Towards comparable environmental product declarations of concrete: insights from a meta-analysis and probabilistic comparative LCA approach

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Project Sponsors:

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Executive Summary

The comparability of environmental product declarations (EPDs) and the heterogeneity of their life cycle assessment (LCA) methods are considered the main challenges facing the credibility of results. The objective of this project is to promote the robustness and accuracy of the comparability in concrete mixture decision-making based on the EPD results. This project started with conducting a meta-analysis of the currently published EPD results in the national ready mixed concrete association (NRMCA) program. Then, the EPD results were compared with those in the NRMCA industry benchmarks (industry averages) mixtures. Then, a probabilistic tool was proposed and developed to gain insight into what is necessary to achieve the unrealized vision of comparable EPDs. The developed framework incorporated several uncertainty sources, such as life cycle inventory and allocation rule choices, and data quality of the input parameters in a consistent way. Also, the variability of the materials and activities was included. Then, the framework was applied to a case study of concrete mix designs. To do so, 219 concrete mix designs were adapted to compare the global warming potential (GWP) impact of mixtures with different compressive strength levels against the industry average mix designs.

The meta-analysis results showed a considerable variation and lack of transparency in the inventory selections. In fact, certain parts of the EPDs were not clear nor complied with the referred product category rule (PCR). A significant overlap was observed among the GWP results of the concrete mixtures with various 28-day compressive strengths (2,000-10,000 psi). The 25th and 75th percentile values of the washing water were about 0 and 0.2 m^3 per cubic meter of concrete, respectively. Moreover, almost 30% of the mixtures with compressive strength of 2,000-6,000 psi reported less than 0.1 m^3/m^3 concrete batching water, implying a discrepancy in the methodology of water calculation among EPDs.

The outcomes of the probabilistic tool show that the uncertainty and variability sources in the stand-alone evaluation induce an overlap among the GWP results of the benchmark mixtures. The comparative results of the industry benchmarks and the mix design population show that for a given compressive strength level, all the ternary blended cement mixtures have a statistically significant lower GWP than that of the industry-average benchmark. However, a 40 kg CO_2eq difference in the comparative GWP results of portland cement and binary mixtures may not result in a statistically significant different. The major source of variation, i.e. more than 46% contribution to the total variance, in the stand-alone LCA results comes from the methodological choice of database with portland cement inventory data. However, the impact of methodological choices on the variance of the concrete comparative results is trivial. Therefore, as long as the LCI database is representative of the context, the methodological choices may be a minor concern in the comparative analysis.

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1. Introduction

The first version of the standard series for environmental product labeling was drafted and published by the International Standard Organization (ISO) in 1999 to manage and oversee claims for the environmental impacts of products. Following the previous efforts, the ISO 14025 standard was published in 2000 to regulate principles of the procedures for producing Type III environmental product declaration (EPD) programs [1]. The requirement of type III labeling includes formal verification of information as well as transparency and accountability of the calculations for the life cycle impacts of the product. To define a roadmap for conducting a life cycle assessment (LCA) in EPDs, product category rules (PCRs) have been developed. In fact, PCRs specify a set of criteria for a specific product category, such as ready-mixed concrete. These criteria include the LCA requirements, such as methodological rules to be implemented into the LCA. It was also stated that the intention of PCR is to ensure that different products EPDs developed under the rule of similar PCR can be fairly compared. Previous research studies reported that EPDs can be used as a means during the design process to allow for comparisons between different product systems that fulfill the same function [2]. This comparison is permitted if certain criteria, such as those discussed in ISO 14025 Section 6.7.2 Requirements for comparability, are met. Moreover, development and incorporation of rating systems, such as LEED and Green Road for buildings and pavement, respectively, for certification of infrastructures promotes the use of these EPDs to achieve certain credits for construction materials. These credits intend to incentivize manufacturers to create EPDs for products to be used on LEED-certified projects [3]. Similar to other products, the industry average EPDs of concrete have been used as a set of benchmarks to represent the environmental impacts of building products across a range of producers and product types. The producers and users of concrete can use these benchmarks to compare the environmental impacts of their own to those of the industry averages. For example, the optimization credit in multiple attribute optimization (Option 2) mentions that third-party certified products that show an environmental impact reduction below the industry average values in three categories or more are considered at 100% of their cost for getting the credit. Hence, if the mix design impacts are lower than the industry average, then the producer or user can report their contribution to option 2 of the LEED v4 materials and resources (MR) credit on EPDs. This improvement shall be clearly shown through lower EPD results than those in the industry averages. These EPD applications demonstrate the importance of the decision to be made based on the environmental impact results. Furthermore, the comparative assessment of EPDs encourages special attention to the confidence of the conclusions.

2. Research Motivation

Concerns about the environmental impacts of concrete mixtures have been primarily focused on their GHG emissions owing to almost 8-9% of total global anthropogenic GHG emissions [4]. Yet, one of the challenges that the concrete industry is facing is to understand the GHG footprint of the selected mixtures through trusted and transparent information. As described in ISO 14025, one of the objectives of developing environmental labels and declarations is to assist purchasers and users to make informed comparisons among different mixtures. Recent efforts of different governments increase the importance of EPD results. For example, the Buy Clean California Act [5] specified that starting from 2019, the state of California requires EPDs for certain construction materials. Hence, various agencies in California plan to develop benchmark values of environmental impacts of construction materials based on the collected EPD results to assure that the environmental impacts of these materials are lower impacts than that of the benchmark. Concrete is one of the materials that will be included in the Act. Similar efforts have been legislated in various states such as Washington [6] and Oregon [7], which reflects the increased interest in including the environmental aspect of government purchase decisions for infrastructure development. Moreover, the comparison between EPD and industry-average results also enables producers and users to take advantage of the credits specified in the LEED rating system. These comparison opportunities urge concrete stakeholders to consider harmonized results for a consistent and reliable assessment of mix designs. Usually, this type of comparison results in single-point estimates, based on deterministic data, which in many cases represents an average numerical output that embeds little information on the significance or variability of that value. For example, in comparative LCA of concrete mix designs, the LCA point value results are superposed and directly compared. The less environmentally alternative is chosen in a deterministic way without considering the risk of making a wrong decision.

To provide a guideline for program operators to estimate the potential environmental impacts of concrete mixtures, certain PCRs for each geographical context have been developed and used. Indeed, concrete industry organizations set up an operator and a committee consisting of a group of experts to specify the LCA methodology for conducting EPDs for a given geographical context. Nevertheless, different EPDs can be developed and stayed valid in the same region under an updated and outdated PCRs given a validity period of 5 years [8]. To develop an EPD, to collect the input data, practitioners may need to refer to various EPDs developed under different rules.

For example, there is no consensus regarding the allocation rule as each PCR mandated a rule that maximizes the benefits for the main product for that specific industry. More specifically, in various aggregate PCRs, an economic allocation is proposed for dividing the impacts between pig iron and granulated blast furnace slag (GBFS), whereas in most ready mix concrete PCRs, GBFS is considered as a waste, and therefore, zero upstream impacts are allocated to this SCM. While there are certain specifications for foreground processes in the PCR, the reason behind these choices may not be clear as there are multiple life cycle inventory (LCI) datasets available that have their benefits or flaws (e.g. incompleteness of the environmental flows in a database as opposed to a lower temporal, geographical and technological correlation in a more complete database). Therefore, there may be a trade-off for the rule specifications. Also, LCA results are often questioned through the level of uncertainty in the conclusions. To the best of author's knowledge, the robustness of conclusions has never been required by any PCR. The assessment of the robustness may be more important for the concrete EPDs as most of the unit processes in LCA modeling were developed before 2015 and has not been updated yet. Therefore, when the facility-specific data is not available, the LCA result may have a significant uncertainty stemmed from the quality of input data. As data quality assessments of life cycle inventory are explicitly reported in the EPDs but are not used in a quantitative way to assess its impact on results, there is a significant potential to incorporate this uncertainty source in the robustness of the decision. Analyzing the uncertainty related to this data quality can provide a comprehensive perspective on the transparency, reliability, comparability, and clarity of the scoring. To understand each point that is discussed in this research motivation section, a meta-analysis of published EPDs under the NRMCA program was the first step. Then, based on the meta-analysis outcomes, a probabilistic framework was proposed to overcome the addressed challenges.

3. Methodology of meta-analysis

Meta-analysis is a statistical procedure for combining data from multiple studies. Decisions about the environmental impacts of a mix design with single attributes or the validity of a hypothesis cannot be based on the results of a single mix design results, because the impacts of mixtures with the same level of functionality can typically vary from one EPD to another. Hence, a mechanism is needed to synthesize data across different mix designs. Meta-analysis is widely used in basic research to evaluate the evidence in the discrepancies and to find opportunities for harmonization. It can also play an important role in planning new studies.

To investigate the consistency and compatibility issues described in the previous section, a systematic review of concrete EPDs and their underlying PCRs are performed. The selected PCRs are those published for the North American and European contexts to analyze the possible lessons that can be learned from each other. About the EPDs, this review focuses on the resultant North American EPDs and the ability to compare products within each material category and focuses on GHG emissions and water inventories. Hence, the meta-analysis incorporates the GWP impact of 2,892 mix designs verified and published by NRMCA as a part of the industry average program. Only facility-specific EPDs for plants located in Texas, Florida, California, Washington, Oregon, Oklahoma, and Alabama were publicly available. The meta-analysis results of mix designs are provided in SI1 (Excel file) associated with this report. Also, we included the data quality assessment scores described in the EPDs. Overall, the 56-day compressive strength results were reported for 80 mix designs and there were less than ten 7-day test results. Therefore, the GHG and water inventories of the mix designs were divided into various categories of 28-day compressive strength (as the most prevalent attribute in the EPDs). Then, the results were compared with those reported for the U.S. averages. The number of mixtures corresponding to each compressive strength range is shown in Figure 1.

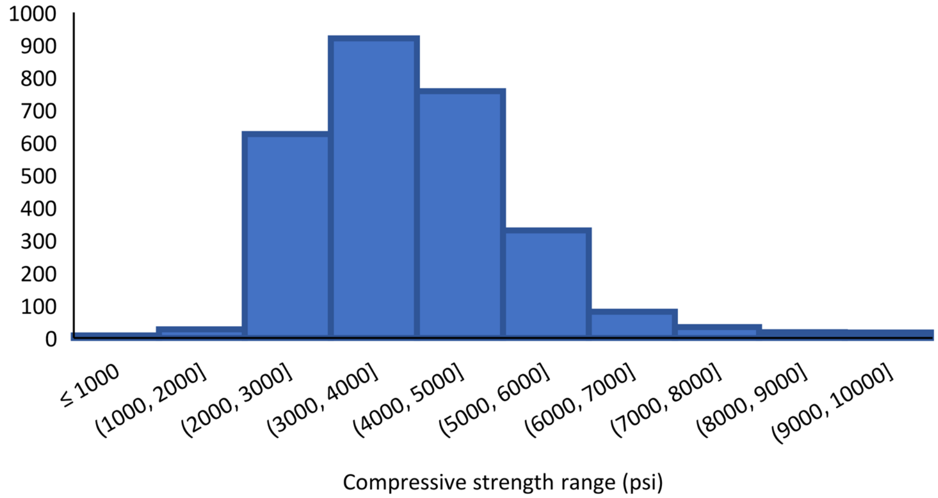


FIGURE 1. NUMBER OF MIX DESIGNS CORRESPONDING TO EACH COMPRESSIVE STRENGTH COLLECTED FROM NRMCA INDUSTRY AVERAGE PROGRAM

Several LCI datasets were incorporated in the published concrete EPDs. Certain EPDs reported that they entirely used a currently unavailable LCI database called Boustead (BEST). For the rest of the mixture, a mix of datasets was implemented. For example, the published EPDs used GaBi and USLCI for cement production. One EPD reported that the use of MIT 2014 paper, which is the update of portland cement (USLCI) modified to include upstream impacts of fuel and energy production, was used. The majority of EPDs used the Slag Cement Association (SCA) EPD data for the emissions and resource consumptions of slag. For aggregates, ecoinvent (version 2 and 3) and GaBi along with USLCI were employed. Ecoinvent and GaBi are the major sources of data for water LCI. The major source of LCI data for chemical admixtures comes from the European Federation of Concrete Admixtures Association (EFCA) EPDs. For background processes, such as fuels and electricity production and transportation, data from ecoinvent, GaBi, and USLCI database was used. For the hazardous and non-hazardous waste treatment, the ecoinvent database was used. There is a data quality section in most of the EPDs. Five categories represent different aspects of data quality for each process. The categories cover technology, time, geography, completeness, and reliability of the chosen LCI. These categories are often rated as poor=1, fair=2, good=3, very good=4 in the EPDs. In this study, the data quality scores were collected to assess the ranges of quality for different concrete constituents. This centralized resource can effectively help improve and facilitate the verification process through a systematic procedure of disaggregating the inputs and calculation steps into a reasonably fine level, that enables the consultant to update the changed processes. Moreover, the digitalization of EPD production and parts of the review and verification process can possibly contribute to lowering the EPD cost. This centralized source would help apply the proposed method in this research as well.

4. Meta-analysis results of global warming potential and water inventory

The global warming potential (GWP) results of concrete mix design are presented in Figure 2. The red dash line represents the U.S. average results. In the box and whisker plot:

- the ends of the box are the 25th and 75th percentiles, so the box spans the interquartile range
- the median is marked by a vertical line inside the box
- the mean value is marked by a cross
- the whiskers are the two lines outside the box that extend to the 5th and 95th percentiles.
- The outliers are shown by dots

The U.S. average GWP results are very close to the mean of the EPD results. However, for the 28-day strength above 5000 psi, the U.S. mean values are significantly larger than the mean values of EPD results still with the quantiles. As the mean values were calculated based on the individual EPD results, lack of harmonization in the LCA methodology possibly results in such divergences.

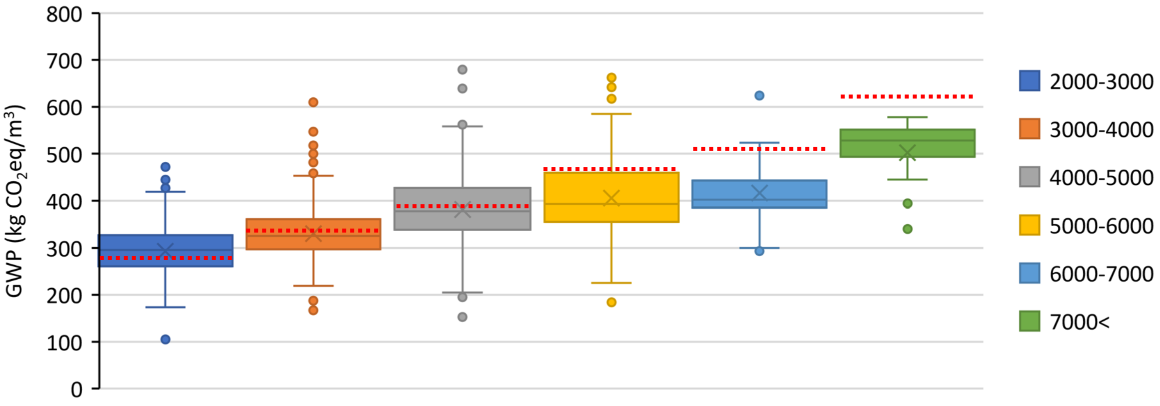


FIGURE 2. META-ANALYSIS OF GWP IMPACT OF CONCRETE MIXTURES BASED ON 28-DAY COMPRESSIVE STRENGTH (INTERVALS = 1000 PSI)

The concrete water inventories extracted from EPDs are significantly different from the average U.S. results as shown in Figures 3 and 4. Therefore, the lack of harmonization in the system boundary and the inconsistencies in the studied unit processes in the system possibly cause such a divergence. The significant difference between the average and the median values of the inventory supports the hypothesis that a considerable number of EPDs reported lower than 0.1 m^3 batching water. Further investigation is required to understand the calculation of water inventory.

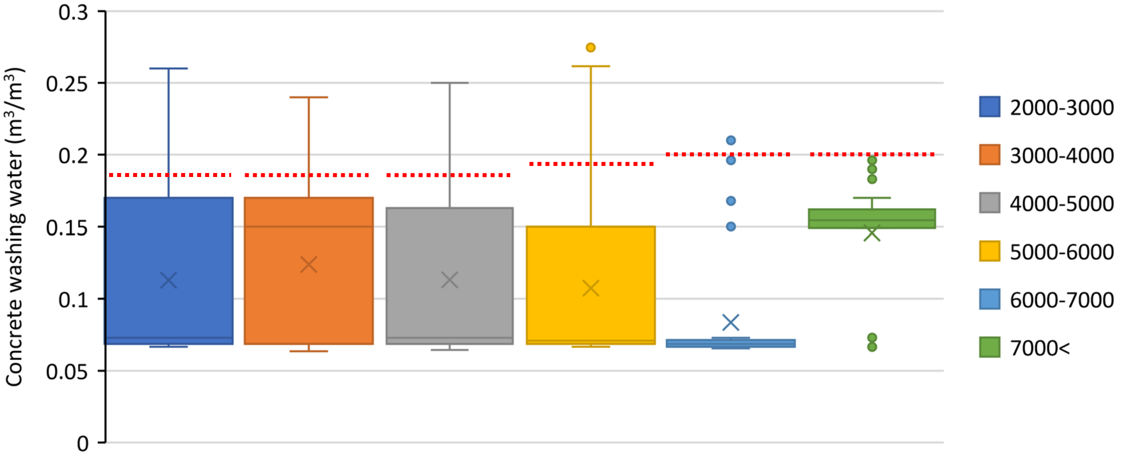


FIGURE 3. META-ANALYSIS OF CONCRETE BATCHING WATER INVENTORY OF CONCRETE MIXTURES BASED ON 28-DAY COMPRESSIVE STRENGTH (INTERVALS = 1000 PSI)

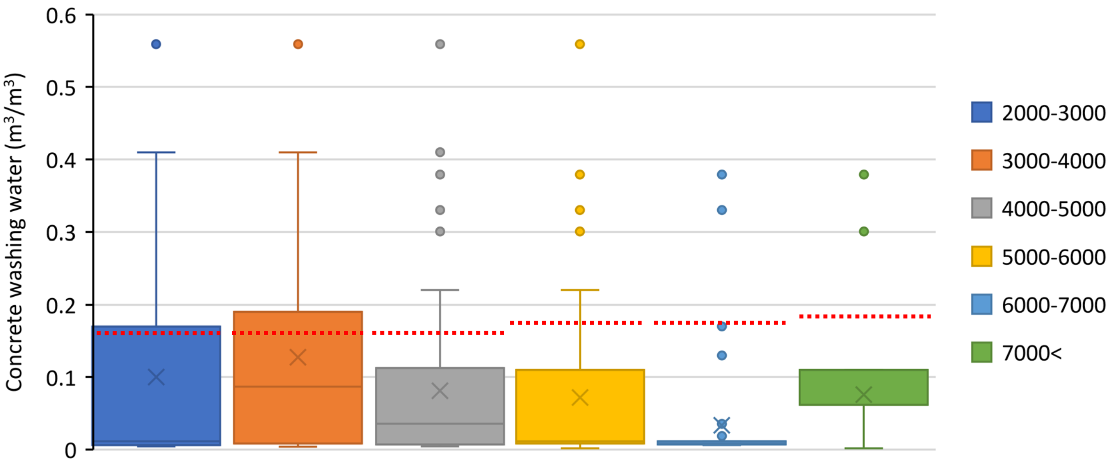


FIGURE 4. META-ANALYSIS OF CONCRETE WASHING WATER INVENTORY OF CONCRETE MIXTURES BASED ON 28-DAY COMPRESSIVE STRENGTH (INTERVALS = 1000 PSI)

There is an interesting momentum among concrete stakeholders to shift from a prescription-based design to performance-based design. Considering this momentum, it seems quite relevant and critical to track the EPD results reported through a more comprehensive specification level. One should note that only the 28-day compressive strength (and in few cases 56-day compressive strength) was reported in the published EPDs and the industry benchmarks. Indeed, the 28-day compressive strength might not reflect all the required performance metrics for structural applications. As different design standards and guidelines require different metrics, it seems inaccurate to estimate these performances (e.g. flexural strength, workability, and durability) based on the 28-day compressive strength. Therefore, a fair comparison of EPDs for different mix designs selected for a specific structural element, that is exposed to an aggressive environment, may not be viable with the current format. The other example is for concrete pavement that flexural strength is the main input for the mechanical properties used in pavement design. Therefore, we propose to incorporate at least, the exposure class (according to Table 19.3.1.1 in ACI 318-19- Building Code Requirements for Structural Concrete) for concrete used in buildings as a mandatory performance specification to be reported in EPDs. In addition, we propose to include flexural strength, shrinkage, and stiffness (Young’s modulus) as the mandatory specification for EPDs used for concrete pavement. These properties will give a clear apple-to-apple comparison among the other results.

One important point about these published documents is that EPDs were published and remained valid for five years. These long validity period may not be reflective of continuous improvements in production efficiency. More specifically, if a concrete plant aims to invest in the improved technologies to mitigate the emissions and consumptions of resources, they should request a new EPD rather than a possibility of updating the previously published document. A centralized resource (e.g. NRMCA) with a capability of EPD digitalization may help update the content of the already published EPDs.

5. Review of published concrete PCRs

The major sources of input data are the current PCR developed by the Carbon Leadership Forum (CLF), which was recently updated by NSF© in March 2019. Other PCRs are the Cement Sustainability Initiative (CSI), and EN Standards that follow the specification of ISO 21930. The geographical scope of this study is delimited to North American EPDs. However, we included EN 16757 and EN 15804 to have a broader perspective of the defined methodology of conducting an EPD. The explicit classification of methodology and information of the three PCRs is presented in SI2 (Word file). The following is a summary of each PCR content that is presented based on the life cycle stages proposed by ISO 14044.

5.1. Goal and Scope Definition

The North American PCR (NA PCR) considers compressive strength at a specific age as the mandatory performance that must be reported in EPDs and the rest of the properties are optional. However, the other PCRs focus on compressive strength, exposure condition, and slump value as mandatory information. The NA PCR is the only guideline that does not assign the upstream processes of supplementary cementitious materials to the cradle-to-gate system boundary of concrete. The term, “recovered materials” (this term is not defined in the ISO standards) is used in the recently published PCR for materials such as fly ash and slag. Nevertheless, the NA PCR recommends a scenario analysis if the developer predicts a 20% change in the results. While other PCRs referred to the ISO definition of “by-products” and considered economic allocation for such co-products. Referring to Rodríguez-Robles et al. [9], slag and fly ash need to be allocated although it is explicitly mentioned in the ISO 13315-8 to exclude the burdens allocated to upstream processes of electricity and iron production.

Similarly, in the NA PCR, it is stated that only the impacts related to materials transportation from end-of-life state to manufacturing facility shall be included. Provided examples were secondary fuels, such as waste tires, and supplementary cementitious materials (SCMs), such as fly ash and slag. The CSI PCR, on the other hand, stated that satisfying four criteria will result in calling a material as secondary rather than a waste. These five criteria are the common use of the material, the market existence, the satisfaction of technical requirements for the application, and the lack of adverse environmental and human health impacts. The CSI PCR defines a co-product as any intended or unintended product and/or wastes as the outputs of a product manufacturing process. Similar to the NA PCR guidance, the CSI PCR emphasized to include the processing waste until it reaches the end-of-waste situation, i.e. when the four above-mentioned criteria are satisfied. Nevertheless, the CSI PCR defined at least 1% revenue contribution of the total output revenue as a threshold for allocating the impacts of upstream processes and therefore, an economic allocation is proposed for different co-products, where the concrete producer or contractor pays for the materials. No impacts are allocated over the system boundary from previous use of post-consumer material that is recycled or reused.

Along with database selection, the allocation method can be considered under the category of "uncertainty due to methodological choices" in LCA. In fact, under the current rules of PCRs developed for the construction products, it is not possible to implement a consistent rule for different constituents of concrete and there is no consensus regarding the allocation rule as each industry proposed the allocation rule that maximizes the benefits for the main product. For example, in the aggregate PCR, an economic allocation is proposed for slag aggregates, while in the concrete PCR, slag is considered as a waste. Therefore, rather than the transportation and grinding processes, no impact is attributed to slag used as a cementitious material. This issue can be solved by treating the allocation method selection as an uncertainty source in the analysis. Answering this question in a probabilistic way can also help users implement the allocation method consistently while examining different possible rules for other products, such as steel. For example, in the PCR of structural steel, system expansion is proposed for slag produced along with the refined product.

For the energy recovery from wastes, in the CSI PCR, there are two different statements for reporting versus attributing the impacts. As most of the wastes cannot satisfy the end-of-waste state, according to the four previously stated criteria, the heat recovery should be linked to the post-consumer waste producer. However, for the sake of being conservative, consistency with the reporting guidelines, and also the complication of separating energy recovery emissions from the use of other fuel, it is stated that the energy recovery of waste shall be included in the system boundary but all the indicators that can be separately estimated for the energy recovery from waste can be reported as the sub-total of the indicator. On the other statement of this guideline, it is mentioned that all impacts occurring before the post-consumer materials reach the end of the waste state are attributed to the system producing the waste, and not the system benefiting from the waste. Although the effort of the PCR towards incentivizing the energy recovery from waste is acknowledged, this complexity between reporting and attributing the heat recovery emissions can result in a divergence in the output results of the EPDs published based on the CSI PCR.

5.2. Life Cycle Inventory

The previous version of the NA PCR excluded waste out of the gate from the boundary, which is now included in the new version. The transportation of waste to the landfilling site, however, has remained a challenge in the recent NA PCR as there is no information to include this process. The recent version of NA PCR specifies background datasets that shall be used for developing the EPDs. However, these datasets are different from the expired PCR (CLF). As there are several valid EPDs (i.e., less than five years passed from their issued date) developed under the rules of the expired PCR, comparing these results versus the recently published industry average results, that follows the new PCR rules, remains a challenge.

The ecoinvent database is one of the main LCI sources that program operators have proposed as a proxy for different processes in the concrete EPD and PCR documents. The practitioners mostly used the “allocation at the point of substitution (APOS)” dataset, which assigns the impacts of valuable by-products of treatment systems together with the activity that produced the material for the treatment. Although it is beneficial to use this rule of allocation to avoid difficult allocations, it introduces complex compromises in different assessments. For example, it is reported that using the APOS dataset resulted in exceeding the environmental impacts of recycled materials compared to virgins or, the irrelevant upstream flows were assigned to the recycled materials. The use of the ecoinvent dataset "allocation-default" may bring inconsistency to the foreground as compared to the background system as the allocation rule in the foreground system is not applicable. Obviously, the allocation rules comply with the ecoinvent-recycled content dataset as no impact will be allocated over to any subsequent recycling or over the system boundary from previous use or post-consumer materials.

5.3. Life Cycle Impact Assessment Method

The NA PCR recommends TRACI V.2.1 for impact assessment. However, this life cycle impact assessment has not been updated and still uses the IPCC 2007 characterization factors (CFs) for GWP calculation. The most recent CFs were published in 2013 and possibly be recommended by the PCRs to improve the credibility of GWP results. The alternative impact assessment method for sensitivity analysis should incorporate the weak points of the main method. Instead of CML, IMPACT World+ can be recommended to provide CFs within a consistent impact assessment framework for all regionalized impacts at four complementary resolutions: global default, continental, country, and native (i.e., original and non-aggregated) resolutions [10]. IMPACT World+ enables the practitioner to calculate the water footprint of concrete mix design in impact level as opposed to inventory level in the current format. With the development of regionalized and update impact assessment methods, such as Impact World+, using TRACI v.2.1 would be an alternative for a sensitivity analysis. In addition, the impact categories results of construction materials, such as concrete mixtures, whose results are not correlated, do not exist in the ISO or

EN 15978 or 15804 standards [11]. The examples are land use or toxicity, which are neglected mostly due to lack of consensus in their calculation methods and high uncertainty in the CFs of toxicity.

5.4. Interpretation

The data quality of the inventory and background processes are recommended to be included in the EPD report. The data quality metric incorporates four levels of very good, good, fair, and poor for each inventory adapted by the LCA developer. Reporting data quality can provide a base for calculating the impact results reliably and compare them with other conducted EPDs consistently.

6. Proposed framework for comparative analysis of EPDs

The procedure of harmonization is summarized in Figure 5. In this work, we propose a probabilistic method to enable comparison of mix designs with each other and industry-average benchmark results. To develop the probabilistic framework the results of EPDs, we defined a set of key methodological choices and life cycle inventories to match the system boundary and the inventories of the mix designs (step 1). One should note that it is not required to implement *the* LCI dataset or *the* specific EPD as an input for the harmonization and as long as the LCI can give users an appropriate data quality scores (i.e., the dataset is complete, reliable, and geographically, temporally, and technologically representative), it can be used in this proposed framework. The key feature in this framework is to apply the methodological choices and to consider the assumptions consistently among the alternatives that are being compared (step 2).

To initiate this task, it is required to fully understand and explicitly compile the LCI or the EPD that was developed for the inputs. Then, the criteria specified in ISO 14025 (section 6.1) were implemented as a checklist for the processes in steps 1 and 2. A detailed description of step 4 is presented in section 6.2 of this report.

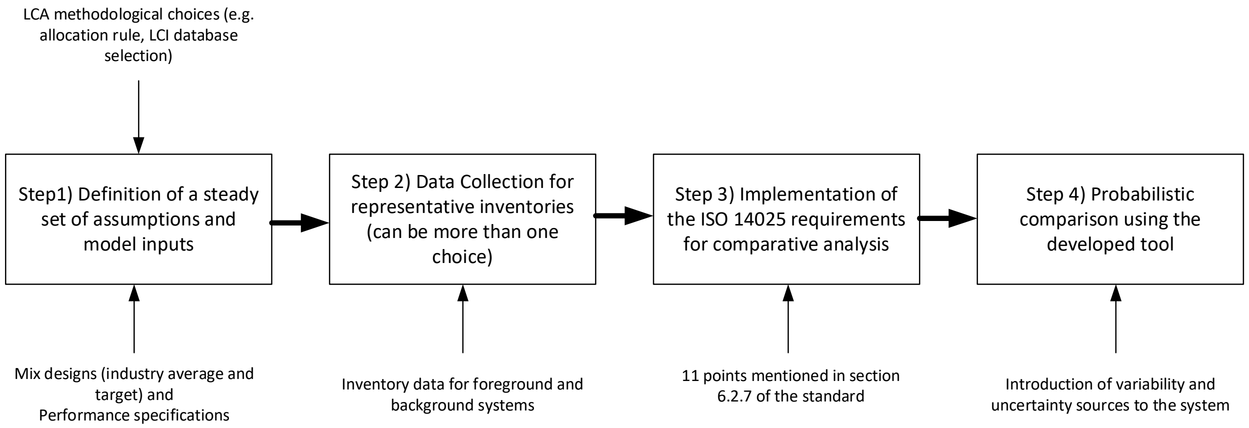


FIGURE 5. OVERVIEW OF HARMONIZATION PROCEDURE AND PROBABILISTIC COMPARISON OF EPD RESULTS WITH INDUSTRIAL BENCHMARKS

6.1. Requirements of ISO 14025 for comparability of EPDs

To compare the generated EPDs, a valid procedure shall be established, and the following criteria must be met according to ISO 14025:

More specifically, the product category definition and description (e.g. function, technical performance, and use) are identical. An identical functional unit, an equivalent system boundary (including the life cycle stages and components), a description of data, an identical cut-off approach, and an equivalent data quality score shall be considered and clearly reported in the goal and scope definition for the LCA of the product. Also, the data collection method, calculation procedure, and applied allocation rules shall be identical in the inventory analysis stage. The impact category selection and calculation rules, including characterization factors, shall be identical. The predetermined parameters for reporting of LCA data shall be identical and the requirements for the provision of additional environmental information, including any methodological requirements shall be equivalent. All the materials used in the product system boundaries shall be declared and instructions for producing the data required to create the declaration are equivalent. Hence, our current method may not be applied to currently published EPDs since the input data is proprietary of the companies and are not publicly available. Also, instructions on the content and format of the report and the validity period shall be equivalent as well.

6.2. Uncertainty and variability assessment methodology

2.1. Probabilistic approach for comparative analysis

A probabilistic method was implemented to quantify the uncertainty derived from the parameters and the methodological choices and to conduct a robust comparative LCA. The method evaluates a broad range of possible scenario space while considering uncertainty in input data. Here, a terminology of uncertainty and variability is presented. To distinguish between uncertainty and variability, it should be noted that variability is related to the variations that inherently exist in the real world. Therefore, the variability sources can be captured in the data collection stage that LCA calculation has not yet been applied. An example of variability can be the expected variations in the mass of mix design constituents due to the loss of materials in a batching plant.

On the other hand, uncertainty is related to converting the bill of materials or activities to potential environmental impacts. A source of uncertainty in LCA can be empirical parameters that are measurable (e.g. an emission factor associated with a process where no empirical measurement exists). Another type of uncertainty incorporated not this study is called value parameters that are to do with the methodological choices. For this type of uncertainty, based on the preferences of decision-makers, an appropriate value is selected. Examples include the allocation method or database selection. In this study, we divided the parameters into the three categories of, variability source, empirical parameter (related to the data quality uncertainty), and value parameters (uncertainty due to allocation and database selection). Monte Carlo analysis, which is the most conventional method used in LCA to assess the propagation of the uncertainty of unit process data, is applied [12]. The sampling method was performed using Monte Carlo simulation, which is a set of computational algorithms that rely on repeated random sampling to obtain numerical results. Therefore, a probability distribution was assigned to each variable included in the analysis.

For the value parameters, related to the allocation choice of slag and fly ash as well as database selection between ecoinvent and GaBi, the possible scenarios were considered as discrete choices. An equal probability of occurrence was considered for individual scenarios related to a methodological choice. Let X be a discrete random variable sample from scenarios $x_1, x_2, x_3, ..., x_n$, the probability of the methodological choice was calculated the probability mass function in Eq. 1.

$$P_X(x_k) = P(X = x_k), \text{ for } k = 1, 2, 3, .., n \quad (1)$$

where P is the probability of occurrence for the scenario x_k. An identical probability was assigned to each scenario not to give any preference to any methodological choices for a given value parameter.

There is no data available for the variability of materials expect for a proposed loss value. Hence, to conduct the analysis on the possible variability of each unit process, a continuous uniform distribution is defined according to Eq. 2.

$$P(y) = \frac{1}{Y_1 - Y_0} \text{ for } Y_0 \le y \le Y_1$$
$$P(y) = 0 \text{ for } y < Y_0 \text{ and } y > Y_1 \tag{2}$$

where Y_0 and Y_1 are the minimum and maximum values possible for material, respectively. The values Y_0 and Y_1 are obtained from the possible range of changes in the input data.

Parameter uncertainty is the most conventional type of uncertainty and has been studied in various LCA case studies. To date, the pedigree matrix has been primarily used to code the qualitative judgments into numerical scales with consideration of criteria, such as reliability, completeness, and temporal, geographical, and technological correlation of the input data [13]. For each criterion, an uncertainty factor is calculated by analyzing data from different sources. The variance (σ) of the parameter distributions (i.e., commonly, a lognormal distribution) is calculated based on Eq. 3:

$$\sigma^2 = \sum_{i=1}^{n} \sigma_i^2 \tag{3}$$

where σ_1 to σ_5 are the uncertainty factors (variance) of reliability, completeness, temporal correlation, geographical correlation, and technological correlation, respectively. In addition, a basic uncertainty factor σ_6 is also considered whether the process represents an environmental flow to the technosphere or emissions [14]. It should be noted that this equation is only valid for lognormal distributions.

For assessing the eligibility of mix design for certification credits, the LCA results are often interpreted comparatively against the regional benchmark. In this context, the relative uncertainty may be more important than the overall uncertainty of the system. To characterize the relative uncertainty, a relative impact variable was defined as the ratio between the GWP impact of the target mix design and that of the industry benchmark according to Eq. 4:

$$RI = \frac{A_{x,y,z}}{B_{x,y,z}} \tag{4}$$

in which RI is the relative impact, and $A_{x,y,z}$ and $B_{x,y,z}$ are the GWP impact of a target mix design and industry benchmark, respectively. Since many of the uncertainty and variability sources are similar in comparative LCA, there is often a correlation among parameters across mix designs. Considering this correlation may help practitioners avoid statistical bias and possibly reduce the impact of the uncertainty in the robustness of decision-making [15]. Hence, the Monte Carlo simulation was conducted simultaneously for both mix designs such that for each run, the same sample sets (including, same values obtained from the same database, the same allocation rule, and the same variability distribution) were used to incorporate the parameters interdependencies. Possible interdependencies investigated in this study, are described in section 5.2.2. The relative impact was then calculated at each run. The stored values RI are used to estimate the probability distribution and statistics of this quantity as shown in Figure 6. From this probability distribution, as shown in Figure 6, the area that corresponds to the RI <1 shows the proportion of simulations that the GWP impact of the target mix design is lower than the that of the benchmark mix design (i.e., $\beta = P(RI = \frac{A_{x,y,z}}{B_{x,y,z}} < 1)$ that specifies the likelihood that the target mix design has lower GWP impact than the benchmark. A conclusion on the superiority of the target mix design over the benchmark can then be made when β is greater than a predefined threshold (β_{crit}). In fact, β_{crit} is a parameter that determines the risk level that a decision-maker would like to take. Finally, the Spearman's rank correlation coefficient was performed to assess the contribution to variance in the probabilistic results to understand where the variations come from. Another important part of conducting Monte Carlo is the consideration of various types of interdependencies in the sampling. These interdependencies are explained in detail in Supplementary Information.

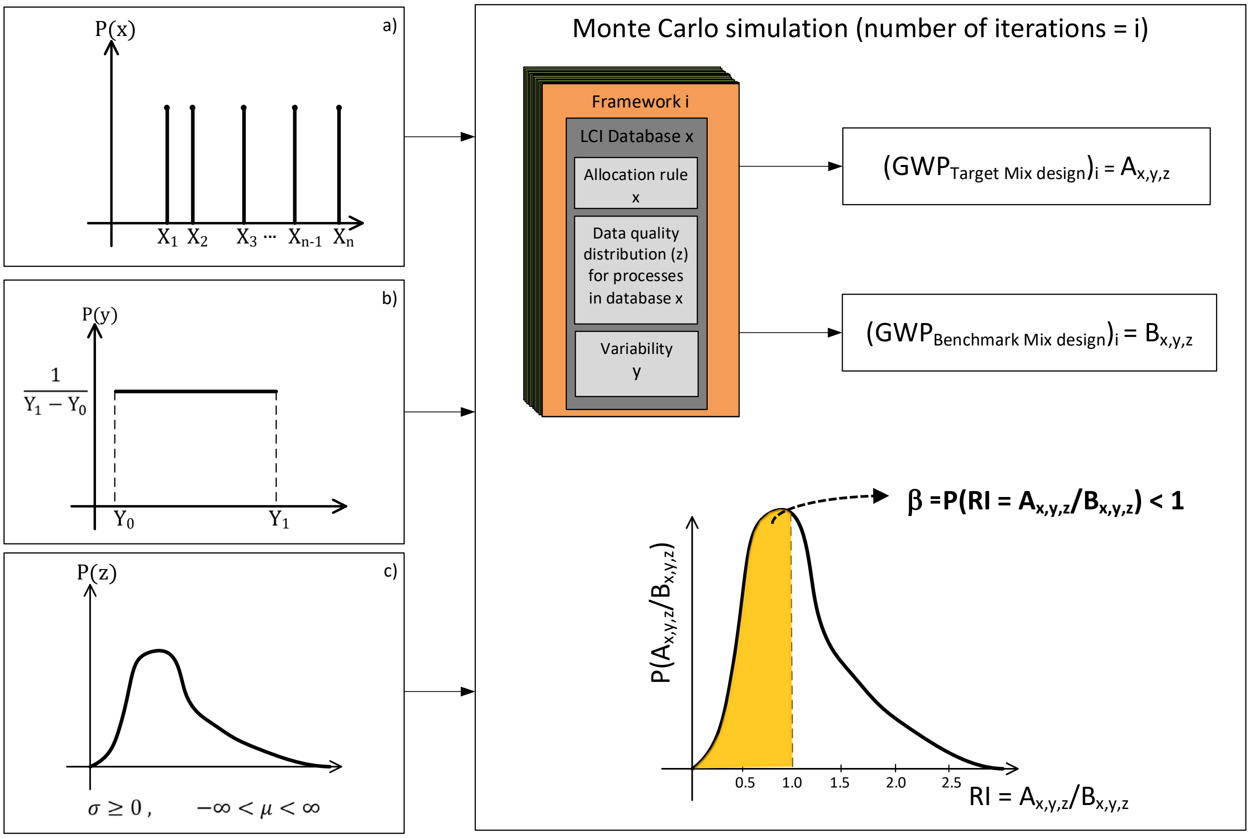


FIGURE 6. GENERAL FRAMEWORK OF THE PROBABILISTIC MODELING INCORPORATING A) UNCERTAINTY DUE TO METHODOLOGICAL CHOICES, B) VARIABILITY OF CONCRETE CONSTITUENTS AND C) PARAMETER UNCERTAINTY MODELING FOR COMPARING A TARGET MIX DESIGN AGAINST AN INDUSTRY BENCHMARK

6.2.1. Interdependency of sampling in Monte Carlo simulation

Using this methodology enables LCA practitioners to consider the following interdependency among parameters and sources:

a) Dependency of sampling from an uncertainty source across all the mix designs

As a specific value is sampled from a probability distribution, this sampled value should be applied consistently to all other places that this unit process is used along with all the product life cycle in the comparative studies. For example, a similar database and allocation rule for a specific product be considered in a single iteration of Monte Carlo when considering the uncertainty due to the methodological choices.

b) Dependency of sampling in different unit processes of a mix design

When the value of a parameter A varies within a source of variation, it may adjust the value of other parameters that are dependent to parameter A. For example, the variability in aggregate weight will change the weight of the cementitious material for a specific volume of concrete (e.g. 10 kg variation in the aggregates weight should be adjusted by the cement content that has an equivalent volume of 10 kg aggregates). Indeed, the normalized volume would have different amounts per m^3, and there would be a need to recalculate the volume due to a change in mass, and then re-normalize to a cubic meter basis to determine the new mass of other ingredients per m^3 mass quantities.

c) Dependency of sampling between different sources

The example for this dependent sampling can be the relationship between the uncertainty due to methodological choices and the parameter uncertainty. A representative case in this study is the database choice (uncertainty due to the methodological choice) and its underlying data quality score (parameter uncertainty) that should be dependently sampled.

All of the probability distributions were analyzed using Monte Carlo simulation to assess the uncertainty and variability coming from different sources with consideration of relative uncertainty (i.e., pair-wise analysis). The method evaluates a broad range of possible scenario space while considering uncertainty in input data. Considering the requirements for comparability in the ISO 14025, the uncertainty analysis enables one to assess the statistical significance of the difference between the benchmark and EPD results. Hence a threshold value is implemented to show this significance.

7. Application of the probabilistic methodology to the case study of comparative results (219 mix design in Ohio)

In this work, we proposed a probabilistic method to enable the comparison of the mix designs with each other and with the industry-average benchmark results. The probabilistic tool was applied to a case study of 219 mix designs classified into three design strengths of 4,000, 5,000, and 6,000 psi in the state of Ohio. The details of mix designs are presented the supporting information. It should be noted that this mix designs population can show the possibility of applying this method to future EPD and may not be applicable to previously published EPDs unless the mix design constituents are disclosed.

7.1. Goal and scope definition

The goal of this case study is to apply the described methodology in section 2 to calculate the GWP impacts of the industry benchmark mix designs for the Great Lakes Midwest region and compare their results with the mix designs collected from different cities in the state of Ohio. The scope of this case study was limited to A1-A3 stages of the life cycle system boundaries. In addition, for fly ash and slag, two scenarios of “waste” (burden-free) and economic allocation were employed to assess the effect of allocation rule as a methodological choice. The detailed structure of inputs and components of the model is presented in Figure 7.

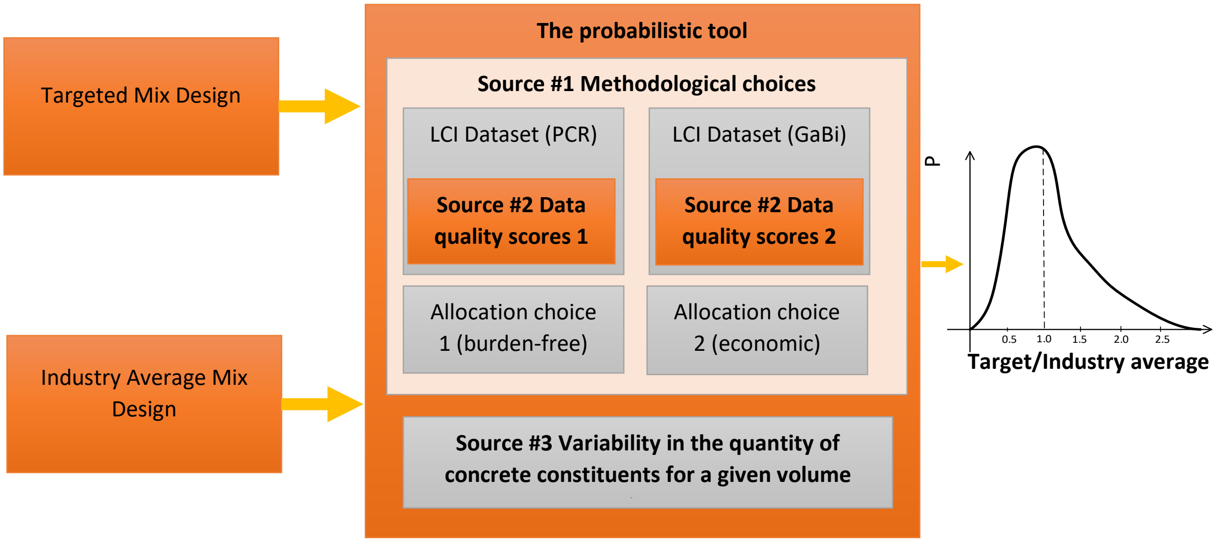


FIGURE 7. SOURCES OF UNCERTAINTY AND VARIABILITY AND THE LOCATION OF EACH SOURCE IN THE PROPOSED FRAMEWORK FOR COMPARING THE GWP IMPACT OF A MIX DESIGN AGAINST THE INDUSTRY AVERAGE ONE.

7.2. Life cycle inventory

For this study, the default LCI data provided in the NA PCR were adapted. As an alternative, GaBi (adapted from Tally® tool 2019) was used as an alternative database for ecoinvent v.3.4, NREL, USLCI, and the ASTM EPDs for PC and slag to assess the effect of database selection on the comparative analysis and the conclusion on the preferred scenario. It should be noted that only the chemical admixtures emissions and their data quality scores were identical due to the lack of an alternative database. The list of different scenarios for the datasets used in this analysis is presented in Table 1.

TABLE 1. LIST OF DATASETS USED FOR DIFFERENT PROCESSES

Flow	Database 1	Database 2
Portland Cement	ASTM EPD	GaBi
Fly Ash	ecoinvent (default value is zero)	GaBi
Slag	ASTM EPD	GaBi
Water	ecoinvent	GaBi
Aggregates	ecoinvent	GaBi
Chemical Admixtures	EFCA[1]	EFCA[1]
Purchased Electricity	Ecoinvent (NERC regions)	GaBi
Site Energy	NREL	GaBi
Transportation (road, water, and rail)	USLCI	GaBi

[1] European Federation of Concrete Admixtures Associations

7.3. Life cycle impact assessment method and interpretation

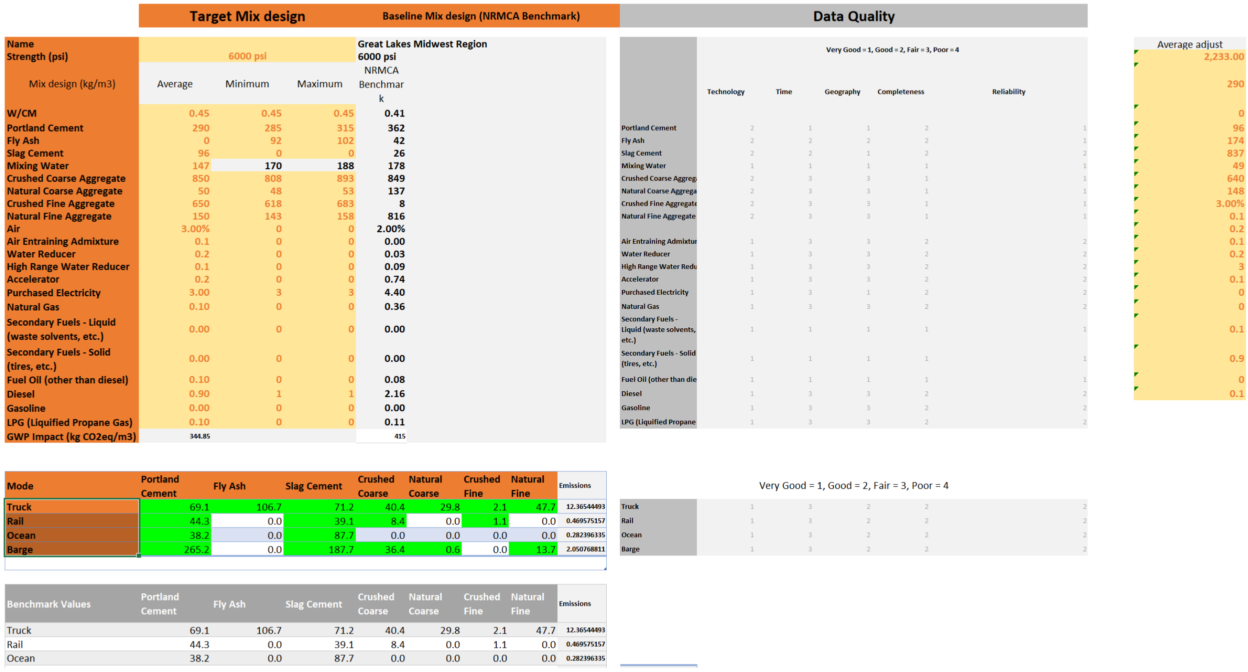
When the LCI was available, the IPCC 2013 characterization factors for GWP100 were adopted for calculating the emission factors. On the other hand, for the product EPDs, the values stated in the EPD were extracted and used as an emission factor for each product.

The sources of uncertainty and variability that were investigated for this case study, is divided into three categories. The first category is the methodological choices (referred to as method in the graphs), which includes database selection and allocation rule for co-products, such as fly ash or slag. For the slag allocation, in the first scenario, only the postprocessing emissions were incorporated. In the second scenario, the economic allocation was applied to partially add the GHG emissions of iron production to the post-processing activities. For fly ash, it was considered either as a burden-free material or the economic allocation rule was applied to assign a portion of GHG emissions associated with electricity generation in a coal powerplant. The variability of concrete constituents is the second source of variation applied to this case study. A discrete uniform distribution was assigned to each of the uncertainty sources due to the methodological choices. The NA PCR specifies a 5% material loss for the A3 stage. Hence, this 5% loss was consistently considered across all the A1-A3 stages as a source of variability. Since no data on the typical loss percentage was available, a continuous uniform distribution was assigned to the variability of the mix design materials. In addition, a sensitivity analysis of the variability source (5% and 10% loss) was also applied to evaluate the extent to which this variability source can affect the decision on the environmentally preferred scenario. The other source of uncertainty investigated in this case study is data quality uncertainty. For the data quality scores, the recommendation in the ecoinvent v.3 report was implemented to estimate the uncertainty associated with each unit process specified in Table 1. Hence, the uncertainty scores presented in Table 2, applied to eq. 3 to calculate the variance of probability distributions.

TABLE 2. DATA QUALITY SCORES ASSIGNED TO UNIT PROCESSES OF STAGE A1-A3 OF THE CONCRETE LIFE CYCLE

Indicator\quality of data	Facility specific	Very good	Good	Fair	Poor
Reliability	0.000	0.001	0.002	0.008	0.040
Completeness	0.000	0.000	0.001	0.002	0.008
Temporal	0.000	0.000	0.002	0.008	0.040
Geographical	0.000	0.000	0.000	0.001	0.002
Further technological	0.000	0.001	0.008	0.040	0.120

These sources and their underlying probability distribution were implemented to the LCA study using Crystal Ball® in the Excel tool. An overview of the developed Excel tool in this study is presented in Figure 8.



	Target Mix design			Baseline Mix design (NRMCA Benchmark)
Name				**Great Lakes Midwest Region**
Strength (psi)	6000 psi			**6000 psi**
Mix design (kg/m3)	Average	Minimum	Maximum	NRMCA Benchmark
W/CM	0.45	0.45	0.45	**0.41**
Portland Cement	290	285	315	**362**
Fly Ash	0	92	102	**42**
Slag Cement	96	0	0	**26**
Mixing Water	147	170	188	**178**
Crushed Coarse Aggregate	850	808	893	**849**
Natural Coarse Aggregate	50	48	53	**137**
Crushed Fine Aggregate	650	618	683	**8**
Natural Fine Aggregate	150	143	158	**816**
Air	3.00%	0	0	**2.00%**
Air Entraining Admixture	0.1	0	0	**0.00**
Water Reducer	0.2	0	0	**0.03**
High Range Water Reducer	0.1	0	0	**0.09**
Accelerator	0.2	0	0	**0.74**
Purchased Electricity	3.00	3	3	**4.40**
Natural Gas	0.10	0	0	**0.36**
Secondary Fuels - Liquid (waste solvents, etc.)	0.00	0	0	**0.00**
Secondary Fuels - Solid (tires, etc.)	0.00	0	0	**0.00**
Fuel Oil (other than diesel)	0.10	0	0	**0.08**
Diesel	0.90	1	1	**2.16**
Gasoline	0.00	0	0	**0.00**
LPG (Liquified Propane Gas)	0.10	0	0	**0.11**
GWP Impact (kg CO2eq/m3)	344.85			415

Data Quality

Very Good = 1, Good = 2, Fair = 3, Poor = 4

	Technology	**Time**	**Geography**	**Completeness**	**Reliability**
Portland Cement	2	1	1	2	1
Fly Ash	2	2	2	2	1
Slag Cement	2	2	1	2	2
Mixing Water	1	1	1	1	1
Crushed Coarse Aggreg	2	3	3	1	1
Natural Coarse Aggrega	2	3	3	1	1
Crushed Fine Aggregate	2	3	3	1	1
Natural Fine Aggregate	2	3	3	1	1
Air Entraining Admixtur	1	3	3	2	2
Water Reducer	1	3	3	2	2
High Range Water Redu	1	3	3	2	2
Accelerator	1	3	3	2	2
Purchased Electricity	1	3	1	2	2
Natural Gas	1	3	3	2	2
Secondary Fuels - Liquid (waste solvents, etc.)	1	1	1	1	1
Secondary Fuels - Solid (tires, etc.)	1	1	1	1	1
Fuel Oil (other than die	1	1	1	1	1
Diesel	1	3	3	2	2
Gasoline	1	3	3	2	2
LPG (Liquified Propane	1	3	3	2	2

Average adjust
2,233.00
290
0
96
174
837
49
640
148
3.00%
0.1
0.2
0.1
0.2
3
0.1
0
0
0.1
0.9
0
0.1

Mode	**Portland Cement**	**Fly Ash**	**Slag Cement**	**Crushed Coarse**	**Natural Coarse**	**Crushed Fine**	**Natural Fine**	**Emissions**
Truck	69.1	106.7	71.2	40.4	29.8	2.1	47.7	12.36544493
Rail	44.3	0.0	39.1	8.4	0.0	1.1	0.0	0.469575157
Ocean	38.2	0.0	87.7	0.0	0.0	0.0	0.0	0.282396335
Barge	265.2	0.0	187.7	36.4	0.6	0.0	13.7	2.050768811

Very Good = 1, Good = 2, Fair = 3, Poor = 4

Truck	1	3	2	2	2
Rail	1	3	2	2	2
Ocean	1	3	2	2	2
Barge	1	3	2	2	2

Benchmark Values	**Portland Cement**	**Fly Ash**	**Slag Cement**	**Crushed Coarse**	**Natural Coarse**	**Crushed Fine**	**Natural Fine**	**Emissions**
Truck	69.1	106.7	71.2	40.4	29.8	2.1	47.7	12.36544493
Rail	44.3	0.0	39.1	8.4	0.0	1.1	0.0	0.469575157
Ocean	38.2	0.0	87.7	0.0	0.0	0.0	0.0	0.282396335

FIGURE 8. OVERVIEW OF THE DEVELOPED TOOL FOR COMPARATIVE ANALYSIS OF THE CONCRETE MIX DESIGNS

7.4. Results and discussion

7.4.1. Stand-alone results of industry benchmarks

The probabilistic results of industry benchmark mix designs for three compressive strengths of 4,000, 5,000, and 6,000 psi for the Great Lakes Midwest region are presented in Figure 9. It should be noted that the results of other benchmark mix designs are provided in the SI3 (Excel file). The results show that while the base case GWP values (continuous line on the whisker-box plot) are quite distinguished, there is a significant overlap among the GWP range of mix designs.

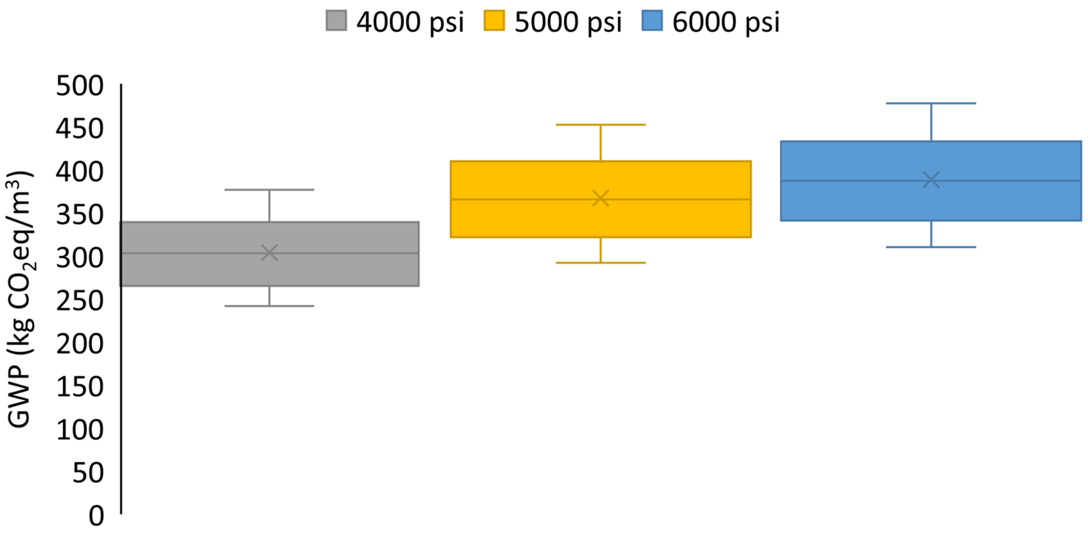


FIGURE 9. GWP IMPACTS OF THE GREAT LAKES BENCHMARK MIX DESIGNS INCORPORATING THE UNCERTAINTY SOURCES FOR THREE LEVELS OF COMPRESSIVE STRENGTH

To understand the extent to which a source of uncertainty or variability can contribute to the variances, a global sensitivity analysis was conducted, and the results are presented in Figure 10. Analogously, the major contributor to the variance is the methodological choices (database selection) for portland cement and the data quality for portland cement modeling. These two sources contribute to more than 97% of the total variance. Therefore, once a practitioner attempts to improve the confidence in the "stand-alone" GWP results of concrete mix designs, it will be critical to improve the data quality of portland cement and to specify a methodological choice for the portland cement process. These two proposed efforts have been already well discussed and implemented in the recently published PCR for ready-mixed concrete. The second major contributor, as shown in Figure 10, there is an opportunity to improve the data quality associated with truck transportation. Although the dataset for the transportation system belongs to a geographical context of North America, the temporal correlation of the process has a score of 3 indicating that an update may be required to reduce the uncertainty associated with the transportation of materials.

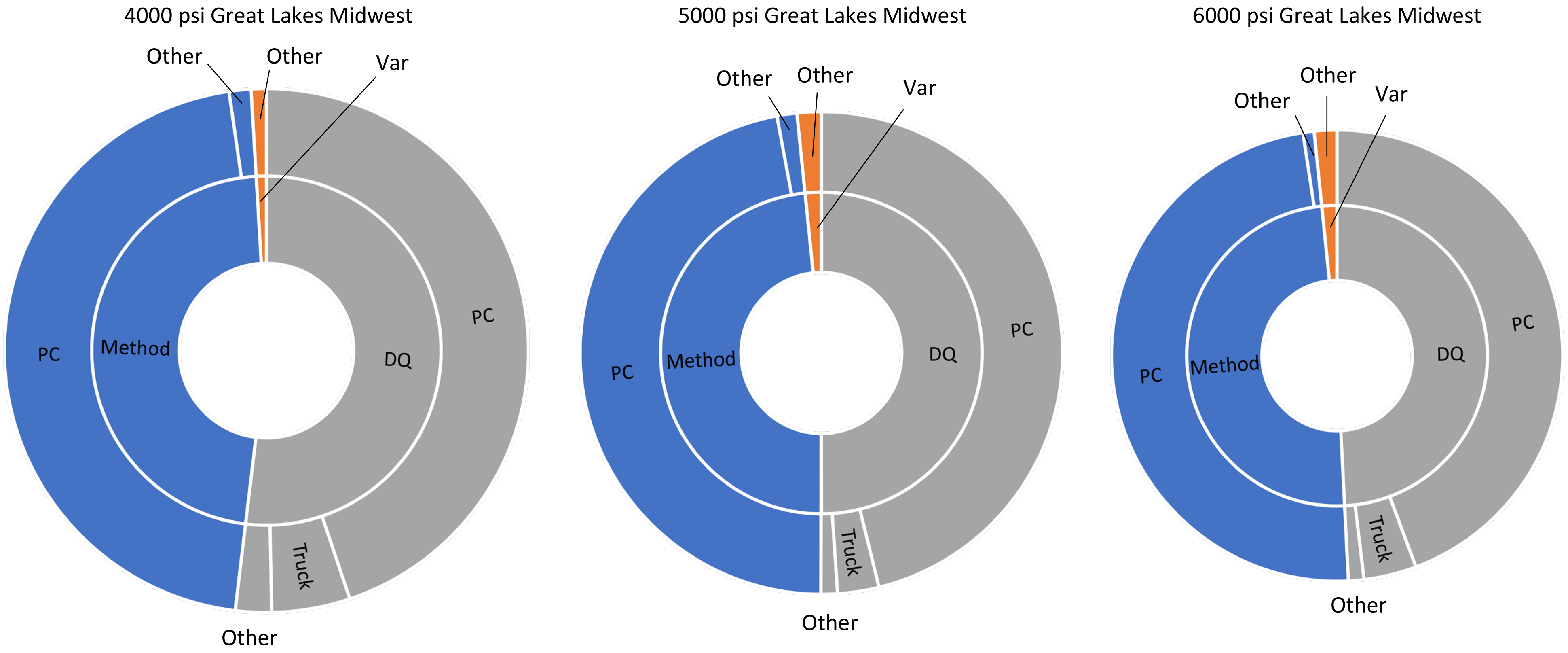


Figure 10. Contribution of uncertainty and variability sources to variance of the three benchmark mix designs (4000, 5000, and 6000 psi) with 5% materials variability (DQ = data quality, PC = portland cement, Method = methodological choices, Var = variability).

7.4.2. Deterministic comparative results of Ohio mix designs vs. the Great Lakes Midwest benchmarks

In order to understand the range of GWP impact exist in the mix design populations, the deterministic impact of mix design was calculated and compared against the industry benchmark results. The deterministic results were calculated since it is the way that environmental results are reported in EPDs. The details about the binder percentage of the mix designs and their corresponding GWP impact are provided in the SI4 (Excel file). As shown in Figure 11, there is a range of GWP impact for a given class of compressive strength. For the 4000 psi mix designs, for all the mix designs that the PC replacement rate is larger than 35%, the GWP impact is lower than the benchmark value (the replacement rate in the benchmarks is around 10% slag and 5% fly ash). The minimum percentage of replacement materials (slag and fly ash) for the 5000 psi and 6000 psi mixtures that result in a lower GWP impact than the benchmark is 20%.

All the mix designs that have a higher GWP impact than that of the benchmark are only incorporated PC or have a binary binder. Moreover, none of the ternary mixtures in these three classes of compressive strength has a higher GWP impact than the benchmark values. While the attention of the concrete industry is mostly towards reducing the PC content by incorporating different SCMs, achieving a lower GWP may be more impactful if the synergistic effect of different SCMs will be taken into account. This environmental advantage of using ternary mixtures was addressed in Azarijafari et al. [16]. In fact, considering the benefits and disadvantages of each SCM, the simultaneous use of these materials can improve the mechanical and durability performance of mixtures while enabling users to use a lower quantity of PC to achieve the minimum design performance. Considering the current limitations in the practical levels of achieving a minimum threshold for concrete specification, the incorporation of ternary blended types of cement in the mixtures can be an alternative to effectively reduce the GHG emissions associated with the A1-A3 scope of the concrete life cycle.

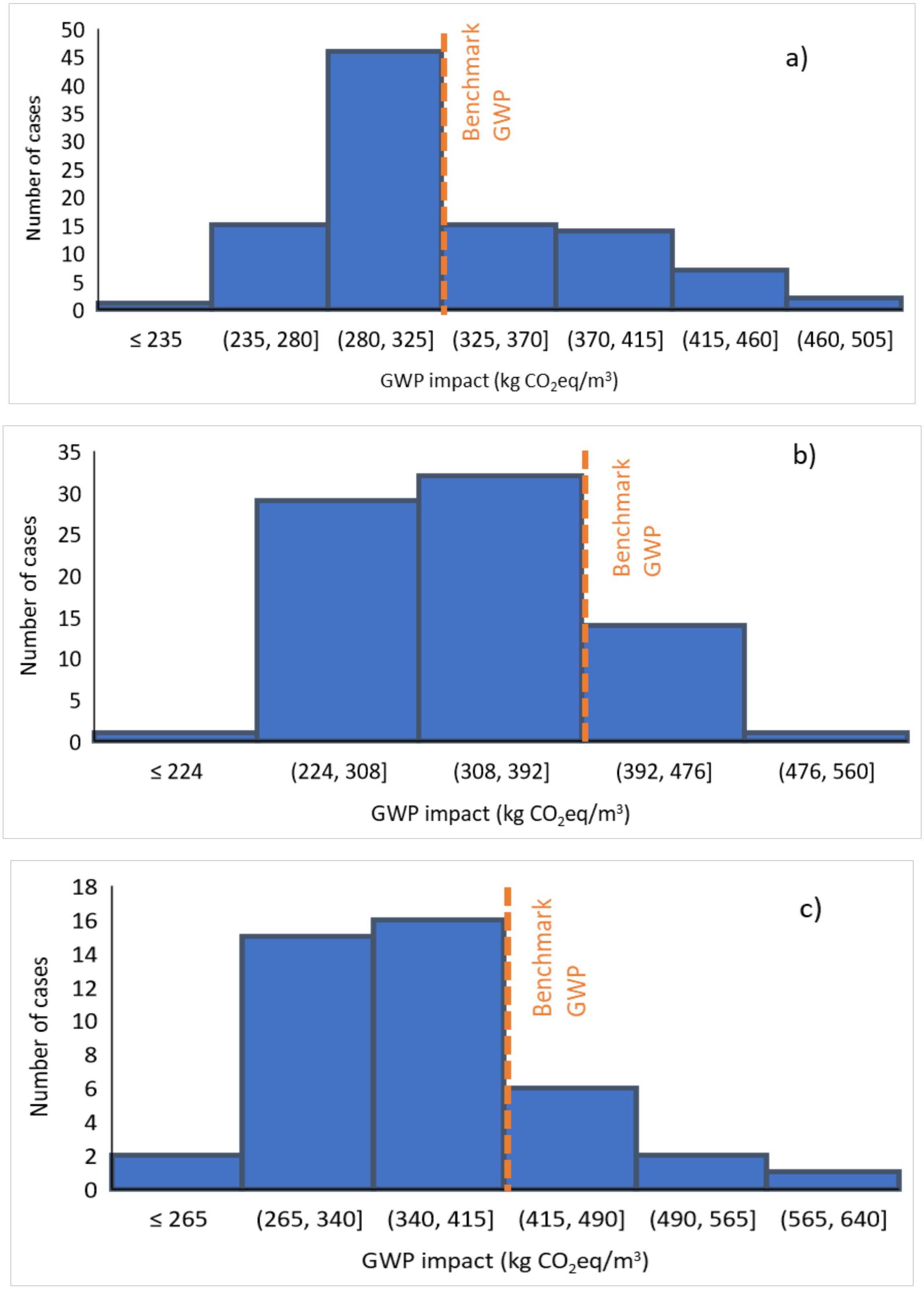


Figure 11. GWP impacts of the mix designs with design compressive strength of a) 4000 psi (n = 100), b) 5000 psi (n = 77), and c) 6000 psi (n = 42) without the incorporation of uncertainty and variability sources

7.4.3. Probabilistic comparative results of Ohio mix designs vs. the Great Lakes Midwest benchmarks

With the incorporation of uncertainty and variability in the decision-making process, the robustness of the conclusion on the environmentally preferred scenario was assessed. Table 3 presents the share of cases that did not satisfy the specific confidence in the results. In fact, the percentages reflect the number of cases within each compressive strength level and under different assumptions which will give an “unresolved” conclusion on whether the GWP impact of the mixture is lower or higher than the benchmark. As shown in Table 3, the conclusion on whether the GWP impact of the target mix design is lower than that of the benchmark cannot be robustly determined on the 8-31% of the mix designs if the accepted robustness corresponds to 90% of the RI samples. For the 6,000 psi mixtures, the 10% variability induces a significant amount of uncertainty on the RI values, increasing the unresolved comparison share from 12% to 31% of the total population.

TABLE 3. SHARE OF CASES THAT DID NOT GIVE THE SPECIFIC CONFIDENCE (β_{crit}) IN THE RESULTS

Compressive grade	β_{crit} = 0.7		β_{crit} = 0.8		β_{crit} = 0.9	
	Variability = 5%	Variability = 10%	Variability = 5%	Variability = 10%	Variability = 5%	Variability = 10%
4000 psi (n = 100)	9%	13%	10%	17%	13%	19%
5000 psi (n = 77)	4%	5%	4%	6%	5%	8%
6000 psi (n = 42)	5%	17%	12%	21%	12%	31%

Looking deeper into the probabilistic analysis of individual mix designs (SI4), the robustness threshold (β_{crit}) of the decision on the comparative results of those 4,000-psi mix designs that have a range of 314-342 kg CO_2eq (vs. 325 kg CO_2eq for benchmark mix design) is not satisfied. This range for the 5000-psi mixtures is 367-407 kg CO_2eq (vs. 392 kg CO_2eq for benchmark mix design). For the 6,000-psi mixture, a wider range of unresolved cases is observed, whose GWP impacts vary from 400-442 kg CO_2eq, while the calculated benchmark result shows a value of 412 kg CO_2eq/m^3. Interestingly, all the unresolved mix designs for the three levels of compressive strength incorporates either a binary (fly ash or slag) or only PC as a binder. Therefore, as discussed in the deterministic comparative results, owing to the significant environmental improvements associated with ternary blended mixtures, the conclusion may not be affected by the introduced uncertainty and variability.

To improve the robustness of the conclusion, it is required to understand and prioritize the sources of variations in the real world and also within the system boundaries of LCA. This prioritization can provide a guideline about where the efforts and resources should be implemented. The results of contribution to variance show that the most significant source of variation is different from one mix design to another. In fact, the GWP results in the mixtures without any SCM can be varied mainly because of the 5% variability in the mix design constituents and it mostly stems from the PC variability. It should be noted that when a facility intends to generate an EPD from a mix design, the mix design will be deterministically defined. So, any variability would be due to natural variation (i.e. no intention of changing the mix design). For example, the mix may unintentionally have 10 kg more aggregate than the stated mix design but since this was done unknowingly, there would be no intention to alter the quantities of other inputs. However, to have a realistic result and to assess the robustness of the conclusion, it is required to incorporate the mix design variability in this probabilistic assessment.

The contribution to variance in those binary mixtures that only incorporate fly ash as an SCM is similar to that of PC-only mixtures. Since fly ash is considered as a burden-free component of the mixtures, there is no uncertainty and variability associated with this material in the waste-allocation rule. Also, in the economic allocation rule, fly ash has a negligible GWP impact (around 1% of the electricity generation from the coal powerplant). In addition, the quality scores of the coal powerplant inventory is a recent, and complete one update which can be reliable, and an appropriate representative of the geographical, temporal and technological context. Therefore, there is a trivial contribution from fly ash to the total variance. On the contrary, the LCI data for downstream activities of slag manufacturing processes was developed five years ago and needs to be updated to improve the data quality scores related to the temporal, technological and completeness categories. Hence, for the mix designs incorporating a considerable amount of slag (herein 35%), the data quality role is playing a major role in the variance due to the mediocre correlation of the dataset. For future investigations, the quality of data for slag grinding and other post-processing activities is proposed as a priority for updating and therefore, efficiently reducing the uncertainty. While the methodological selection plays a significant role in the variation of the GWP impact of stand-alone mix designs (Figure 10), it may not be the case for a comparative analysis of concrete as shown in Figure 12-14. As concerns are rising about the selection of allocation rule for co-products, such as slag and fly ash, the economic allocation and no allocation of GWP impact associate with the main process of iron production and electricity generation from a coal source may not be as important as the variability and data quality of LCI.

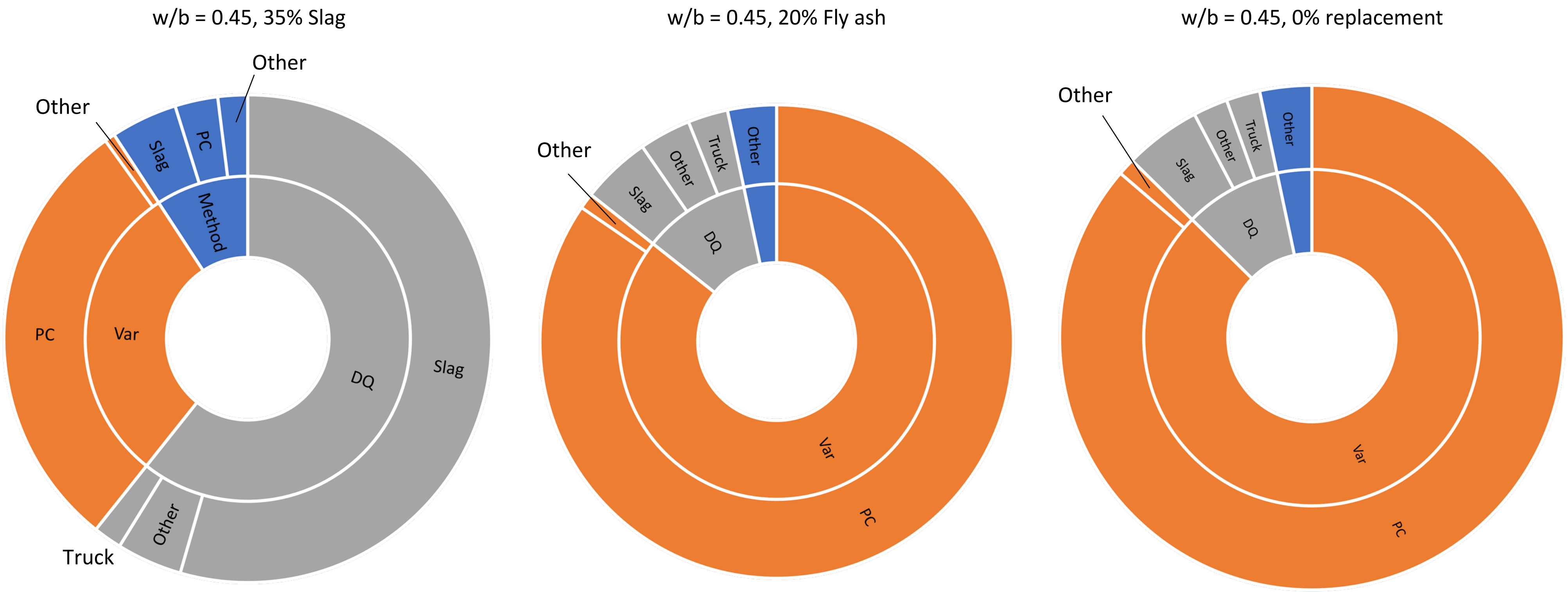


Figure 12. Contribution of uncertainty and variability sources to the variance of the comparative results for three cases with compressive strength of 4000 psi and 5% materials variability (DQ = data quality, PC = portland cement, Method = methodological choices, Var = variability).

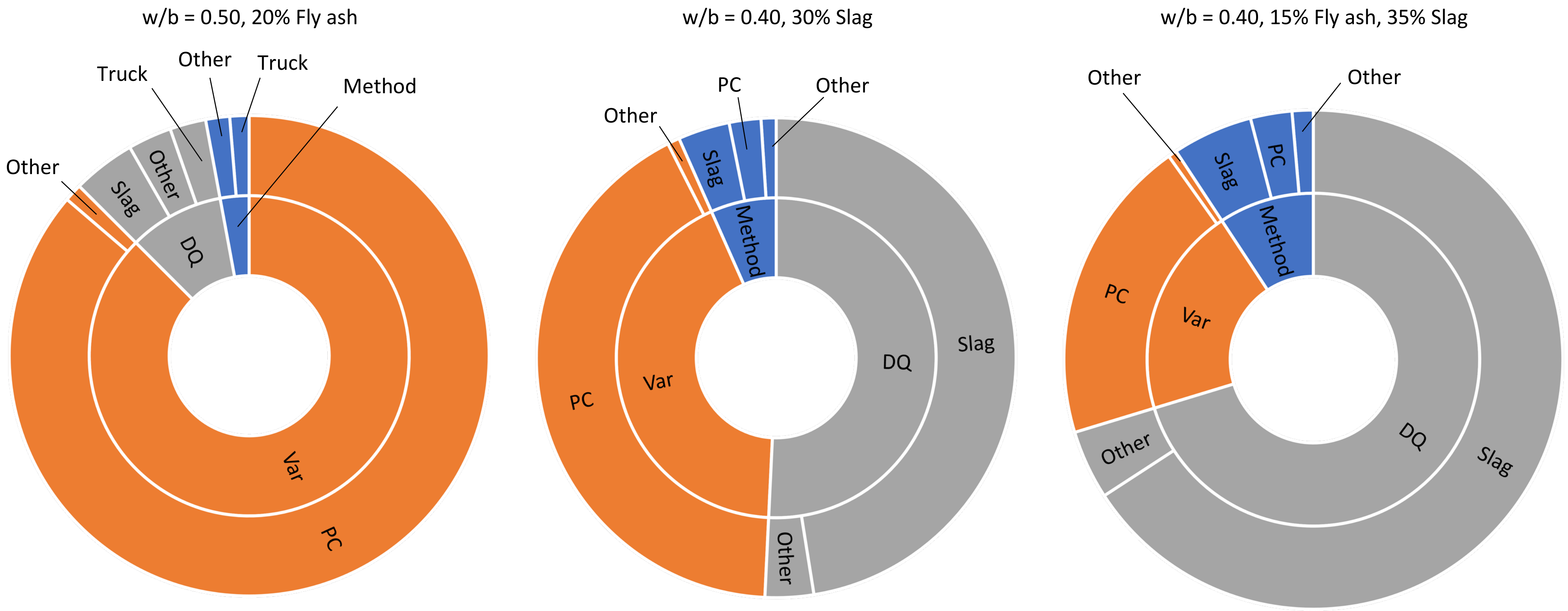


FIGURE 13. CONTRIBUTION OF UNCERTAINTY AND VARIABILITY SOURCES TO THE VARIANCE OF THE COMPARATIVE RESULTS FOR THREE CASES WITH COMPRESSIVE STRENGTH OF 5000 PSI AND 5% MATERIALS VARIABILITY (DQ = DATA QUALITY, PC = PORTLAND CEMENT, METHOD = METHODOLOGICAL CHOICES, VAR = VARIABILITY).

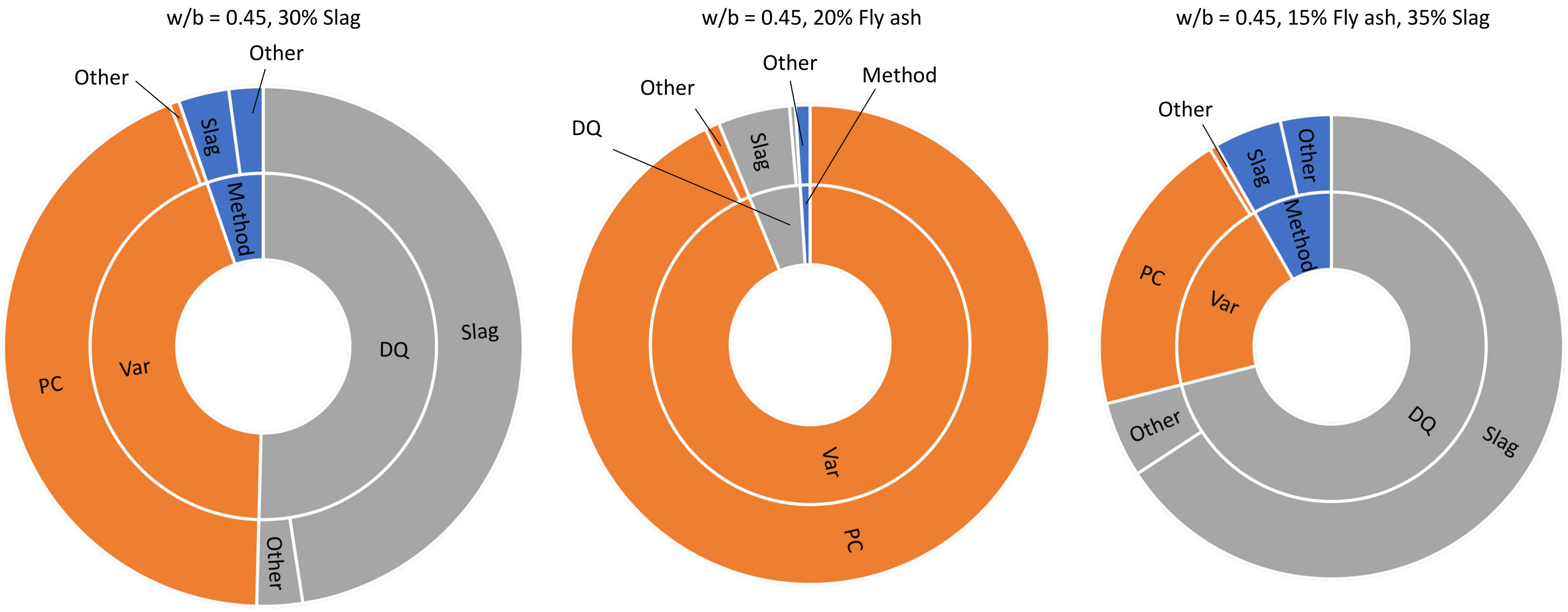


FIGURE 14. CONTRIBUTION OF UNCERTAINTY AND VARIABILITY SOURCES TO THE VARIANCE OF THE COMPARATIVE RESULTS FOR THREE CASES WITH COMPRESSIVE STRENGTH OF 6000 PSI AND 5% MATERIALS VARIABILITY (DQ = DATA QUALITY, PC = PORTLAND CEMENT, METHOD = METHODOLOGICAL CHOICES, VAR = VARIABILITY)

8. Conclusions and outlook

The goal of concrete EPDs is to enable comparisons of the performance of different mix designs. However, the LCA methodology of concrete EPDs in the current shape may not adequately help decision-makers have a robust comparative analysis of the environmental results of concrete mix designs. To identify the sources of discrepancies such as methodological choices and life cycle inventory, a meta-analysis of EPDs was performed through a review of the currently published EPDs and their underlying PCR documents. The GWP impact and batching water inventory were selected and the meta-analysis was conducted through a compilation of 2,892 concrete mix designs presented in the EPDs (verified and published by NRMCA). The methodological framework and criteria related to system harmonization were categorized into different stages of conducting LCA according to the ISO 14044 framework. Then, the parameters defined for the system and the technical harmonization was employed to minimize the difference in scope, assumptions, data sources, and calculation procedure for life cycle assessments of the same products. Following the meta-analysis, this study proposed a method for a robust, probabilistic and comparative assessment of concrete environmental results that can be applied to any other construction products. To do so, the proposed method for LCA calculation was developed considering the requirements of the ISO standards and based on the life cycle inventory proposed in the underlying PCR. Then, a probabilistic method was developed and implemented to enable users to have a robust comparison of the EPD results with those in the industrial benchmark. 219 concrete mix designs with three different levels of compressive strength were adapted to compare the global warming potential (GWP) impact of mixtures against those of industry average. Moreover, data quality assessments of background life cycle inventory data, which are reported in EPDs but are not used in a quantitative way to assess its impact on results, were incorporated into the probabilistic analysis.

The meta-analysis results show that although the reported GWP impact of mixtures may exert a consensus with the ranges of GHG emission reported in the technical and scientific literature, the CBW inventory remains an ambiguous question as for major of the mixtures since a value of less than 0.1 m^3/m^3 batching water was reported (52% of the total published mixtures). Although there is no clarification for the assumptions, an idea is that only the added water at the batching plant (and not the water added on site) is included in the EPD calculation. Regardless of the reason, a reconsideration for third-party reviewing seems necessary. The differences in the LCA inventory, methodological choices, and specifications of the concrete of EPDs and industry benchmarks were identified as the sources of uncertainty and variability in the published EPDs.

The deterministic results show that the uncertainty and variability sources can induce an overlap among the GWP results of the concrete benchmark mixtures with different compressive strengths (4000, 5000 and 6000 psi). The major source of variation in the stand-alone LCA results comes from the methodological choice category. On the other hand, the slag data quality and variability play a major role in the variance of comparative results. Therefore, as long as the LCI database is representative of the context, the methodological choices may be a minor concern in the comparative analysis, which in line with other conclusions, offers an understanding of the important criteria for making a robust comparative analysis of EPDs. Also, the GWP results in the mixtures without any SCM can vary as the portland cement variability plays a major role in the variance. The GWP impact of all ternary blended mixtures was shown to be statistically lower than that of the industry benchmark mix designs.

We use this framework to show how LCA practitioners and concrete EPD consultants can confidently compare future versions of EPDs that comply with comparative assertion requirements outlined in standards and find the key drivers of differences among alternatives. Moreover, we detail how program operators and committees can identify the changes to PCRs (e.g. ASTM WK56699 "New Specification for Selecting a Sustainability-Related Certification or Rating System") required to achieve the comparative analysis of EPDs. The flexibility and simplicity of this methodology enable the potential users to implement this framework to any EPD software tools to "explore" the difference between alternatives and to "confirm" a decision on the preferred scenario. Future research can focus on the integration process of this method to the EPD software tool.

9. Research outcomes

Journal Publication:

- Towards comparable environmental product declarations of construction materials: insights from a probabilistic comparative LCA approach (Submitted)

Conference presentation:

- "Developing a Harmonized and Probabilistic Tool for Comparative Analysis of the Environmental Product Declarations: A Case Study of Concrete Embodied Carbon"; ACLCA 2020 Virtual Conference; September 2020; USA.

- “Enabling Comparability of Environmental Product Declarations Through Harmonization: A Case Study of Concrete”; LCA XVX Conference; Tucson; September 2019; USA.
- “Assessing the comparability of concrete Environmental Product Declarations (EPDs) through a probabilistic analysis”; ACI 123- Research in Progress, ACI Fall Convention; Cincinnati; October 2019; USA.
- “Why do we need a harmonization and probabilistic analysis of structural concrete EPDs?”; LCA^2 Initiative - TC14. Using EPDs for product and whole-building LCA comparisons - comparability issues, National Research Council of Canada, January 2020.

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