.	9,6E-01	13	9,7E-01	13	9,0E-01	24	9,1E-01	24
HT	kg 1,4-DB eq.	5,2E-02	51	5,9E-02	33	5,7E-02	319	7,2E-02	38
MAET	kg 1,4-DB eq.	1,4E+02	29	1,5E+02	26	1,7E+02	145	2,0E+02	31
ODP	kg CFC-11 eq.	2,3E-08	48	2,4E-08	47	2,2E-08	51	2,3E-08	50
PO	kg C2H4 eq.	6,7E-05	13	6,9E-05	13	6,7E-05	23	7,1E-05	23
TET	kg 1,4-DB eq.	1,0E-03	22	1,1E-03	21	9,6E-04	30	1,1E-03	28

Table 1 – LCIA results with and without infrastructure (average values) and corresponding coefficients of variation (continuation).

Product		Concrete				Concrete block			
Impact category	Unit	without infra		with infra		without infra		with infra	
		Result	C.V. (%)	Result	C.V. (%)	Result	C.V. (%)	Result	C.V. (%)
AD-E	kg Sb eq.	1,4E-05	24	2,1E-04	38	6,0E-09	37	3,3E-07	73
AD-F	MJ	1,0E+03	19	1,1E+03	18	4,2E-01	33	5,7E-01	33
AP	kg SO2 eq.	4,8E-01	18	5,5E-01	17	1,9E-04	28	2,7E-04	30
EP	kg PO43- eq.	1,2E-01	32	1,5E-01	32	5,1E-05	41	9,0E-05	49
FAET	kg 1,4-DB eq.	1,1E+01	65	2,1E+01	31	5,5E-03	49	2,0E-02	60
GWP	kg CO2 eq.	1,9E+02	22	2,0E+02	21	7,1E-02	29	8,3E-02	28
HT	kg 1,4-DB eq.	1,7E+01	98	3,2E+01	28	8,6E-03	39	3,6E-02	67
MAET	kg 1,4-DB eq.	4,4E+04	55	7,3E+04	27	1,9E+01	47	5,5E+01	52
ODP	kg CFC-11 eq.	8,0E-06	49	8,9E-06	49	4,1E-09	53	5,2E-09	53
PO	kg C2H4 eq.	2,0E-02	18	2,4E-02	17	9,6E-06	30	1,5E-05	37
TET	kg 1,4-DB eq.	2,0E-01	27	2,7E-01	23	4,1E-05	55	1,8E-04	77

Figure 2 – Increase in LCIA results by the addition of infrastructure (average values).

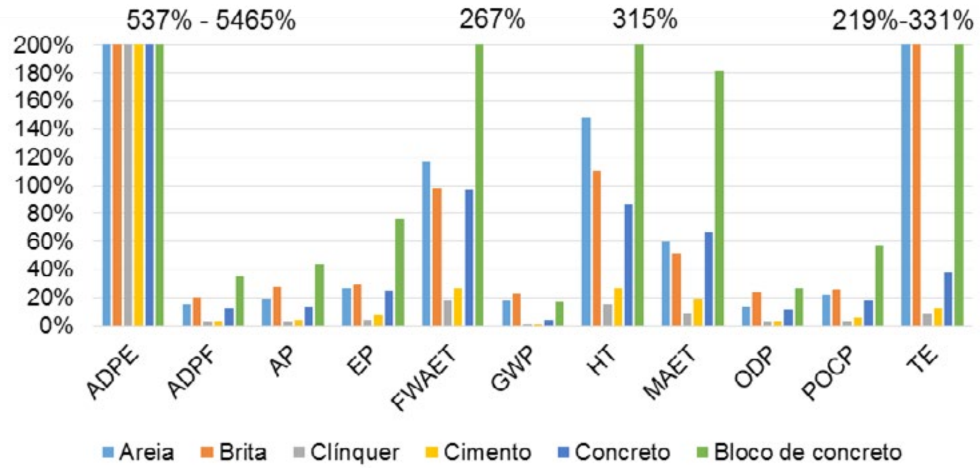
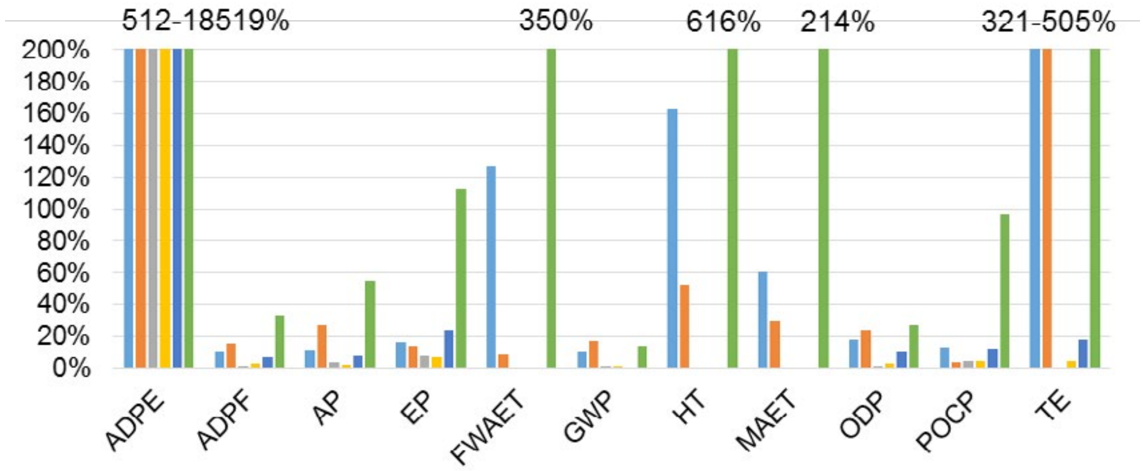


Figure 3 - Increase in standard deviation of LCIA results by the addition of infrastructure (average values).



We notice that the impact categories most influenced by infrastructure are abiotic depletion, terrestrial ecotoxicity, freshwater aquatic ecotoxicity, human toxicity and marine aquatic ecotoxicity, while the least influenced ones are abiotic depletion of fossil fuels, acidification, eutrophication, global warming, ozone depletion and photochemical oxidation. This is coherent with the findings of Frischknecht et al. (2007) for construction products. The lowest increases are observed for clinker and cement production, since the direct process emissions causing environmental impacts are significant, while the highest increase level is observed for the concrete block, which has an input of packing that contributes to a significant share of the impact results (30%-40% in toxicity related categories and abiotic depletion, the ones most influenced by infrastructure along its upstream processes).

We also notice that the increase in the standard deviation is similar to or, in some cases, even higher than the increase in the LCIA results, due to the uncertainty of infrastructure flows: the default value set by ecoinvent

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for infrastructure basic uncertainty (σb^2 - variance of logtransformed data) is 0,3, while for all other energy and material inputs σb^2 is 0,0006. To better understand this difference, we may convert these variances into coefficients of variations based on the properties of the lognormal distribution, resulting in 59% for infrastructure flows and 2,4% for the others. Furthermore, the additional uncertainty is also high, due to Pedigree scores resulting from the low quality of infrastructure data (WEIDEMA et al., 2013).

Table 2 shows the results of the probability of coincidence of LCIA results with and without infrastructure, detailed by product and impact category, where lighter cells correspond to the lower values and darker cells to the higher ones.

Table 2 – Probability of coincidence of LCIA results with and without infrastructure.

Impact category	Sand	Gravel	Clinker	Cement	Concrete	Concrete Block
Abiotic depletion	0%	0%	0%	0%	0%	0%
Abiotic depletion (fossil fuels)	88%	84%	95%	94%	90%	82%
Acidification	85%	74%	94%	94%	89%	70%
Eutrophication	90%	90%	95%	94%	88%	60%
Fresh water aquatic ecotox.	39%	57%	92%	90%	42%	10%
Global warming	82%	81%	95%	95%	95%	91%
Human toxicity	14%	39%	91%	86%	22%	3%
Marine aquatic ecotoxicity	53%	68%	95%	89%	38%	25%
Ozone layer depletion	94%	89%	95%	95%	94%	90%
Photochemical oxidation	92%	91%	94%	94%	84%	59%
Terrestrial ecotoxicity	0%	0%	93%	93%	76%	10%

For six impact categories (abiotic depletion of fossil fuels, acidification, eutrophication, global warming, ozone layer depletion and photochemical oxidation), the probability of coincidence of results is over 50% for all products and over 70% for most results. A 50% probability of coincidence is

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considered a good threshold level, as it is more probable that results coincide than not. These are also the categories with lower increases in LCIA results by infrastructure addition.

Toxicity related categories only show a probability of coincidence higher than 50% for clinker and cement (in all of them); looking at specific toxicity issues, there are also other values above the 50% threshold, such as FAET for gravel (57%), MAET for sand and gravel (53% and 68% respectively) and TET for concrete (76%). The clinker production process has air emissions that have a direct contribution to toxicity results (which consequently affects cement), while other processes do not generate such emissions and are thus more affected by infrastructure, in different levels.

Despite the significant difference observed for most toxicity results with and without infrastructure, there are other aspects to consider. The uncertainty of the characterization factors for human and ecotoxicity can reach 6 orders of magnitude (HUIJBREGTS et al., 2000) and this has not been taken into account in the Monte Carlo sampling performed for this study. As a result, it is difficult to consider toxicity impact scores in decision making processes based on LCA, especially for comparative assessments, since the uncertainty of characterization factors by far surpasses any existing difference between products. For instance, EN 15804 (DIN, 2014), the standard for construction product EPDs, does not require the assessment of human- and ecotoxicity impact categories, because they were not considered a consensus by the time the standard was published.

Regarding abiotic depletion of elements, there is no probability of coincidence of results obtained with and without infrastructure, for any product. This impact category also presents the highest uncertainty levels for the impact values that consider infrastructure, with an average coefficient of variation of 59%, which alone limits the use of this indicator in decision processes. Furthermore, although required by EN 15804, this impact category does not properly assess the consumption of natural resources usually

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applied by the construction industry, as mineral resources like quartz sand, granite, limestone, etc. do not have characterization factors, because they are considered to be globally abundant, although they are often locally scarce (HABERT et al., 2010). Infrastructure becomes so important because abiotic depletion of elements is mainly influenced by the consumption of metallic substances, required for manufacturing steel and other alloys commonly used in machinery and buildings.

If the uncertainty of infrastructure flows is reduced, some differences deemed insignificant based on the current results may become more important. This can only be achieved by collecting better data for infrastructure activities. However, non-infrastructure flows also deserve improvement, as uncertainty of LCIA results without infrastructure is also substantial (Table 1). Since data collection efforts must be optimized, it seems more relevant to focus data collection on process variables, than on detailing capital goods. Furthermore, considering that the ultimate goal of LCA is improving the environmental performance of products, the changes that can be done in capital goods are limited, as buildings and machinery are not easily modified or replaced due to required investments and long service lives.

4. Conclusion

Including capital goods in construction products' inventories leads to higher impact results, but also to increased uncertainty, as they are often based on rough estimates. Based on the probability of coincidence of LCIA results with and without infrastructure, capital goods are not considered relevant for six impact categories – abiotic depletion of fossil fuels, acidification, eutrophication, global warming, ozone layer depletion and photochemical oxidation. For freshwater aquatic ecotoxicity, human toxicity, marine aquatic ecotoxicity and terrestrial ecotoxicity, infrastructure becomes more important, but the uncertainty of toxicity characterization factors is substantial, limiting the use of these results for decision making. Capital goods have also a big influence on the abiotic depletion of elements; however, this only happens because this indicator does not account for bulk construction materials.

Hence, we consider that the inclusion of capital goods does not add significant quality to life cycle inventories of construction products. To enhance the reliability of LCA studies, it is more interesting to spend resources on collecting good and representative primary data for process flows that can be modified by construction product manufacturers to improve the environmental performance of their materials, and on increasing the number of representative national LCIs. Until good infrastructure life cycle inventories become available and the uncertainty of toxicity impact modelling is reduced, we thus suggest that capital goods are excluded from the minimum scope of life cycle inventory initiatives and databases.

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