

Life cycle impact assessment methods for water use in concrete production

Métodos de evaluación del ciclo de vida del uso del agua en la producción de hormigón

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ABSTRACT

Within the concrete industry, production requires large amounts of water and generates significant amounts of wastewater. Most of the concrete production impacts studied to date are related to CO₂ emissions and energy consumption. In order to assess the impacts related to water use, knowledge and understanding is required of available life cycle impact assessment methods that include water-related impact categories relevant to the life cycle of concrete production. The aim of this article is to summarize the life cycle impact assessment methods needed to translate environmental aspects related to water use in concrete production into potential environmental impacts. Four impact categories were found to be relevant to concrete production: water use, acidification, eutrophication and toxicity. Twenty-eight life cycle impact assessment methods suitable for concrete production are presented. Further study will be needed for a better understanding of the characterization models and calculation procedures for each method.

Keywords: concrete production, water use, water impact assessment, sustainability

RESUMEN

Dentro de la demanda de agua de la industria, la producción de hormigón requiere grandes cantidades de agua y genera importantes cantidades de aguas residuales. La mayoría de los impactos de la producción de hormigón que se han estudiado hasta ahora están relacionados con las emisiones de CO₂ y el consumo de energía. Con el fin de evaluar los impactos vinculados al agua, es necesario conocer y comprender los métodos de evaluación de impacto del ciclo de vida disponibles, que incluyen categorías de impacto relacionadas con el agua relevantes en el ciclo de vida de la producción de hormigón. El objetivo de este trabajo es resumir los métodos de evaluación del impacto del ciclo de vida necesarios para traducir los aspectos medioambientales relacionados con el uso del agua en la producción de hormigón en impactos medioambientales potenciales. Se encontraron cuatro categorías de impacto relevantes en la producción de hormigón: uso del agua, acidificación, eutrofización y toxicidad. Se presentan 28 métodos de evaluación del impacto del ciclo de vida adecuados para la producción de hormigón. Se necesitan más estudios para comprender los modelos de caracterización y los procedimientos de cálculo de cada método.

Palabras clave: producción de hormigón, uso del agua, evaluación del impacto del agua, sostenibilidad



1. Introduction

Globally, society relies on only 0.5% of the world's water for all its needs (World Business Council for Sustainable Development, 2009). Availability of this resource varies, due to factors such as urbanization and population growth, increasing food production, climate change and industrialization (United Nations Global Compact, 2011). After agriculture, industry is the second largest consumer of water (United Nations Educational, Scientific and Cultural Organization, 2015). Until a couple of decades ago, water consumption was not a major issue; however, due to water scarcity problems, companies have started to express their concern (Holcim, 2012; Lafarge, 2012, 2014; BASF, 2014). In order to guarantee access to water for future generations, water efficiency and sustainable practices must be addressed.

In the specific case of the concrete industry, large amounts of water are required throughout the production chain, from cradle to gate. Global concrete demand per year is approximately 11 billion m³ (Mack-Vergara and John, 2019), and demand is projected to increase by 2050 (Mehta and Monteiro, 2006). In the literature referenced as part of this study, it was observed that only 3 out of 15 cement life cycle assessments (LCA) include water consumption and 2 out of 15 include waste water (Josa *et al.*, 2004, 2007; Gäbel and Tillman, 2005; Marceau, Nisbet and VanGeem, 2006; Navia *et al.*, 2006; Boesch, Koehler and Hellweg, 2009; Huntzinger and Eatmon, 2009; Boesch and Hellweg, 2010; Chen *et al.*, 2010; Zabalza Bribián, Aranda Usón and Scarpellini, 2011; Valderrama *et al.*, 2012; Li *et al.*, 2014). In the case of concrete LCAs, only 11 out of 27 include water consumption and 9 out of 27 include waste water (Jonsson, Bjorklund and Tillman, 1998; Jaques, 2001; Nisbet, Marceau and VanGeem, 2002; Prusinski, Marceau and VanGeem, 2004; Athena Sustainable Materials Institute, 2005; Sjunnesson, 2005; Xing, Xu and Jun, 2008; O'Brien, Ménaché and O'Moore, 2009; Chen *et al.*, 2010; Marinković *et al.*, 2010; de Schepper *et al.*, 2011; Habert, d'Espinose de Lacaillerie and Roussel, 2011; McLellan *et al.*, 2011; Zabalza Bribián, Aranda Usón and Scarpellini, 2011; Blengini *et al.*, 2012; Van den Heede and De Belie, 2012; Ramsey *et al.*, 2014; Ingrao *et al.*, 2014; Jiang *et al.*, 2014; Celik *et al.*, 2015; Gursel, Maryman and Ostertag, 2016).

Several life cycle impact assessment (LCIA) methods take into account different environmental aspects related to water (Berger and Finkbeiner, 2010; Lérová and Hauschild, 2011; Kounina *et al.*, 2012; Ridoutt and Pfister, 2012; Zeng, Liu and Savenije, 2013; Bayart *et al.*, 2014; Boulay *et al.*, 2014, 2015; Hess, Lennard and Daccache, 2015; Pedro-Monzonis *et al.*, 2015; Pfister *et al.*, 2015; Hoekstra, 2016). A number of such environmental aspects are observed in concrete production life cycles which demand large amounts of water. Considering a total of more than 11 billion m³ of annual concrete production globally and an average of 160 liters of water per cubic meter of concrete,

it is estimated that approximately 1.7 trillion liters of water are used every year for mixing concrete (Mack-Vergara and John, 2019). In addition, cleaning activities such as the cleaning of trucks and cleaning of yards also require large amounts of water and generate wastewater.

The aim of this article is to identify the LCIA methods needed to translate environmental aspects related to water use in concrete production into the identification of potential environmental impacts, and to arrive at a better understanding of the water related impacts associated with concrete production. At the same time, this research does not offer a recommendation regarding the use of any single method over another.

1.1. Water use throughout the concrete production life cycle, from cradle to gate

Concrete is a mixture of cement, water and aggregates (PCA America's Cement Manufacturers, 2024). In addition, chemical admixtures with a range of different purposes can be added to concrete (CO9 Committee, 2013). The volume of water used is the total of the water in the aggregates (approximately 5% of the weight of the aggregates) and the water added during mixing (Jaques, 2001). During the mixing stage, the different components come together to produce a uniform mass.

Within the concrete production life cycle, concrete mixing is the main activity. However, other activities are also required in order to deliver every 1 m³ of concrete, and these activities entail water consumption and the generating of wastewater.

Within the parameters of a concrete plant system, water is required for cleaning the yard (Sealey, Phillips and Hill, 2001), for cleaning the trucks (Paolini and Khurana, 1998; Chini *et al.*, 2001; Nisbet, Marceau and VanGeem, 2002; Ekolu and Dawneerangen, 2010), and in the task of dust suppression (Ekolu and Dawneerangen, 2010). In addition, water use in other concrete plant system facilities such as offices, laboratories and vehicle workshops must also be considered (Holcim, 2013).

In terms of water use, the main impact during concrete mixing is water depletion due to evaporation and water integration into the product. During concrete mixing, there are no changes in water quality, as there are in activities associated with the washing of the yards and washing of trucks. Where water used for the different production processes is combined with rainwater runoff, large amounts of wastewater are generated (Ekolu and Dawneerangen, 2010). Such is the case where no water recycling activities are employed; however, many concrete plants have implemented water recycling strategies, and, depending on the way that dust suppression is carried out, the majority of water depletion is the result of evaporation. At the same time, for the most part, water use in laboratories and other facilities is associated with

domestic water use –faucets and toilet water- as well as the water required for samples, and this water is usually discharged into the local sewer system.

In terms of indirect water use processes, water is used for energy production in the case of hydropower plants, and this use of in-stream water results in a range of impacts, such as changes in water flow, changes in aquatic biota, changes in water quality, increased temperature, and water pollution (Rashad and Ismail, 2000).

1.2. Water impact assessment methods

Life Cycle Impact Assessment (LCIA) is the third phase of a Life Cycle Assessment (LCA). The primary objective of the LCIA method is to transform the long list of Life Cycle Inventory (LCI) results –the second phase of a LCA– into a limited number of indicator scores. These indicator scores express the relative severity of an environmental impact category. In this context, this article aims to identify the main LCIA methods relevant to the concrete industry.

According to the provisions of ISO 14044 (International Organization for Standardization, 2006), the LCIA process involves four steps:

1. Classification (mandatory): all substances are sorted into the selected impact categories (the impact categories are selected at the Goal and Scope definition phase –the first phase of a LCA– according to the effect they have on the environment.
2. Characterization (mandatory): all substances are multiplied by a factor which reflects their relative contribution to environmental impact. The result is expressed as an impact score in a unit common to all contributions within the impact category.
3. Normalization (optional): the quantified impact is compared to a certain reference value, for example the impacts caused by one person during one year in a stated geographic context. This facilitates comparisons across impact categories and/or Areas of Protection.
4. Weighting (optional): different value choices are given to impact categories in order to generate a single score. The different environmental impact categories and/or areas of protection are ranked according to their relative importance.

An impact category indicator result can be chosen either at the midpoint or endpoint level. A midpoint indicator (problem-oriented approach) is defined as a parameter in a cause-effect chain for a particular impact category –such as climate change, acidification, human toxicity– that lies between the inventory data and the category endpoints. An endpoint indicator (damage-oriented approach) is calculated in order to translate environmental impacts into issues of concern such as human health, natural environment and natural resources, and may be of direct relevance to society's understanding of the final effect.

Both the midpoint and endpoint methods require the building of a proper inventory and use of a LCIA method to transform emissions to potential environmental impacts. Endpoint characterization is more complex and rather more uncertain, while midpoint results are more robust and certain. The choice between midpoints and endpoints is driven mainly by the goal of the LCA and the LCA audience. For instance, endpoint results are easier for decision makers to understand, while midpoint results are more interesting for specialists.

Fourteen LCIA methods are presented in Mendes *et al.* (2016) and JRC European Commission (2010) (see Table 1). In addition, another 14 water impact assessment methods were found in the literature review. These LCIA methods employ a midpoint, endpoint or combined approach. Each method incorporates a list of impact categories, and in some cases impact categories with similar names are observed, demonstrating an absence of consolidation. In addition, some methods are more specific than others with regard to impact categories; for instance, CML 2002 presents acidification and eutrophication, IMPACT 2002+ is more specific in presenting aquatic acidification and aquatic eutrophication, while Eco-indicator 99 combines these impact categories into a single category. It is important to note that those methods which are more comprehensive tend to be more generally accepted, in contrast to more specific methods.

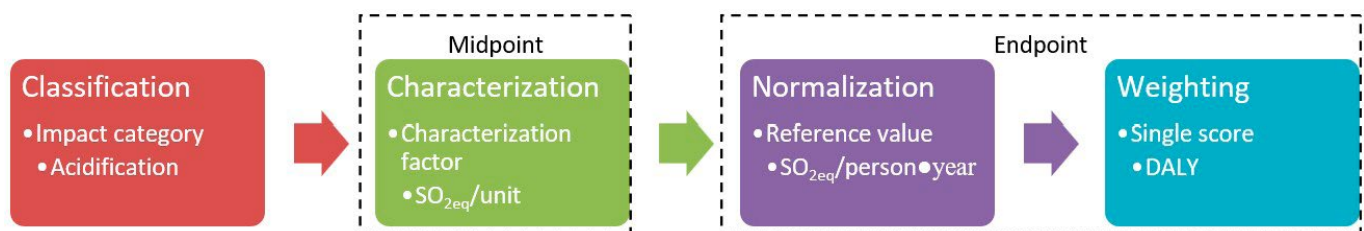


Figure 1. Life cycle impact assessment steps according to ISO 14044. DALYs (disability-adjusted life year) quantify the difference between an ideal situation in which people live to the standard life expectancy in perfect health and the actual situation.

Table 1. Life Cycle Impact Assessment Methods

Method	Level of impact assessment	Impact categories
CML 2002	Midpoint	Abiotic resources depletion
		Human toxicity
		Aquatic ecotoxicity (fresh water)
		Aquatic ecotoxicity (marine)
		Acidification
		Eutrophication
		Fresh water ecotoxicity (sediments)
Eco-indicator 99	Endpoint	Marine ecotoxicity (sediments)
		Smelly water
		Acidification and eutrophication (combined)
Ecological scarcity	Combined - using the distance from target principle	Ecotoxicity
		Mineral resources
		Fossil resources
EDIP 1997	Midpoint	Water consumption
		Emissions to surface water
		Emissions to groundwater
		Acidification
EDIP 2003	Midpoint	Nutrients enrichment
		Human toxicity
		Ecotoxicity
		Resources consumption
		Acidification
EPS 2000	Endpoint	Terrestrial eutrophication
		Aquatic eutrophication
		Human toxicity
		Ecotoxicity
IMPACT 2002+	Combined	Natural resources consumption
		Mineral reserves depletion
		Potable water production capacity
		Human toxicity
		Aquatic ecotoxicity
LIME	Combined	Aquatic acidification
		Aquatic eutrophication
		Mineral extraction
		Human toxicity
		Ecotoxicity
		Acidification
MEEuP	Midpoint	Eutrophication
		Human toxicity
		Aquatic eutrophication
		Emission of heavy metals (water)
ReCiPe	Combined	Eutrophication (fresh water and marine)
		Human toxicity
		Ecotoxicity (terrestrial, fresh water and marine)
		Mineral resources depletion
TRACI	Midpoint	Fresh water resources depletion
		Acidification
		Eutrophication
USEtox	Midpoint	Ecotoxicity
		Water use
IMPACT World+	Combined	Human toxicity
		Ecotoxicity
		Acidification
		Eutrophication
		Water use
Pfister <i>et al.</i> , 2009	Combined	Resources use
Ridoutt Pfister, 2010	Midpoint	Fresh water use
Veolia (Bayart <i>et al.</i> , submitted)	Midpoint	Fresh water use
Hoekstra <i>et al.</i> , 2011	Midpoint	Fresh water use
Boulay <i>et al.</i> , 2011b	Combined?	Fresh water use
Bayart, 2008	Midpoint	Fresh water use
Milà i Canals <i>et al.</i> , 2009	Midpoint	Fresh water use
Motoshita <i>et al.</i> , 2010a	Combined	Fresh water use
Motoshita <i>et al.</i> , 2010b	Endpoint	Fresh water use

Table 1 (Continued).

Method	Level of impact assessment	Impact categories
LUCAS	Midpoint	Acidification
		Ecotoxicity (aquatic and terrestrial)
		Human toxicity
MEEuP	Midpoint	Abiotic resources destruction
		Water consumption (process)
		Water consumption (for cooling)
		Acidification
		Human toxicity
ReCiPe	Combined	Aquatic eutrophication
		Eutrophication (fresh water and marine)
		Human toxicity
		Ecotoxicity (terrestrial, fresh water and marine)
TRACI	Midpoint	Mineral resources depletion
		Fresh water resources depletion
		Acidification
USEtox	Midpoint	Eutrophication
		Ecotoxicity
IMPACT World+	Combined	Water use
		Human toxicity
		Ecotoxicity
		Acidification
		Eutrophication
Pfister <i>et al.</i> , 2009	Combined	Resources use
Ridoutt Pfister, 2010	Midpoint	Fresh water use
Veolia (Bayart <i>et al.</i> , submitted)	Midpoint	Fresh water use
Hoekstra <i>et al.</i> , 2011	Midpoint	Fresh water use
Boulay <i>et al.</i> , 2011b	Combined?	Fresh water use
Bayart, 2008	Midpoint	Fresh water use
Milà i Canals <i>et al.</i> , 2009	Midpoint	Fresh water use
Motoshita <i>et al.</i> , 2010a	Combined	Fresh water use
Motoshita <i>et al.</i> , 2010b	Endpoint	Fresh water use

Table 1 (Continued).

Method	Level of impact assessment	Impact categories
Boulay <i>et al.</i> , 2011b	Endpoint	Fresh water use
Hanafiah <i>et al.</i> , 2011	Endpoint	Fresh water use
Van Zelm <i>et al.</i> , 2011	Endpoint	Fresh water use
Moendly Humbert submitted	Endpoint	Fresh water use
Boesch <i>et al.</i> , 2007	Endpoint	Fresh water use

Even though several LCIA methods deal with water related impacts, there is no consensus on weighting methods across these methodologies. Many LCIA methods have been developed and applied to LCA studies; however none has been internationally accepted in accordance with the requirements of the International Standard Association (Bueno *et al.*, 2016).

Water use is divided between consumptive water use (this means water that is withdrawn from one source and discharged into a different source or not returned, such as water integrated into a product or evaporated) and degradative water use, which involves changes in water quality (Ridoutt and Pfister, 2012). Both consumptive water use and degradative water use modify the resource's availability, which is translated into environmental impacts such as those affecting human health and ecosystem quality, as well as the availability of freshwater (Curran, 2012).

Potential impacts from consumptive water use are included in the resource depletion impact category, while impacts related to degradative water use are usually included in ecotoxicity, acidification and eutrophication impact categories.

1.3. Environmental aspects related to water use throughout the concrete production life cycle, from cradle to gate

Concrete-mix plants generate different types of waste, including fresh concrete, wastewater and concrete slurry (Férriz Papí, 2014). The discharging of fresh concrete, wastewater and slurry waste may cause acidification, toxicity and eutrophication (ILCD, 2010; Kim and Chae, 2016).

Nitric oxides (NO_x) and sulfur dioxide (SO₂) released to water increase the hydrogen ion concentration in rivers and oceans and reduce their pH, causing acidification. Regarding ammonia (NH₃) and phosphate (PO₄³⁻), as these nutrients flow into an ecosystem through the sewage systems of concrete plants, microorganism activity increases, causing eutrophication. These compounds are the result of concrete components such as cement and chemical admixtures reacting.

As mentioned in the introduction, concrete production consumes large amounts of water. Water consumption in concrete production occurs mainly in the form of water vapor and water incorporated into the product, with the mixing water requirement for global concrete production estimated at approximately 1.7 trillion liters annually (Mack-Vergara and John, 2019). Consequently, two main aspects related to water use are considered: quality and quantity.

Water is considered polluted when certain substances or conditions are present to such an extent that water cannot be used for a specific purpose. This implies changes in its physical, chemical and biological characteristics with respect to suitability for intended use by humans or ecosystems, and is defined as water degradation (ISO 14046:2014, 2014), while water depletion is the lack of sufficient available water resources to meet the local demand for water.

It should be noted that there is a relationship between water pollution (quality) and the depletion of water resources (quantity), since water depletion is one of the effects of water pollution.

2. Materials and methods

In order to identify LCIA methods needed to translate environmental aspects related to water use in concrete production into potential environmental impacts, the following steps were followed:

1. Study of water use in concrete production life cycle, from cradle to gate.
2. Study of water impact assessment methods.
3. Cross water related impact categories that are covered in the different impact assessment methods with impact categories related to water use in the concrete production life cycle, from cradle to gate.

With the purpose of contextualizing the life cycle of concrete from cradle to gate and outlining water use activities and processes, a literature review was conducted. This literature review included relevant material published in scientific journals, books and conference proceedings, taken from bibliographic databases such as Google Scholar, Web of Science and Scopus, which are the largest abstract and citation databases. The keywords used for the literature review search included: water use, water consumption, water quantity, water quality, water footprint, environmental impact assessment, life cycle assessment AND cement-based materials production OR concrete production.

This study comprises concrete's life cycle processes from raw material extraction to placing concrete into a clean truck, with all of these processes occurring within the concrete plant. The use phase and disposal phase of the product are not included in this study.



Twenty-eight LCIA methods, developed mainly in countries in Europe and used worldwide, were selected from Mendes *et al.* (2016) and JRC European Commission (2010). These methods were filtered by level of application, leaving only midpoint LCIA methods. This filter resulted in a total of 12 LCIA methods. The impact categories included and the comprehensiveness of application for each method are presented.

This study presents available LCIA methods; however, it does not state which is most appropriate, given that a deeper analysis is required in order to reach such a conclusion. Variability in LCA results according to the method used is not addressed in this work.

3. Results

From the LCIA methods in Table 1, our filter resulted in 12 methods for concrete production impact assessment. These methods are presented and compared in Table 2.

Table 2. LCIA methods suitable for concrete life cycle assessment

Method	Impact categories	Comprehensiveness of application
CML 2002	Abiotic resources depletion	Global
	Human toxicity	Global
	Aquatic ecotoxicity (fresh water)	Global
	Aquatic ecotoxicity (marine)	Global
	Acidification	Europe
	Eutrophication	Global
	Fresh water ecotoxicity (sediments)	Global
	Marine ecotoxicity (sediments)	Global
	Smelly water	Global
	Acidification	Global
EDIP 1997	Nutrients enrichment	Global
	Human toxicity	Global
	Ecotoxicity	Global
	Resources consumption	Global
EDIP 2003	Acidification	Europe
	Terrestrial eutrophication	Europe
	Aquatic eutrophication	Europe
	Human toxicity	Europe
	Ecotoxicity	Europe
LUCAS	Acidification	Canada
	Ecotoxicity (aquatic and terrestrial)	Canada
	Human toxicity	Canada
	Abiotic resources destruction	Canada

Table 2 (Continued).

Method	Impact categories	Comprehensiveness of application
MEEuP	Water consumption (process)	Europe
	Water consumption (for cooling)	Europe
	Acidification	Europe
	Human toxicity	Europe
	Aquatic eutrophication	Europe
	Emission of heavy metals (water)	Europe
TRACI	Acidification	North America
	Eutrophication	North America
	Ecotoxicity	USA
	Water use	-
USEtox	Human toxicity	Global
	Fresh water ecotoxicity	Global
Bayart, 2008	Fresh water use	-
Milà i Canals <i>et al.</i> , 2009	Fresh water use	-
Ridoutt Pfister, 2010	Fresh water use	-
Bayart <i>et al.</i> , 2010	Fresh water use	-
Hoekstra <i>et al.</i> , 2011	Fresh water use	-
Bayart <i>et al.</i> , 2010	Fresh water use	-

Only midpoint LCIA methodologies were selected, since there already exist many uncertainties associated with the life cycle inventory phase, and endpoint adds even more uncertainty, due to the assumptions and calculations required to get to an endpoint indicator such as human health, natural environment or natural resources. Furthermore, midpoint indicators work better for the communication of LCIA results.

In addition, where different methods must be used, since there is not one method that covers all impacts related to concrete production, each method will differ in terms of the way in which the endpoint indicators are calculated. Therefore, endpoint indicator results should not be compared as if they were calculated using the same approach. Potential disparities in LCIA results from different methods are of fundamental importance to the LCA practitioner, given that they may provide misleading results, and therefore the different LCIA methods should be used with care, and the results explained with equal care.

Understanding their differences and the relative advantages of these methods is essential for the conducting of a thorough life cycle assessment, and

in the making of informed decisions for promoting sustainability. With this in mind, below we describe the different life cycle impact assessment methods, including their characteristics and benefits.

3.1. CML 2002 (Database and Support team at PRé Sustainability, 2022)

The Institute of Environmental Sciences (Centrum voor Milieukunde Leiden, CML) of Leiden University, in the Netherlands, quickly established itself as the authority on the «agenda setting» for additional LCA research within the European discourse surrounding the creation of a uniform LCA methodology.

For the impact assessment step, in 2001 a group of scientists led by CML developed a set of impact categories and characterization methods. The midpoint approach defines the impact assessment method that is used in conjunction with the CML methodology. Although there is no addition or weighting, normalization is offered. Normalization is thought to be required for a complete LCA, but optional for simplified LCA.

3.2. EDIP 1997 (Sharaai, Mahmood and Sulaiman, 2011)

The EDIP 1997 impact assessment method is another widely used method in life cycle assessment. This method makes use of the midpoint approach, which addresses the effects of resource use, working environment and emissions. While weighting is based on political reduction targets for environmental impacts, resource supply horizons and working environment impacts, normalization is person equivalent. The key-property approach, which is the most significant part of a simple module structure and only requires data on a few chemical substances for characterization computation, has simplified ecotoxicity and human toxicity models.

3.3. EDIP 2003 (Various authors and PRé Sustainability, 2020)

EDIP 2003, an update to the EDIP 97 method, covers a larger range of impacts and is more adjacent to the damage-oriented approach. EDIP 2003's primary innovation is its persistent effort to incorporate exposure into the characterization modeling of the primary non-global effect categories. The original version of EDIP 2003 supports spatial differentiation and can also be used without it. SimaPro is limited to implementing the characterization elements for site-generic effects, which do not account for geographical variation. Since there are no normalization variables for ecotoxicity, the value is set to zero for weighting, while normalization and weighting for resources are set to zero because they are already accounted for in the characterization factor.

While the CML 2002 method offers a broad assessment, the EDIP 1997 and EDIP 2003 methods provide in-depth

analysis within specific impact categories, allowing for a more targeted evaluation of environmental impact.

3.4. LUCAS (Toffoletto et al., 2007)

Another important method in the realm of life cycle assessment is the LUCAS impact assessment method. Due to the lack of appropriate models, efforts have been made to create an LCIA approach specifically for the Canadian setting. The best practices in LCIA as recommended by SETAC serve as the foundation for this approach. This midpoint Canadian-specific method was based on models from three recent LCIA site-dependent methods: EDIP2003, IMPACT2002+ and TRACI. The selection of characterization models was based on factors such as scientific sophistication, comprehensiveness and the ability to incorporate site-specific information into the models.

Site-differentiated categories for local and regional impact are all present. Since regionally-differentiated models accounting for fate and effect were already available for ecotoxicity impact categories, these models' parameters were adjusted to fit the Canadian environment. Canadian ecozones were chosen as the method's default spatial resolution. Existing models for acidification were geographically separated for fate; regionalization of the effect component was also incorporated, depending on each ecozone's degree of sensitivity, as determined by vulnerability variables. Because the process is transparent, site-dependent characterization factors for additional compounds and for various locations can be recalculated.

Incorporating the LUCAS impact assessment method into life cycle assessments can further enrich the understanding of the environmental implications of products and processes, supporting informed decision-making for sustainable practices and resource management. This method serves as a valuable tool for evaluating and promoting environmental sustainability across various industries and sectors.

3.5. MEEuP (VHK for European Commission, 2005)

The primary aim of the Methodology Study for Ecodesign of Energy-using Products (MEEUP) is to aid in the development of a methodology that will enable the assessment of whether and to what degree different energy-using products meet specific requirements, thereby qualifying them for the implementation of measures under the Ecodesign of EuP Directive 2005/32/EC.

The approach employed for environmental impact assessments should be used after, not before, existing environmental legislation formulated within the framework of international treaties such as Kyoto, Montreal, Gothenburg, Stockholm, Århus, etc., and implemented under relevant EU legislation, primarily



consisting of grid-based emission limit values, such as the Water Framework Directives and the Ambient Air Quality Directives. In this regard, managing the end-of-life period is consistent with a postWEEE scenario.

The MEEuP impact assessment method offers a progressive approach to assessing the environmental impacts of emerging technologies. It takes into account the complexities and uncertainties surrounding the production process, parameters of use and potential disruptions within the broader system. This method acknowledges the rapid evolution of technology and its indirect effects on society, making it well-suited for evaluating innovative and disruptive technologies.

3.6. TRACI (Database and Support team at PRé Sustainability, 2022)

The US Environmental Protection Agency created the stand-alone computer program Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) specifically for the US, utilizing input settings corresponding with US locations. For many effect categories, site specificity is accessible; however, where the location is unknown, a US average value is always available. Characterizing environmental stressors with possible consequences, such as acidification, eutrophication, ecotoxicity and land-use effects, is made easier through the use of TRACI.

TRACI is a life cycle impact assessment methodology that is directed towards the midpoint approach and aligns with the EPA's approach of not combining data from different environmental effect categories. It encompasses normalization, characterization and classification.

The TRACI method adopts a more exploratory nature, considering a broader range of possible future conditions. By incorporating a larger scope of potential scenarios, TRACI provides valuable insights into the potential impacts and uncertainties associated with the product or service under evaluation. Emphasizing novel interpretation and presentation techniques, the TRACI method ensures that stakeholders understand the degrees of uncertainty and the value of directional insights.

3.7. USEtox (Database and Support team at PRé Sustainability, 2022)

The environmental model known as USEtox is used in life cycle impact assessments and comparative risk assessments to characterize the effects on humans and the environment. It was produced by a group of researchers from the UNEP-SETAC Life Cycle Initiative's Task Force on Toxic Impacts (TF LCIA 2). USEtox incorporates both midpoint and endpoint approaches and is intended to explain the fate, exposure and consequences of chemicals.

The USEtox team regularly updates and maintains the model, which has undergone peer review. The UNEP/

SETAC Life Cycle Initiative has officially endorsed USEtox, and the US Environmental Protection Agency, the European Commission's Joint Research Center, the World Business Council for Sustainable Development, and the European Commission have all officially recommended it as an assessment method.

Mid-to-endpoint factors are included in USEtox 2, which enables an endpoint level assessment of impacts. The unit used to quantify the effects on ecosystems is PDF (potentially disappeared fraction of species), while DALY (disability-adjusted life years) is used to quantify the effects on human health.

3.8. Bayart, 2008 (Bayart, 2008)

This approach establishes the framework for evaluating freshwater use in life cycle assessments (LCAs), taking into account the effects of off-stream use of the freshwater resource, and recognizing that the degree of impact varies, depending on the source type, quality, location and type of use.

It is vital that the kind of water be specified, and that the water entering and leaving the product system is measured and assessed, in order to differentiate between various resource use scenarios during the inventory phase. Environmental loads are produced by an imbalance in one of these components and manifest themselves in the cause-and-effect cycle.

The impact category known as freshwater deprivation for human uses refers to a lack of resources for human requirements, which eventually affects human life. The impact category known as freshwater deprivation for ecosystems refers to an inadequate resource for ecosystems, which in turn impacts the biotic environment. A resource's depletion may result from misuse, and this phenomenon is expressed in the impact category known as freshwater depletion, which eventually has an impact on the abiotic environment.

Three characteristics are taken into account when calculating the characterization factor: availability, quality and utilization. The latter covers the potential applications of the water type under consideration, as well as the capacity of downstream users to adjust to water scarcity.

Furthermore, two novel impact indicators are modeled to measure ecosystems' freshwater deprivation; it is recommended that the resource's ecological value and freshwater availability be taken into account. When the rate of consumptive use surpasses the rate of renewability, freshwater depletion occurs.

Characterization factors are calculated for certain countries and the process is regionalized. Integration of the temporal dimension is also necessary. An estimation of uncertainty must also be conducted.

3.9. *Milà i Canals et al., 2009 (Milà i Canals et al., 2009)*

The LCI must quantify and differentiate between the evaporative and non-evaporative uses of «blue» and «green» water, as well as changes in land use that affect freshwater availability. For the two primary effect pathways, freshwater ecosystem impact and freshwater depletion, appropriate indicators are proposed, and operational characterization variables are given for various nations and circumstances. Indicators that compare the amount of freshwater currently used to the amount of freshwater resources available are recommended for freshwater ecosystem impact, whether with or without special attention to the needs of water ecosystems. The parameters needed to assess the widely-used abiotic depletion potentials for freshwater depletion are investigated.

Ignoring or failing to take into account how non-evaporative water uses affect ecosystems is a critical value judgment in the context of water use implications. Even though abstractions during droughts may have dramatic effects on ecosystems, variation in seasonal river flows is not taken into account in the FEI method, because this has been thought to be outside the LCA purview.

This method enhances how freshwater use-related consequences are represented in life cycle assessments (LCAs). For LCA practitioners, the information required for employing the technique is typically readily available.

3.10. *Bayart et al., 2010 (Bayart et al., 2010)*

Each of the water types defined by the authors represents a basic flow. Each type's water balances make it possible to quantify variations in the availability of freshwater. Freshwater deficits for human uses, the first proposed midpoint impact category ultimately affecting the area of protection of human life, can result from insufficient freshwater supplies for modern human users. Freshwater deficits in ecosystems, the second proposed midpoint impact category, are linked to the area of protection biotic environment. The last intermediate category, freshwater depletion due to intensive overuse exceeding regeneration rate, is ultimately associated with the abiotic environment of protection.

The suggested framework addresses factors of regionalization in connection with data availability, spatial and temporal resolution, and software capacity to support computations, because freshwater is a resource with considerable spatial and temporal variability. The framework offers suggestions for creating practical Life Cycle Assessment (LCA) techniques related to water consumption. It consistently establishes the relationship between LCI and LCIA, models of the water-use mechanism and impact pathways leading to environmental impacts.

3.11. *Ridoutt and Pfister, 2010 (Ridoutt and Pfister, 2010)*

In order to tackle the unsustainable depletion of freshwater resources worldwide, transparent indicators that reveal the effects of production systems and consumption patterns are required. This approach incorporates an updated water footprint estimation method that includes parameters for characterizing water stress. The approach provides a straightforward, yet insightful, means of conducting quantitative comparisons between goods, services and production methods, enabling an assessment of how much each can potentially exacerbate the scarcity of water. This updated approach offers an alternative to the volumetric water footprint calculation methods currently in use, which combine water use from locations with plentiful and scarce water supplies, making it difficult to determine exactly where the real risk of harm is.

3.12. *Hoekstra et al., 2011 (Hoekstra et al., 2011)*

Based on a consumption to availability ratio (CTA) that is computed as the percentage of water that is consumed (also known as the «blue water footprint») compared to the water that is available, the water scarcity indicator (WSI) is determined. Results are available for the world's major watersheds, but for many remote areas results are not available. This indicator evaluates consumptive water use; that is, the volume of water drunk. The weighted averages of the regional components are derived from the Pacific Institute's freshwater extraction data by country.

It should be noted that water related impacts vary according to the location where the water is obtained and discharged, as well as the availability and local use rates (O'Brien, Ménaché and O'Moore, 2009; Pfister, Koehler and Hellweg, 2009; World Business Council for Sustainable Development, 2012). Most of these methods were developed within Europe and specifically with Europe in mind. Efforts have been made to expand their applicability, given the regional spatial differences exhibited across different global environments (Bueno *et al.*, 2016); however local information remains scarce.

4. Conclusions

In addition to CO₂ emissions and energy consumption, the concrete production life cycle leads to several other environmental impacts, including those impacts related to water, which must be considered.

Four main impact categories were found to apply to the life cycle assessment of concrete: water use, acidification, eutrophication and toxicity.

Twenty-eight LCIA methods were found in the literature, twelve of which adopt a midpoint approach, while fourteen are specific to water related issues.

The origin of water, its use and its discharge are local factors that influence water-related impacts. This stands



in contrast to CO₂ emissions, the impacts of which occur on a global scale regardless of where the emissions originated. In the same way that it is important to understand that there exist different methods, it must be noted that each method involves a different approach. This is crucial when reporting or interpreting life cycle assessment results.

Further study will be needed in order to better understand the characterization models and calculation procedures for each method.

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Research (Y.M.), conceptualization (Y.M.), writing of the article (Y.M).

Conflict of interest

The author has no conflicts of interest to declare.

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