Concrete Uncertainty Methodology

1. Introduction

1.1 Purpose of the document

The purpose of this document is to ensure the methodology and calculations of the concrete uncertainty factors used in EC3 are transparent. This document primarily uses the methodology for quantifying the uncertainty of a material or product category described in the General Uncertainty Methodology document [1], which can be found on the EC3 website documentation tab. Please refer to this document for general definitions, vocabulary, equations, and explanations of this methodology.

1.2 Scope of the analysis

As discussed in [1], conducting an uncertainty analysis requires analyzing a base LCA model for the product. The base LCA model used for this analysis is the 30 MPa concrete in the Ecoinvent 3.5 database, but the analysis has been conducted in Microsoft Excel. Furthermore, the uncertainties in GWP discussed herein are related to A1-A3 impacts since EPDs for concrete mixtures typically report cradle-to-gate impacts.

2. General description of the concrete life cycle

To gain an understanding of the greatest contributors to concrete GWP impacts, a 30 MPa concrete mixture was analyzed from the Ecoinvent 3.5 database. This analysis, as seen in Figure 1, illustrated that the largest contributor to concrete emissions is cement production.

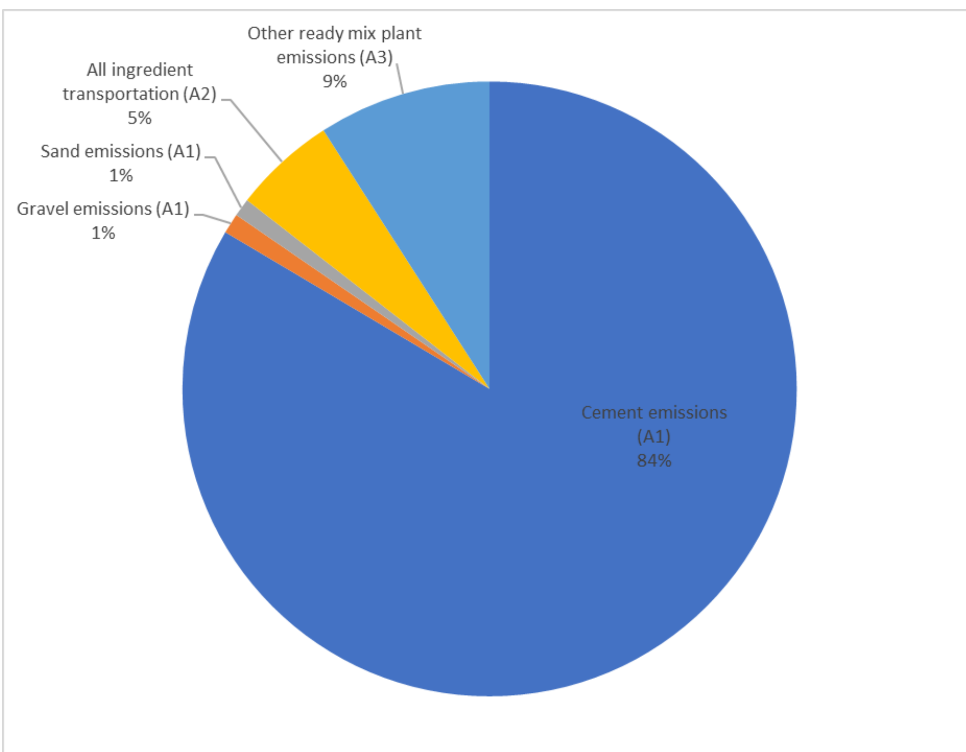

Figure 1. Contributions of LCA modules to total GWP impact for a 30 MPa concrete, grouped by module

2.1 Brief description of cradle-to-gate modules (A1-A3)

Cement production (A1) is generally associated with embodied carbon emissions due to several manufacturing processes. First, cement raw materials including limestone and clay are mined and then ground into a fine powder (raw meal). To produce clinker, raw meal is heated to a sintering temperature as high as 1450° C in a cement kiln. Then, clinker nodules are ground into a fine powder in a cement mill and mixed with a small amount of gypsum to produce cement powder.

The other major constituents of concrete are typically sand and gravel (*i.e.,* fine and coarse aggregate)[1]. Aggregate production (A1) generally includes quarrying and crushing activities that are associated with a relatively small amount of CO_2e emissions.

Cement, sand, and gravel must then be transported to a concrete ready-mix plant (A2). The emissions associated with this module typically contribute to only a small percentage of concrete's GWP because these materials are generally locally sourced. However, there are exceptions when locally available materials are of low quality or when more distant supply is cheaper.

GWP-related emissions at the ready-mix plant (A3) are generally due to batching and mixing activities as well as building-related fuel and electricity consumption.

3. Identification of uncertain variables

3.1 Cement production uncertainties

To investigate uncertainties related to cement emissions, survey data from the Global Cement and Concrete Association (GCCA) [1] was analyzed. The GCCA survey data is presented as cumulative distributions, showing that emissions due to cement production are highly variable and depend on variables such as cement kiln technology (efficiency) and primary fuel types used in the cement plant. We identified the median and 80th percentile values for uncertain variables that impact total GWP impact for cement production. **Table 1** describes these variables and shows the references that were used for approximating the median and 80th percentile values for each variable.

Table 1. Cement production uncertain variables (A1)

Variable	Units	x_{avg}	x_{80th}	Description of variability	References
fuel consumed during clinkering	MJ/kg clinker	3.650	4.000	Quantities of fuel used during clinkering vary due to the efficiencies of cement kilns. Percentiles are taken from the distributions in reference.	[2]
fuel emissions factor during clinkering	kgCO2e/MJ	0.095	0.104	Primary fuel types can vary and are associated with different GWP emissions per unit of energy produced. A cumulative distribution of clinkering fuel emissions was	[3-6]

[1] Note that water is also a major constituent used in concrete production, but its contributions to GWP impact negligible relative to the other ingredients and is therefore ignored.

				developed using fuel market share data and fuel GWP emissions factors.	
calcination emissions	kg CO2e/kg clinker	0.513	0.525	Emissions generated during calcination can differ due to variability in the raw feed composition and temperature of the reaction.	[7]
cement plant electricity use	kWh/kg cement	0.138	0.158	Electricity usage in a cement plant varies. A cumulative distribution is provided in the reference.	[2]
electricity emissions factor at cement plant	kg CO2e /kWh	0.632	0.743	Electricity emissions factors vary regionally due to different generating resources on the grid. A cumulative distribution is provided in the reference	[2], [8]
cement quantity	kg	352.6	355.4	Quantities of cement used per batch can vary due to batch tolerances. We estimate the 80th percentile batch value to be 80% of the batch tolerance limit provided in the standard.	[9]

Other variables in the life cycle of cement production that are assumed to be non-variable are listed below in **Table 2**. These variables are assumed to be deterministic because their variance is low or their impact on the final uncertainty of a concrete is low.

Table 2. Deterministic variables related to cement production emissions (A1)

Variable	Units	x_{median}	References
clinker quantity	kg clinker/kg cement	0.910	[7]
crushed limestone emissions	kg CO2e/kg limestone	0.003	[7]
crushed limestone quantity	kg limestone/kg cement	0.050	[7]
gypsum emissions	kg CO2e/kg gypsum	0.003	[7]
gypsum quantity	kg gypsum/kg cement	0.040	[7]

3.1 Other variable uncertainties (non-cement)

Tables 3-5 provide uncertainty information for variables associated with aggregate production, material transportation, and ready-mix plant emissions. Information associated with median and 80th percentile emissions for each of these variables is less available than for cement; thus, for some of these variables we use expert judgement as reasoned in the description column. Such assumptions have less impact on the uncertainty results since cement's impact dominates the total GWP impact for concrete. In other words, the precision of our analysis for these variables is less critical than the precision of our analysis for cement.

Table 3. Uncertain variables in aggregate production (A1)

Variable	Units	x_{median}	x_{80th}	Description	References
Sand production emissions	kgCO2e/kg sand	0.0042	0.0045	This analysis assumes that the increase in sand production emissions from the median value to	[7]

				the 80th percentile value to be 8% for sand and gravel.	
Gravel production emissions	kgCO2e/kg gravel	0.0042	0.0045	See description for sand production emissions above.	[7]

Table 4. Uncertain variables in material transportation (A2)

Variable	Units	x_{median}	x_{80th}	Description	References
Sand transportation emissions	kgCO2e/kg sand	0.0075	0.0094	Transportation emissions for sand are a relatively small contribution to the total GWP impact of a concrete. However, they are expected to be relatively variable. We estimate that the increase in emissions from the median value to the 80th percentile value to be 25% for sand, gravel, and cement.	[7]
Gravel transportation emissions	kgCO2e/kg gravel	0.0076	0.0095	See description for sand above	[7]
Cement transportation emissions	kg CO2e/kg cement	0.0192	0.024	See description for sand above	[7]

Table 5. Ready-mix plant uncertainty

Variable	Units	x_{median}	x_{80th}	Description	References
Electricity quantity used at the ready-mix plant	kWh/m^3 concrete	0.046	0.051	This analysis estimates that electricity use at the ready-mix plant can vary by 10% from the median to the 80th percentile value.	[7]
Emissions from natural gas and diesel use at the ready-mix plant	kgCO_2e/m^3 concrete	1.432	1.289	This analysis estimates that fuel use at the ready-mix plant can vary by 10% from the median to the 80th percentile value.	[7]
Cement quantity	kg cement/m^3 concrete	352.6	355.4	Batch tolerances from the ASTM C-94 allow for a +/-1% quantity of cement. It is estimated that the 80th percentile value is 0.8% higher than the median.	[7], [9]
Sand quantity	kg sand/m^3 concrete	0.138	0.158	Batch tolerances from the ASTM C-94 allow for a +/-2% quantity of aggregate. It is estimated that the 80th percentile value is 1.6% higher than the median.	[7], [9]
Gravel quantity	kg gravel/m^3 concrete	0.632	0.743	Batch tolerances from the ASTM C-94 allow for a +/-2% quantity of aggregate. It is estimated that the 80th percentile value is 1.6% higher than the median.	[7], [9]

4. Calculation of uncertainty factors

4.1 Calculating supply chain, facility, and batch uncertainty factors ($UF_{S,80th}$, $UF_{F,80th}$, $UF_{B,80th}$, respectively)

First, $GWP_{prod,median}$ is calculated to have an impact of 347.4 $kgCO_2e$ per m^3, which is the GWP impact of 1 m^3 of 30 MPa concrete when all variables listed in Section 3 are set to their median values. Next, $GWP_{prod}|x_{80th}$ is calculated for each uncertain variable in the concrete system boundary by changing each variable to its 80th percentile value (x_{80th}), one at a time. Then, Equation 1 can be used to calculate the uncertainty factor for each variable ($UF_{x,80th}$)

$$UF_{x,80th} = \frac{GWP_{prod}|x_{80th},- GWP_{prod,median}}{GWP_{prod,median}} * 100\% \qquad \text{Eq 1}$$

Table 6 reports the $UF_{x,80th}$ for each uncertain variable as well as its associated uncertainty group (supply chain, facility, or batch)

Table 6. Calculation of uncertainty factors for each uncertain variable

Variable	$GWP_{prod}\|x_{80th}$ ($kgCO_2e$)	$UF_{x,80th}$ (%)	Uncertainty group
Fuel consumed in clinkering	359.2	3.4	Supply chain
Fuel emissions factor in clinkering	358.8	3.3	Supply chain
Calcination emissions	351.5	1.2	Supply chain
Cement plant electricity use	351.9	1.3	Supply chain
Electricity emission factor at cement plant	352.9	1.6	Supply chain
Sand production emissions	347.7	0.1	Supply chain
Gravel production emissions	347.8	0.1	Supply chain
Sand transportation emissions	349.0	0.5	Supply chain
Gravel transportation emissions	349.3	0.5	Supply chain
Cement transportation emissions	349.1	0.5	Facility
Electricity quantity used at the ready-mix plant	349.3	0.5	Facility
Fuel quantity used at the ready-mix plant	349.4	0.6	Facility
Cement quantity	350.0	0.7	Batch
Sand quantity	347.6	0.0	Batch
Gravel quantity	347.6	0.1	Batch

Next, we calculate the aggregated uncertainty factors representing the supply chain data ($UF_{S,80th}$), facility-specific data ($UF_{F,80th}$), and batch-specific data ($UF_{B,80th}$) by summing each $UF_{x,80th}$ belonging to each uncertainty group. The summed uncertainty factors for each uncertainty group are presented in Table 7.

Table 7. Group uncertainty factors for supply chain, facility, and batch uncertainty

Uncertainty Group	$UF_{group,80th}$ (%)
Supply chain	10.8%
Facility	2.6%
Batch	0.8%

4.2 Calculating the product uncertainty factor ($UF_{P,80th}$)

Guidance from ISO 21930 states that EPDs may only report an average GWP to represent multiple products if the products included differ by no more than +/- 10%. Thus, if an EPD is not product-specific (*i.e.,* it has one GWP value covering multiple similar products), then a product uncertainty factor of 10% is applied.

4.3 Calculating the manufacturer uncertainty factor ($UF_{M,80th}$) for an industry-wide EPD

This section addresses how uncertainty should be applied to industry-wide EPDs (which are not manufacturer-specific). Concrete industry-wide EPDs typically are published with a prescribed compressive strength range and prescribed replacement of fly ash as shown in Table 8. Thus, $UF_{M,80th}$ is calculated by finding the percent increase in GWP impact from the median GWP value to the 80th percentile value for each subset of concretes and taking the average. The average value for $UF_{manufacturer,80th}$ is 13.4%.

Table 8. Calculation of $UF_{manufacturer,80th}$ for subsets of concrete, separated by strength and by fly ash replacement subsets

Strength group	Fly ash content	Median GWP (kg CO_2e per m^3)	80th % GWP (kg CO_2e per m^3)	$UF_{manufacturer,80th}$
2500 - 3000 psi	**10-19% fly ash**	330	362	9.7%
	20-29% fly ash	293	326	11.3%
	30-39% fly ash	n/a	n/a	n/a
3000 - 4000 psi	**10-19% fly ash**	356	406	14.0%
	20-29% fly ash	320	355	10.9%
	30-39% fly ash	297	306	3.0%
4000 - 5000 psi	**10-19% fly ash**	388	434	11.9%
	20-29% fly ash	352	388	10.2%
	30-39% fly ash	301	381	26.6%
5000 - 6000 psi	**10-19% fly ash**	451	500	11.0%
	20-29% fly ash	401	498	24.3%
	30-39% fly ash	303	395	30.4%
6000 - 8000 psi	**10-19% fly ash**	487	526	8.0%
	20-29% fly ash	492	503.8	2.4%
	30-39% fly ash	n/a	n/a	n/a

5. Calculation of $UF_{total,80th}$ for an EPD

The $UF_{total,80th}$ will be a different value for each EPD, depending on the specificity of the data used to calculate the GWP impact. To calculate $UF_{total,80th}$, we need to know whether each group uncertainty factor should apply to the EPD. The following algorithm can be used:

Table 9. Algorithm for calculating $UF_{total,80th}$ for an EPD

	True	False
1. EPD is an industry-wide EPD	UF_M = 13.4% Stop at this step. All other UFs = 0%	UF_M = 0% This is a product EPD. Continue with all other steps.
2. EPD is product-specific	UF_P = 0%	UF_P = 10%
3. EPD has specific LCI information for s% of the supply chain. (The supply chain contribution must be reported in GWP contribution, not by mass.)[2]	UF_S = 10.8% * (1-s)	UF_S = 10.8%
4. If the EPD uses facility-specific data from the manufacturing plant	UF_F = 0%	UF_F = 2.6%
5. EPD is batch-specific, meaning it includes data for the specific batch produced.	UF_B = 0%*	UF_B = 0.8%

Lastly, a *vestigial uncertainty (UF_V)* of 3% is applied to all EPDs since even EPDs which have uncertainty factors of 0% for the supply chain, facility, manufacturer, product and batch still have a small amount of uncertainty.

All of the group uncertainty factors are then used to calculate the total uncertainty factor ($UF_{total,80th}$) via the equation below for a given EPD.

$$UF_{total,80th} = \sqrt{UF_{S,80th}^2 + UF_{F,80th}^2 + UF_{P,80th}^2 + UF_{B,80th}^2 + UF_{M,80th}^2 + UF_V^2} \qquad \text{Equation 2}$$

References

[1] Uncertainty methodology documentation as referenced on the EC3 website.

[2] Klee, Howard, Roland Hunziker, Rob van der Meer, and Richard Westaway. "Getting the numbers right: a database of energy performance and carbon dioxide emissions for the cement industry." Greenhouse Gas Measurement & Management 1, no. 2 (2011): 109-118.

[3] Guide, Energy Consumption Benchmark. “Cement Clinker Production.” Natural Resources Canada-Office of Energy Efficiency (2001).

[4] USEPA “Emission factors for greenhouse gas inventories.” Stationary Combustion Emission Factors,” US Environmental Protection Agency 2014, Available:

[2] If GWP contributions of the supply chain are unknown from the EPD, then UF_S can be recalculated with the uncertainty for the supply-chain specific material removed.

http://www.epa.gov/ghgreporting/documents/pdf/2013/documentsmemo-2013-technical-revisions.pdf (2014).

[5] Cement Sustainability Initiative. “CO2 Accounting and Reporting Standard for the Cement Industry.” World Business Council for Sustainable Development (2005).

[6] USEPA. “Documentation for greenhouse gas emission and energy factors used in the waste reduction model (WARM).” (2015).

[7] Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., 2016. “The ecoinvent database version 3 (part I): overview and methodology.” The International Journal of Life Cycle Assessment, [online] 21(9), pp.1218–1230. Available at: <http://link.springer.com/10.1007/s11367-016-1087-8> [Accessed 12 26 2020].

[8] Skone, Timothy J. Mon. "Grid Mix Explorer Version 4". United States. https://www.osti.gov/servlets/purl/1580052.

[9] Daniel, D. Gene, and Colin L. Lobo. User's Guide to ASTM Specification C 94 on Ready-mixed Concrete. ASTM International, 2005.