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Sustainability Evaluation of Concrete Materials Utilizing the Desirability Approach with Varying Function Shapes

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Abstract

To address sustainability issues, concrete design and specification must consider a variety of evaluation criteria, necessitating analytical methods that can optimize mixes to meet performance requirements while maximizing sustainability. This paper proposes the desirability approach, a multi-response optimization technique, as a new method for the sustainability evaluation of concrete materials. A demonstration study, using four sustainability indicators and six concrete mixes with varying binder compositions and aggregate types, is presented that explores how changing the shape of the desirability function, which translates indicator values to desirability, affects the sustainability evaluation output. Treating the function shapes as a source of uncertainty, sustainability evaluation is conducted with uncertainty analysis to produce a sustainability score distribution for each mix, which is described by statistical measures. Mixes with the highest and lowest indicator values exhibited the least variance in their scores, as these values were unaffected by the function shape. Sensitivity analysis, which measures the contribution of the sources of uncertainty to the total output uncertainty, found that the interactions when varying multiple function shapes simultaneously were the most influential source of uncertainty, which may be caused by multi-collinearity among the indicators. It was also found that sustainability scores calculated by geometric aggregation were lower than those calculated by linear aggregation.

1. Introduction

1.1 Sustainability challenges of concrete

The sustainability challenges facing concrete materials are diverse (Sakai and Noguchi 2013). The most critical issue is concrete’s contribution to climate change, as the industry is responsible for approximately 9% of total global greenhouse gas emissions (OECD 2019). Concrete is also estimated to account for up to 4% of global energy use (Hooton and Bickley 2014), and these are both expected to increase in the future as demand for cement and concrete continues to rise (Imbabi et al. 2012). The extraction of natural resources, such as sand, gravel, crushed rock, and water, for usage in concrete is also projected to dominate worldwide resource consumption (Torres et al. 2017), and demand may overwhelm natural reserves, especially in countries facing freshwater supply issues (Miller et al. 2018).

The aforementioned issues may be tackled at the material design and specification stage in multiple ways. The replacement of Portland cement, which is the primary contributor of CO₂, NOx, SOx, particulate matter, and other emissions, as well as the most energy-intensive constituent material, with supplementary cementitious materials and blended cements has long been considered one of the primary approaches to improving the sustainability of concrete (Mehta 1998, 1999). The optimal utilization of these materials may reduce the CO₂ footprint of concrete by up to 50%, compared to traditional Portland cement (Aïtcin and Mindess 2011), with a comparable reduction in energy consumption. Other CO₂ and GHG mitigation strategies include optimal aggregate gradation and the use of water reducing admixtures to reduce the cement paste content (Hooton and Bickley 2014), which also contributes to reducing the water consumption in concrete.

Aggregates, which comprise the bulk of the concrete volume, may also be replaced with a wide variety of waste and recycled materials to reduce the intensity of raw material consumption in concrete. Recycled concrete aggregates, which are produced by crushing hardened waste concrete, have received particular attention as one solution to the concrete sustainability problem, as their usage can greatly reduce the usage of natural resources while also diverting usable materials from waste disposal facilities (Akhtar and Sarmah 2018). However, higher quality recycled aggregates require a greater energy investment in the recycling process, leading to a complicated trade-off between concrete performance, raw materials consumption, and energy consumption when considering the usage of recycled aggregates in concrete (Henry et al. 2011).

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1.2 Sustainability evaluation for concrete materials

To support sustainable decision-making in material specification and design, it is necessary to quantitatively evaluate the sustainability of concrete materials to identify the optimal, or “most sustainable” constituent materials and mix proportions, while at the same time meeting the specified performance requirements. This evaluation is important because the sustainability of concrete spans multiple dimensions, and the means for improving concrete sustainability affect these dimensions in differing, and sometimes conflicting, ways.

As environmental issues are among the most challenging in the concrete field, much effort has focused on quantifying the environmental dimension of concrete sustainability. Among the approaches reported in literature, Life Cycle Assessment (LCA), as established by the ISO 14000 series, has emerged as a valuable tool for evaluating and managing the environmental performance of concrete across its life cycle. The principles of LCA serve as the basis of ISO 21930 (Sustainability in building construction - Environmental declaration of building products) as well as ISO 13315-1 (Environmental management for concrete and concrete structures Part 1: General principles) that tailor the LCA methodology to the concrete field. Numerous examples of the application of LCA to both concrete materials (Kim et al. 2016; Mohammadi and South 2017) and concrete structures (Kawai et al. 2005b; Yeo and Potra 2017) have been reported.

The ISO standards do not cover the social and economic aspects of sustainability, however, and thus it is necessary to explore a broader set of indicators that represent better the multi-dimensionality of concrete sustainability. This process may be guided by documents such as the CEN EN 15643 series “Sustainability of construction works” and “Sustainability assessment of buildings and civil engineering works” that provides guidelines for the selection of appropriate environmental, social and economic indicators to be used in sustainability evaluation. However, interpretation of evaluation results becomes increasingly complicated as an indicator set grows in size, so composite indices, which aggregate individual indicators into a single value, are often adopted to represent overall sustainability performance. Single values make the comparison of decision alternatives more straightforward, which facilitates interpretation by, and engagement with, the general public and policy makers (Martin 2015; Burgass et al. 2017). In the growing literature on the sustainability evaluation of concrete, various methods have been adopted for calculating composite values to represent multidimensional sustainability characteristics. For example, normalized values, such as benefit to cost ratio, and weighted means have been applied to both small and large indicator sets (Müller et al. 2014; Rageh et al. 2017; Konečný et al. 2020). Multicriteria decision-making approaches, such as analytic hierarchy process and TOPSIS (Henry and Kato 2011; Moretti et al. 2017; Rashid et al. 2017), as well as statistical techniques, such as conjoint analysis and fuzzy logic (Kawai et al. 2005a; Caño et al. 2016), have also been used to reflect multiple characteristics in the sustainability evaluation.

However, aggregation leads to information loss by masking the behaviors of the underlying indicators (Saisana et al. 2005), as well as raises issues related to compensability when indicators exhibit conflicting behaviors. The latter is particularly critical when considering whether to adopt a weak sustainability approach, wherein substitution between indicators is permitted as long as the total performance is maintained or improved (Wu 2013), versus a strong sustainability approach, wherein environmental degradation cannot be substituted with other performance improvements (Mayer 2008).

1.3 Research problem and objectives

This research explores a new method for the sustainability evaluation of concrete materials using the desirability approach to aggregate individual sustainability indicators into a single composite value, or sustainability score. The desirability approach, proposed by Derringer and Suich (1980) based on the earlier work of Harrington (1965), is a method for simultaneous optimization of multiple response variables. Optimization is a common challenge in the field of construction materials, wherein the goal is to identify the design values that provide the “best” performance characteristics, and desirability-based approaches to the optimization of various materials have been reported in literature (Kim and Lin 2000; Şimşek et al. 2013; Bhaumik and Maity 2017). This multi-response optimization approach is thus ideally suited for identifying the “most sustainable” constituent materials and mix proportions under a given set of design requirements, as it can determine which combination results in the most optimized sustainability characteristics.

A key characteristic of the desirability approach is the ability to define the relationship between each indicator and its desirability through the “desirability function”. However, the selection of the shape of the desirability function is a subjective judgement, and different shapes will produce differing desirability values for the same indicator values. Uncertainty arising from the selection of the desirability function shape may then propagate to the evaluation results, which creates uncertainty in the sustainability evaluation of concrete materials when using the desirability approach. However, if this uncertainty is quantified, then this information can be used by the decision maker to improve the robustness and reliability of the sustainability evaluation process.

The objective of this research is therefore to clarify how uncertainties arising from the shape of the desirability functions impact the sustainability evaluation of concrete materials utilizing the desirability approach. This is achieved by carrying out a demonstration study using a set of concrete materials with varying binder
compositions and aggregate types, and the uncertainty caused by differing desirability shape functions is quantified and examined using variance-based uncertainty and sensitivity analyses. In addition, two different methods for aggregating the desirability values, which reflect weak and strong approaches to sustainability, are also tested to explore how the degree of compensability affects the sustainability evaluation results calculated by the desirability approach.

2. Sustainability evaluation methodology

2.1 Mix proportions of concrete material alternatives

To demonstrate the sustainability evaluation of concrete materials utilizing the desirability approach, a set of six concrete material alternatives, with differing sustainability characteristics, was constructed. First, three concrete mixes were sampled from Noguchi et al. (2009), with a target compressive strength of 30 MPa at 28 days. The mix proportions are given in Table 1 as mixes Ref, B1, and F1, and represent concretes with binder compositions of ordinary portland cement (OPC) only, OPC and blast furnace slag (BFS), and OPC and fly ash (FA), respectively.

Three additional mixes were generated assuming full replacement of normal coarse aggregates (NG) with high-grade (class H) recycled coarse aggregates (RG). These are shown as mixes A, B2, and F2 in Table 1. The Japan Industrial Standard (JIS A 5021) specifies that high-grade recycled aggregates perform equivalently to normal aggregates in the concrete matrix; as such, compressive strengths were assumed to remain the same as the mixes with normal aggregates.

2.2 Selection of sustainability indicators

The sustainability of concrete may be evaluated using indicators, which represent an adopted sustainability paradigm by a set of discrete, measurable criteria (Azapagic 2004). However, there are numerous issues to be considered in the selection of sustainability indicators, including availability of data, feasibility of measurement, and appropriateness and representativeness of the indicator set (Hak et al. 2012; Wu and Wu 2012).

To facilitate indicator selection for the sustainability of concrete materials, Opon and Henry (2019) developed a holistic framework consisting of 65 quantitative indicators. These “sustainable concrete material indicators” or SCMI s, were categorized as driving force, state and impact indicators, and aggregated into a causal network that revealed their interrelationships. This network showed that just four indicators serve as the “driving force” underlying the sustainability of concrete materials: consumption of raw materials; recovered, recycled or waste material content; water consumption; and primary energy consumption. Furthermore, they span the three pillars of environment, society, and economy, as well serve as the basis for all other SCMIs, and thus can be judged as the most basic, yet still comprehensive, indicator set for concrete sustainability.

Considering the balance between indicator quantity, ease of analysis, inventory data availability, and overall representativeness, the four driving force SCMIs were adopted for this sustainability evaluation (Table 2). It is noted that these four indicators will also facilitate measurement of concrete’s contribution to three Sustainable Development Goals (SDGs): clean water and sanitation, affordable and clean energy, and responsible consumption and production.

2.3 Characterization of concrete material alternatives

The sustainability characteristics of the six concrete material alternatives were calculated from the mix pro-
portions using inventory data (Table 3) available from the Japan Society of Civil Engineers (JSCE) and the Life Cycle Assessment Society of Japan. The calculation was carried out focusing on the production stage of concrete, and considered only the footprints attributable to the individual constituent materials. Table 4 summarizes the calculated indicator values for each alternative, with a functional unit of one cubic meter of concrete. It can be seen that the water consumption (W) varies the least across the concrete material alternatives, with a coefficient of variation (COV) of just 1.9%. In contrast, the recovered, recycled or waste materials consumption (R) varies the most, with a COV of 81.4%.

The correlation between the sustainability indicators was examined by Pearson’s correlation coefficient (Fig. 1). Raw materials consumption (M) and recovered, recycled or waste materials consumption (R) exhibited a nearly perfect negative correlation, as may be expected due to replacement of Portland cement and normal aggregates by alternative cementitious materials and recycled aggregates, respectively. Energy consumption (E) had a strong negative correlation with raw materials consumption (M) and water consumption (W), and a strong positive correlation with recovered, recycled or waste materials consumption (R). While these four indicators conceptually represent the fundamental driving forces of concrete sustainability, this result confirms that they are not wholly independent of one another. Some literature suggests reducing such multi-collinearity in the dataset by applying correction factors to avoid “double counting” (OECD 2008). However, due to the conceptual value of these indicators as driving forces, all four will be retained for the subsequent sustainability evaluation.

### 2.4 Evaluation by the desirability approach

The desirability approach assigns an individual desirability value to each response variable using a desirability function, which defines the relationship between the response and its desirability. Various functional goals are available depending on the context of the multi-response optimization problem, such as target value, minimization, maximization, within range, and so forth.

Considering the sustainability issues facing the concrete industry, minimization (the smaller the better) and maximization (the larger the better) are adopted in this evaluation. Minimization [Eq. (1)] is applied when a decrease in an indicator contributes positively to sustainability, such as raw materials consumption (M), water consumption (W), energy consumption (E), and maximization [Eq. (2)] is applied when an increase in an indicator contributes positively to sustainability, such as recovered, recycled or waste materials consumption (R).

![Fig. 1 Correlation matrix for the indicator values of the concrete materials.](image)

### Table 3 Inventory values for constituent materials.

| Indicator | Unit | OPC | BFS | FA | W | NG | RG | S |
|-----------|------|-----|-----|----|----|-----|-----|-----|
| M (kg/kg) | 1.17 | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 1.00 | 1.00 |
| R (kg/kg) | 0.38 | 1.00 | 1.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 |
| W (kg/kg) | 0.00 | 0.00 | 0.00 | 1.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| E (MJ/kg) | 3.40 | 0.58 | 0.43 | 0.00 | 0.05 | 0.38 | 0.07 | 0.07 |

### Table 4 Indicator values for the concrete materials and associated descriptive statistics.

| Mix | M (kg/m³) | R (kg/m³) | W (kg/m³) | E (MJ/m³) |
|-----|-----------|-----------|-----------|-----------|
| Ref | 2225.8 | 123.8 | 184.0 | 1213.0 |
| A   | 1162.8 | 1186.8 | 184.0 | 1563.8 |
| B1  | 2005.3 | 209.2 | 192.0 | 861.8 |
| B2  | 1039.9 | 1174.6 | 192.0 | 1180.4 |
| F1  | 2075.1 | 184.8 | 186.7 | 956.8 |
| F2  | 1125.2 | 1134.7 | 186.7 | 1270.1 |
| Minimum | 1039.9 | 123.8 | 184.0 | 861.8 |
| Mean | 1605.7 | 669.0 | 187.6 | 1174.3 |
| Maximum | 2225.8 | 1186.8 | 192.0 | 1563.8 |
| St. dev. | 549.9 | 544.7 | 3.6 | 247.9 |
| COV | 34.2% | 81.4% | 1.9% | 21.1% |
where \(d_i\) is the desirability for a response, or indicator, \(y_i\); \(L_i\) and \(U_i\) denote the lower and upper limits, respectively; and \(s_i\) is the function index, which modifies how the desirability function translates the indicator values to their associated desirability by changing the shape of the function.

The effect of \(s_i\) on the desirability function shape is illustrated in Fig. 2. When \(s = 1\), the desirability varies linearly between the upper and lower limits; as such, the rate at which the desirability changes due to changes in the indicator value is the same regardless of where that value lies between the minimum and maximum. However, values of \(s\) greater than 1 produce a concave curve, wherein changes in the desirability become larger as the indicator value becomes closer to the lower limit (for minimization) or upper limit (for maximization). Conversely, values less than 1 produce a convex curve, leading to larger changes in the desirability as indicator values approach the upper (for minimization) or lower (for maximization) limits. The selection of this value is subjective and produces differing desirability values for the same indicator value, which will impact the overall desirability.

The maximum and minimum desirability values shown in Eqs. (1) and (2) are conventionally set to 1.0 and 0.0, respectively, to capture when a response is perfectly desirable or undesirable. However, in this sustainability evaluation, these values are shifted to 0.9 and 0.1 to reflect the assumption that, due to ambiguity in the sustainability concept, it is not reasonable to label any one response as perfectly desirable or undesirable. The functions for maximization and minimization are adjusted accordingly to reflect these redefined boundaries, such that any input values will follow the intended shape of the functions.

Finally, the overall desirability, which is referred to as the sustainability score in this evaluation, is calculated by aggregating the individual desirability of the responses. Two aggregation methods were examined in this evaluation: linear [additive, Eq. (3)] and geometric [multiplicative, Eq. (4)].

\[
SS_{\text{lin}} = \frac{1}{n} \left( \sum_{i=1}^{n} d_i \right) \\
SS_{\text{geo}} = \left( \prod_{i=1}^{n} d_i \right)^{1/n}
\]

where \(SS_{\text{lin}}\) and \(SS_{\text{geo}}\) are the sustainability scores by linear and geometric aggregation, respectively, and \(n\) is the number of indicators. The choice of aggregation method is significant, as different aggregation methods allow for varying levels of compensability between indicators (Nardo et al. 2005). Linear aggregation is useful when full compensability is allowed between indicators (Saisana and Saltelli 2011), as assumed in the case of weak sustainability. On the other hand, geometric aggregation is less compensatory, and the effect of trade-offs between indicator performances on the sustainability score is more pronounced (Dobbie and Dail 2013; Gan et al. 2017).

2.5 Uncertainty and sensitivity analyses

As illustrated by the various desirability function shapes or the multiple approaches to aggregating responses, sustainability evaluation may be carried out using any number of methodological combinations according to the judgment of the analyst or expert (Martin 2015). However, the decision to adopt one method over another may produce vastly differing results, giving rise to “methodological uncertainties” in the sustainability evaluation process (Wu and Wu 2012). In the absence of a standardized framework for the integrated sustainability evaluation of concrete materials, it is therefore important to explore potential sources of methodological uncertainty in the evaluation process so that the extent of their influence on the sustainability evaluation results may be clarified and managed.

In this research, the effect of uncertainty arising from variability in the desirability function shapes on the sustainability evaluation of concrete materials is examined via a combination of uncertainty and sensitivity analyses following the framework developed by Opon and Henry (2020). The analytical structure for sustainability evaluation considering uncertainty in the function...
shapes is shown in Fig. 3. Uncertainty analysis acts here to propagate the effect of each source of uncertainty, in this case, from the value of the function index $s_i$ for each indicator, which determines the shape of its desirability function to the sustainability evaluation output by exhaustively considering each potential combination of function shapes for the four indicators. This process produces a set of 81 sustainability scores for each mix alternative per aggregation method. The distribution of these scores may then be treated probabilistically and described by statistical measures, most notably the variance, which quantifies the uncertainty in each set of sustainability scores arising from varying the shapes of the desirability functions.

Variance-based sensitivity analysis is then carried out to determine the contribution of each source of uncertainty to the overall uncertainty of the sustainability scores of all mix alternatives for each aggregation method. This is beneficial for managing uncertainties in the sustainability evaluation process, such as fixing the shape of the desirability function for non-influential indicators, or focusing more attention on selection of the appropriate function shape for highly influential indicators.

Two sensitivity indices are produced by the sensitivity analysis. The first-order sensitivity index measures the contributions to the total variance from each individual source of uncertainty, as well as the contribution from all second and higher-order interactions between the sources of uncertainty. On the other hand, the total effect sensitivity index for each source of uncertainty includes its first-order effects as well as the second and higher-order interactions between that source and the other sources of uncertainty.

Consequently, when the first-order sensitivity index and total effect sensitivity index for a given source of uncertainty are similar, then it may be concluded that that particular source exhibits little interaction with the other sources of uncertainty. However, a large difference between the two indices indicates that that source of uncertainty experiences a large degree of interaction with other sources. As such, the contribution of second and higher-order interactions to the total variance (i.e., the first-order sensitivity index of the interactions) becomes larger when there is high degree of synergy between multiple sources of uncertainty.

3. Sustainability evaluation results and discussion

3.1 Uncertainty in the sustainability score distributions

Figure 4 shows the distributions of the 81 sustainability scores resulting from the uncertainty analysis for each concrete material alternative and aggregation method. The corresponding descriptive statistics are summarized in Tables 5 and 6 for linear and geometric aggregation, respectively. Three general patterns in the sustainability score distributions, as distinguished by data spread and peak height, can be observed, signaling that the uncertainty arising from varying the desirability function shapes affects each mix differently.

For mixes Ref (geometric), A, and B2, the 81 sustainability scores are equally concentrated at just three peaks, and the ranges of their scores are lower than the other mixes. This is particularly true in the case of mix A, for which the range is just 2.8 for linear aggregation and 1.8 for geometric aggregation. This very narrow spread in the data is captured by the variance estimates, which are close to zero and are by far the lowest among all mixes. Consequently, it can be concluded that the sustainability scores of mix A (both linear and geometric) are minimally affected by changes in the shape of the functions.

Similar to the preceding results, the sustainability scores of mixes B1 and Ref (linear) are generally equally distributed, but across a larger number of shorter peaks. This results in a wider range of scores, with correspondingly higher variances. These values fall within the range of 10.0 to 20.0, which is notably higher than the variances observed for the results of Ref (geometric), A, and B2. It can therefore be concluded that the sustainability scores of mixes B1 (both linear and geometric) and Ref (linear) are relatively more sensitive to the selection of desirability function shape than the preceding scores.

Finally, the sustainability score distributions of mixes F1 and F2 are notably different from the other mixes in that they more closely resemble a gaussian distribution, with higher central peaks that taper off towards both tails, together with a broader range of scores. The variances of F1 and F2 are accordingly much higher than the other mixes, particularly with geometric aggregation, which
produced the largest observed data variance (40.4 and 50.4 for F1 and F2, respectively) among all sets of evaluation results. These comparatively high variances demonstrate that the sustainability scores of mixes F1 and F2, regardless of aggregation method, are highly susceptible to changes in the shape of the desirability functions of the four indicators, and thus there is a high degree of uncertainty in the results of their sustainability evaluation.

The uncertainty in the results of the sustainability evaluation can be visualized through the density distributions shown in Fig. 4. These distributions highlight the variability in sustainability scores across different density levels for each mix under both linear and geometric aggregation methods.
evaluation, or lack thereof, can be understood by examining the raw indicator values of the concrete material alternatives relative to the upper and lower limits for each indicator. Mix A, which exhibited the least uncertainty in its sustainability scores, possessed the highest recovered, recycled or waste materials consumption (R), which was to be maximized, the lowest water consumption (W), which was to be minimized and the highest energy consumption (E), which was to be minimized. These values were set as the upper and lower limits for their respective desirability functions; as such, their desirability did not vary, regardless of the function shape. Only the raw materials consumption (M) of mix A did not fall at either the upper or lower limit, so changes in the desirability function shape only affected the desirability of this indicator, leading to the small degree of uncertainty observed overall for the sustainability scores of mix A.

Conversely, the indicator values of mixes F1 and F2, which exhibited the largest degree of uncertainty in their sustainability scores, never fell at either limit. This meant that all four indicators each possessed three distinct desirability values, depending on the shape of the desirability function. These values were set as the upper and lower limits for their respective desirability functions; as such, their desirability did not vary, regardless of the function shape. Only the raw materials consumption (M) of mix A did not fall at either the upper or lower limit, so changes in the desirability function shape only affected the desirability of this indicator, leading to the small degree of uncertainty observed overall for the sustainability scores of mix A.

Conversely, the indicator values of mixes F1 and F2, which exhibited the largest degree of uncertainty in their sustainability scores, never fell at either limit. This meant that all four indicators each possessed three distinct desirability values, depending on the shape of the desirability function. This is in direct contrast to mix A, for which only one indicator took on three distinct desirability values. This variability in the desirability values associated with each indicator for mixes F1 and F2 was then propagated to the results of their sustainability evaluation by the uncertainty analysis, producing the large degree of uncertainty observed in the sustainability score distributions of mixes F1 and F2.

3.2 Sensitivity indices for quantifying sources of uncertainty

The contribution of each source of uncertainty, as well as their interactions, to the overall uncertainty across all concrete material alternatives was calculated by sensitivity analysis using the sum of the variances of all mixes as the total variance. The results are shown in Figs. 5 and 6 for linear and geometric aggregation, respectively.

First, it can be seen that the first-order effects and total effects are nearly identical for both aggregation methods. Although the summary statistics of the sustainability score distributions showed that the magnitude of the variances differed between aggregation methods for the same mix alternatives, the results of the sensitivity analysis establish that the choice of aggregation method has little effect on the relative contribution of the sources of uncertainty to the overall output uncertainty.

Examination of the first-order effects reveals that the isolated effect attributable to changing the desirability function shape for any one indicator has a comparatively small impact on the total variance. The largest isolated effect was observed for water consumption (W), with 8.2% to 8.7% of the overall uncertainty caused by the choice of function shape for this indicator. The first-order effect of energy consumption (E), on the other hand, is almost non-existent, meaning that the choice of desirability function shape for this indicator has almost no impact, by itself, on the total variance. Overall, just 12.4% to 13.5% of the total variance can be explained by the isolated first-order effects.

In contrast, the interactions between the sources of uncertainty (i.e., the second and higher-order effects) account for 86.5% to 87.6% of the total variance. This suggests that the selection of the shape of the desirability function for one indicator has a large impact on the total variance due to how that choice interacts with the choice of function shape for other indicators, rather than due to its own, isolated effect. The total effects sensitivity index
identifies water consumption (W) as the most influential source of uncertainty when both first-order effects and interactions are considered, with an increase in influence of about 74.3% when including the second and higher-order effects. A similarly large increase in influence (+69.9%) due to the inclusion of interactions can also be observed for energy consumption (E). Although the isolated effect of energy consumption (E) was effectively zero, it is shown to be the second most-influential source of uncertainty when measured by the total effects. Both raw materials consumption (M) and recovered, recycled or waste materials consumption (R) also experienced increases in their influence on the total variance due to the second and higher-order effects, but these were smaller than the increases exhibited by the other two indicators. This result suggests that water consumption (W) and energy consumption (E) interact more with the other sources of uncertainty than raw materials consumption (M) and recovered, recycled or waste materials consumption (R).

From the sensitivity analysis, it was clarified that, when considering the total effects, no single source of uncertainty could be considered as non-influential, as the degree of the total effects for all indicators was large due to the overwhelming presence of interactions between them. As such, factor fixing is not a reasonable approach to reduce the sources of uncertainty in this sustainability evaluation. One potential cause of these interactions may be the high degree of collinearity between indicators, as measured by the correlation coefficients (Fig. 1). The mathematical structure of the aggregation methods, which both possess compensatory effects, although to differing degrees, may be another reason for the synergy between sources of uncertainty.

It is further noted that the sensitivity indices adopted here measure the total uncertainty across all mixes. However, the differing magnitudes of variance between the sustainability score distributions of the mixes confirm that the sources of uncertainty affect the sustainability evaluation of each concrete material alternative differently. Variance decomposition is one approach to quantifying the sensitivity of individual alternatives to each source of uncertainty (Opon and Henry 2020); however, this is outside the scope of this paper.

### 3.3 Comparison of alternatives by mean and variance

While the variance was used to examine the uncertainty arising in the evaluation process due to varying the shape of the desirability functions, the mean of the sustainabili-
ity score distribution may be used as a measure of the overall sustainability performance of the concrete material alternatives. As shown in Tables 5 and 6, the rank order of the mean sustainability scores was the same for both aggregation methods, with mix F2 ranked first, and mix B1 ranked sixth. The mean scores tended to be higher for linear aggregation, and the gap between mixes tended to be smaller. For example, the difference between the mean scores of mix F2 (rank 1) and mix A (rank 2) was just 0.8 for linear aggregation (68.4 vs. 67.6, respectively), but grew to 14.3 for geometric aggregation (64.8 vs. 50.5, respectively). Nonetheless, no rank reversal of the mean scores was observed between the aggregation methods, and, based on the mean sustainability score alone, it may be judged that mix F2 is the “most sustainable” concrete mix among the six alternatives.

However, examination by mean value alone neglects the uncertainty accompanying that value. While mix F2 did possess the highest mean sustainability score by both aggregation methods, there were some analytical combinations for which the score of mix F2 was lower than that of mix A. This can be confirmed by examining the histograms of these two mixes (Fig. 4), wherein some of the distribution of mix F2 falls below the minimum score of mix A. Therefore, the selection of the “most sustainable” concrete mix should aim not only to maximize the sustainability performance, but also to minimize the uncertainty associated with that performance.

Figure 7 plots the mean sustainability scores of the mix alternatives against their variances for both aggregation methods. When plotted in this manner, the “most sustainable” alternatives may be said to lie towards the bottom right, where the mean sustainability score is highest and the variance lowest. This visualization makes it clear that, despite mix F2 having a higher mean sustainability score than mix A, mix A may be the “most sustainable” concrete material in this analysis because there is less uncertainty in its sustainability evaluation result, as evidenced by its positioning as the bottom right-most alternative. Indeed, as previously shown in Tables 5 and 6 for the two aggregation methods, the variance of mix A was ranked first out of the six alternatives, as opposed to mix F2, which was ranked sixth. Nonetheless, selection of the “most sustainable” material will depend on the degree of uncertainty the decision maker is willing to accept in the sustainability evaluation result.

3.4 Effect of aggregation method on evaluation results

When comparing the concrete material alternatives by their mean sustainability scores, it was noted that the results tended to be higher for linear aggregation than for geometric aggregation. The effect of aggregation method on the mean scores is shown in Fig. 8 for each mix. The difference was smallest for mix F2, for which the mean score by geometric aggregation was only 3.6 less than the mean score by linear aggregation, or the equivalent of a 5.2% decrease from the mean linear score. Conversely, the largest difference between scores was observed for mix A, for which the difference was -17.1, or 25.3% lower. When examined by percentage decrease, however, mix Ref showed the largest relative difference, as the mean score by geometric aggregation was 34.4% lower than its linear equivalent.

This trend is examined in more detail in Fig. 9, which plots the relationship between the sustainability scores calculated by linear and geometric aggregation with the same combination of desirability function shapes for all 81 combinations in the uncertainty analysis. The relationship between the scores may be described as mostly linear, but nearly all points visibly fall below the identity line, which further confirms that geometric aggregation produced lower sustainability scores than linear aggregation. The difference between the geometric and linear
scores generally becomes smaller as the linear score increases, with the highest linear scores of mix F2 nearly equal to their geometric equivalents. However, mixes B2 and A did not follow this trend, as all their geometric scores lie far below the identity line, despite their comparatively higher linear sustainability scores.

These results clearly illustrate the effect of compensability on the sustainability evaluation of each concrete mix alternative, with mixes A and Ref most sensitive, and mix F2 least sensitive, to the choice of aggregation method. As previously discussed, two of the four desirability values for mix A always fall at the maximum, and one always falls at the minimum. Similarly, for mix Ref, two of the four desirability values always fall at the minimum, and one at the maximum. The trade-offs between these extreme values are amplified when aggregated geometrically, indicating that the higher performing indicators are unable to fully compensate for the lower performing indicators and resulting in the large differences observed when compared to linear aggregation.

4. Key findings, implications and limitations

Sustainability evaluation inherently involves subjective choices at each stage of the evaluation process, including indicator selection, data normalization, weighting application, and aggregation method (Opon and Henry 2020). The quantification and rational treatment of these sources of uncertainty can contribute to more robust and transparent decision making by explicitly acknowledging and measuring said sources of uncertainty as part of the evaluation process, which provides information to decision makers regarding the degree of uncertainty underlying a given decision alternative. This is particularly important for concrete engineers, as there exists no standardized method for reflecting the sustainability of concrete in the material design and specification processes.

The sustainability evaluation utilizing desirability analysis reported in this paper represents one potential approach to optimizing the sustainability of concrete materials. To focus attention on the uncertainty caused by differing shapes of the desirability function, various analytical and methodological decisions were taken that fixed other potential sources of uncertainty. Although justification was provided for each of these decisions, the results and discussion revealed additional issues that should be explored to strengthen the robustness of the desirability approach as a sustainability evaluation method for concrete.

First, it was found that the setting of the minimum and maximum values in the dataset as the lower and upper limits of the responses in the desirability functions had a large effect on the distribution of sustainability scores obtained from uncertainty analysis. Adopting these limits is similar to conventional min-max normalization, which rescales data to a range of 0 to 1 based on the range of the dataset. Consequently, the responses of multiple mixes
fell at each limit, which resulted in low variance in the sustainability scores when varying the shape of the desirability functions. To address this, other methods for setting the lower and upper limits that result in fewer values, or none, falling at the extreme ends of the scale should be considered when attempting to measure the uncertainty in the sustainability evaluation.

Next, it was established prior to the sustainability evaluation that multi-collinearity existed between the four chosen indicators, but no measures were taken as it was considered that the value of these indicators as the “driving force” of concrete sustainability was of sufficient priority to adopt them as-is. The effect of this collinearity, however, manifested itself in the sensitivity analysis results, as the interactions between the desirability functions shapes of the indicators were the most influential source of uncertainty in the sustainability evaluation results. While this outcome complicated the objective of examining the effect of desirability function shape on the sustainability evaluation, it also highlighted indicator selection as another source of uncertainty in sustainability evaluation of concrete, regardless of the evaluation framework adopted.

As demonstrated in this paper, integrating uncertainty analysis into sustainability evaluation outputs probabilistic, rather than deterministic, evaluation results; as such, the identification of the “most sustainable” concrete becomes more complicated because judgment can no longer be made from a single value. The relationship between the mean and variance of the sustainability score distribution was used here to determine that mix A may be the “most sustainable” among the examined concrete material alternatives under the specified analytical conditions, as it exhibited the second highest mean score, together with the lowest variance. On the other hand, if the uncertainty underlying the sustainability evaluation was not considered, then mix F2 may be judged the “most sustainable” based on either its mean or maximum sustainability scores, which were both the highest among all alternatives.

It should be noted that, in this analysis, the multi-response optimization following the desirability approach is being carried out using a discrete set of concrete material alternatives. Consequently, the “most sustainable” mix is simply the optimal choice among the set of alternatives and under the specified analytical criteria. Both mix A and F2 utilized high-grade recycled aggregates, which demonstrates that, overall, the reduction of raw material consumption and increased recycled materials consumption contributed more to the concrete sustainability than the increase in energy consumption, regardless of the degree of compensability in the aggregation method. However, this result is dependent on both the other decision alternatives, as well as the conditions defined in the sustainability evaluation. Ultimately, for discrete decision-making, the determination of which concrete material is “most sustainable” will depend upon the characteristics of the materials being compared and the chosen analytical conditions, in addition to the level of uncertainty the decision maker is willing to accept in the sustainability evaluation result. The decision-making process may be aided, however, by a standardized and rational method for calculating, comparing and ranking the probabilistic sustainability scores of decision alternatives.

Finally, comparison of the results between the two aggregation methods illustrated how compensability affects the sustainability evaluation when utilizing the desirability approach. The degree to which compensability is accepted reflects whether the evaluation tends more towards weak or strong sustainability, which, in turn, reflects the perspective of the analyst on sustainable development. Although not examined in this paper, the choice of aggregation method may also be treated as a source of uncertainty when conducting sustainability evaluation with uncertainty analysis, and its contribution to the sustainability evaluation results may similarly be evaluated by sensitivity analysis.

5. Conclusions

In this paper, the desirability approach, a multi-response optimization technique, was proposed as a new method for the sustainability evaluation of concrete materials. A demonstration study was carried out for a set of concrete material alternatives using four sustainability indicators, and the shapes of their desirability functions were varied to examine the effect of function shape on the evaluation output. The sustainability evaluation with uncertainty analysis with the variable function shapes as sources of uncertainty, produced sustainability score distributions for each concrete material alternative, which could be described and compared using statistical measures. Sensitivity analysis was then carried out to quantify the contribution of each source of uncertainty to the total uncertainty of the evaluation output. In addition, the effect of compensability on the evaluation of the concrete mix alternatives was examined using two different aggregation methods to calculate the sustainability scores.

Due to multi-collinearity among the selected sustainability indicators, the effects of varying the desirability function shape for any one indicator (i.e., the isolated effects) on the evaluation results were minimal. Instead, the uncertainty in the sustainability evaluation of concrete utilizing the desirability approach could be attributed to the interactions that occur when varying multiple function shapes at the same time (i.e., the second and higher-order effects). Furthermore, the adoption of the minimum and maximum in the dataset as the upper and lower limits had a large impact on the variance observed for the concrete material alternatives, as mixes that fell at the extremes values for the indicators exhibited little variance when changing the desirability function shapes. The effect of compensability when aggregating the individual desirability values into the sustainability scores was also larger for concrete material alternatives that had
more extreme indicator values.

While this paper takes a first step towards the use of the desirability approach for the sustainability evaluation of concrete by quantifying the effect of desirability shape function on the evaluation output, the results also revealed the effects of other subjective decisions in the analytical process, such as the setting of the lower and upper limits in the desirability function and the choice of aggregation method. Unfortunately, as no standardized method has been established to unify and govern the sustainability evaluation of concrete materials, such subjectivity will be present in any analysis. It is thus the responsibility of the analysts to report their chosen methods and provide rationale for their methodological choices. The transparency and robustness of sustainability evaluation results may be improved, however, by carrying out uncertainty and sensitivity analyses, such as those demonstrated in this paper, to establish the degree to which the subjective choices affect the evaluation result.

Finally, it is again noted that the results of the sustainability analysis of the selected concrete materials should be interpreted only in the context of the adopted analytical conditions. In particular, the limited sets of indicators are not comprehensive, and omit commonly adopted metrics, such as CO2 emissions, SOx emissions, material cost and so forth. The simplified set of indicators was adopted to focus attention on the desirability function shape as a source of uncertainty when using the desirability approach for sustainability evaluation, and, thus, the reported results represent only one analytical scenario based on the subjective choice of indicators. Nonetheless, this research mathematically demonstrated how uncertainty propagates from the desirability function shape to the sustainability evaluation result under the adopted conditions, and it is expected that future studies will expand upon these achievements by exploring more diverse indicators sets.

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