

THE ROLE OF CONCEPTUALIZATION IN THE EVALUATION OF SUSTAINABLE CONCRETE

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ABSTRACT.

Improvement of the sustainability of concrete materials will be realized through the development of analytical tools that facilitate sustainable design and evaluation. However, these processes may be dependent on how sustainability is conceptualized for concrete. Conceptualization is the means by which sustainability is operationalized by creating a structure that connects a qualitative goal to its quantitative indicators. As there exists no established definition of sustainability for the concrete field, conceptualization is a source of uncertainty in the sustainability evaluation of concrete. This paper explores the role conceptualization plays in the evaluation of concrete material sustainability by analyzing its effects using multicriteria analysis and a sustainability indicator framework to quantify sustainability for concrete materials. Six analytical scenarios are explored using frameworks based on direct loading, the three pillars of sustainability, and the Sustainable Development Goals, together with two aggregation methods. It was found that the most sustainable concrete mix varied by scenario, but one concrete mix combining blast furnace slag and high grade recycled aggregates could be judged as the most sustainable due to its highest mean score and lowest variance across all analytical scenarios, which suggests it as the mix least sensitive to methodological choices on conceptualization and aggregation. Overall, however, the sustainability scores were highly correlated between the different scenarios.

KEYWORDS: Conceptualization, multi-criteria analysis, sustainable design.

1. INTRODUCTION

The use of concrete incurs significant impacts to environmental systems, including climate change, ecosystem degradation, resources depletion, and pollution [1]. To address these issues, it is necessary to adopt more sustainable materials in construction, which requires evaluation of the sustainability of concrete considering the multi-dimensional nature of sustainable development. Literature presents a variety of indicators and evaluation methods for tackling the sustainability evaluation of concrete [2]. Examples include comparative analysis of the trade-off between environmental impact and other performances, such as safety and cost [3], and the application of life cycle assessment (LCA) to quantify the impacts across the life cycle [4]. Multicriteria decision-making techniques, such as Analytical Hierarchy Process, have also been explored to identify the most sustainable construction material [5]. However, these approaches are non-equivalent and lead to uncertainty in the evaluation result, as differing conclusions may be reached when adopting different methods.

The lack of a formalized conceptual paradigm for concrete sustainability may contribute to the multiplicity of evaluation methods, which introduces uncertainty into the sustainability evaluation. Conceptualization is the process whereby a complex system is decomposed into increasingly smaller components

until they can be measured by individual indicators. This creates a structure that rationally links quantitative measures to a qualitative objective. One of the most well-known conceptualizations of sustainable development is the "three pillars" model, wherein the nebulous goal of "sustainability" is first decomposed into the three dimensions of society, environment, and economy. These dimensions are then further broken down into relevant themes and sub-themes, which are ultimately measured by specific indicators [6]. The three pillars, however, represent just one conceptual paradigm for sustainability, and there exist other, equally valid conceptualizations derived from alternative perspectives on sustainable development [7].

Formalizing a conceptual framework for concrete sustainability is essential to unify sustainability evaluation for the concrete field. In this paper, the effect of conceptualization on the sustainability evaluation of concrete materials is explored through an exploratory evaluation using multicriteria analysis. Three conceptual frameworks for sustainable development are examined: direct loading, wherein sustainability is measured directly from individual indicators; the aforementioned three pillars paradigm; and the Sustainable Development Goals (SDGs), which represent the latest global framework for pursuing sustainable development through a set of 17 goals. Compensability, or the treatment of trade-offs between indicators, pillars, or SDGs, is also examined.

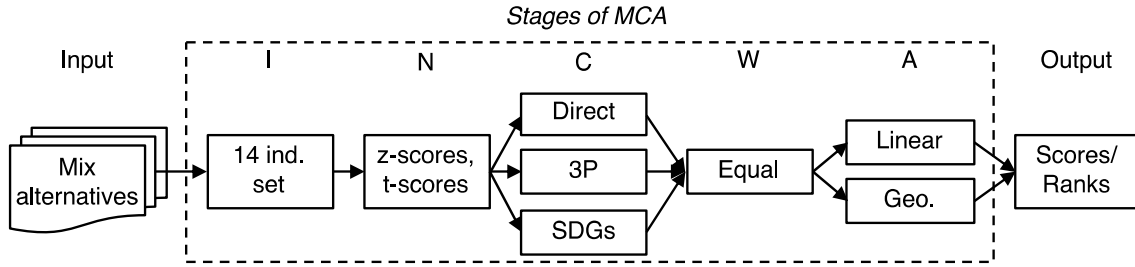


FIGURE 1. Setup for sustainability evaluation by MCA.

Mix	OPC	BFS	FA	W	NG	RG	S	W/B	BFS/B	FA/B	f'_{c-28}
				[kg/m ³]				[-]	[-]	[-]	[MPa]
OPC-NG	325	0	0	184	1063	0	783	0.57	–	–	30.6
OPC-RG	325	0	0	184	0	1063	783	0.57	–	–	30.6
FA-NG	238	0	94	187	950	0	847	0.56	–	0.28	30.2
FA-RG	238	0	94	187	0	950	847	0.56	–	0.28	30.2
BFS-NG	200	133	0	192	965	0	806	0.58	0.40	–	30.4
BFS-RG	200	133	0	192	0	965	806	0.58	0.40	–	30.4

OPC: ordinary portland cement, BFS: blast furnace slag, FA: fly ash, W: water, NG: normal coarse aggregate, RG: high grade recycled coarse aggregate, S: fine aggregate, B: total binder materials

TABLE 1. Mix proportions and 28-day compressive strengths of the concrete mixes.

The results and discussion are expected to provide insights into how to address uncertainty in conceptualization for improving the transparency and robustness of sustainability evaluation for concrete.

2. METHODOLOGY

2.1. MULTICRITERIA ANALYSIS SETUP

Sustainability evaluation was carried out using multicriteria analysis (MCA). MCA is widely utilized to support decision-making by identifying the most sustainable option among a set of potential alternatives [8]. The mix proportions of a set of concrete mixes were used as the inputs. The conventional stages of MCA are: indicator selection (I), data normalization (N), weighting assignment (W), and aggregation (A). The output of this process is typically a sustainability score (S) or rank (R) for each alternative, which can then be used for quantitative comparison and decision-making.

In this paper, the selection of conceptual framework (C) for linking the indicators to sustainability is treated as an additional stage in the MCA process. The setup for sustainability evaluation by MCA is illustrated in Figure 1. Only a single indicator set, normalization method, and weighting scheme were adopted for their respective stages. However, three conceptual frameworks and two aggregation methods were utilized for their stages for a total of six analytical scenarios leading to six sustainability scores for each mix alternative. These scores are then statistically examined to explore how a plurality of perspec-

tives on concrete sustainability may affect the evaluation result.

2.2. INPUT CONCRETE MIX DATA

The concrete mix alternatives were sampled from a database assembled by Noguchi et al. [9]. A target compressive strength of 30 MPa at 28 days was set, and three concrete mixes with different binder contents were chosen. An additional three mixes were then generated assuming 100% replacement of normal coarse aggregates with high grade (class H) recycled coarse aggregates. The Japan Industrial Standard (JIS A 5021) indicates that high grade recycled aggregates should be equivalent to normal aggregates, so the concrete compressive strengths are assumed to remain unchanged. However, the energy consumption and emissions footprints of high grade recycled aggregates are higher than that of normal aggregates due to the recycling process, so the inclusion of these mixes will explore the tradeoff between increased consumption of recycled materials and increased environmental impacts in the sustainability evaluation. The mix proportions are summarized in Table 1.

2.3. SUSTAINABILITY INDICATORS

A subset of 14 quantitative indicators was adopted from a comprehensive set of sustainable concrete material indicators (SCMIs) [2], with descriptions and characteristics given in Table 2. Measurement was carried out using available inventory data from the Japan Society of Civil Engineers (for NG, RG, S) and the Life Cycle Assessment Society of Japan (for OPC, BFS, FA), characterization values from the

SCMI ID	Description	Unit	Loading by concept	
			Three pillars	SDGs
1	Energy consumption, renewable and non-renewable	MJ	All	7
2	Raw materials consumption, primary and secondary	kg	All	12
3	Water consumption	kg	All	6
4	Recycled materials consumption, primary and secondary	kg	All	12
5	CO ₂ emissions	kg-CO ₂	Env	9
6	SOx emissions	kg-SOx	EnvSoc	11
7	NOx emissions	kg-NOx	EnvSoc	11
8	Particulate matter emissions (PM)	kg-PM	Env	11
28	Global warming potential (GWP)	kg-CO ₂ eq	Env	13
29	Photochemical ozone creation potential (POCP)	kg-C ₂ H ₄ eq	Env	11
30.2	Acidification potential, aquatic (AP)	kg-SO ₂ eq	Env	14
31.1	Eutrophication potential, terrestrial (EP)	kg-PO ₄ eq	Env	2
34	Human toxicity potential (HP)	kg-C ₆ H ₄ Cl ₂ eq	Soc	3
40	Material cost of concrete	yen	Eco	8

All: environmental, social, and economic, EnvSoc: environmental and social, Env: environmental, Soc: social, Eco: economic

TABLE 2. Summary of the adopted sustainable concrete material indicators.

Mix	SCMI 1 Energy	SCMI 2 Raw mats.	SCMI 3 Water	SCMI 4 Recyc. mats.	SCMI 5 CO ₂	SCMI 6 SOx	SCMI 7 NOx
OPC-NG	1213.0	2225.8	184.0	123.8	255.1	0.053	0.513
OPC-RG	1563.8	1162.8	184.0	1186.8	270.9	0.053	0.539
FA-NG	956.6	2075.1	186.7	184.8	190.2	0.043	0.379
FA-RG	1270.1	1125.2	186.7	1134.7	204.3	0.043	0.402
BFS-NG	861.8	2005.3	192.0	209.2	162.6	0.038	0.320
BFS-RG	1180.4	1039.9	192.0	1174.6	176.9	0.039	0.344
Mix	SCMI 8 PM	SCMI 28 GWP	SCMI 29 POCP	SCMI 30.2 AP	SCMI 31.1 EP	SCMI 34 HTP	SCMI 40 Cost
OPC-NG	0.015	255.1	0.017	0.412	0.067	0.620	5775
OPC-RG	0.016	270.9	0.018	0.430	0.070	0.652	5775
FA-NG	0.012	190.2	0.013	0.308	0.049	0.458	5266
FA-RG	0.012	204.3	0.013	0.324	0.052	0.487	5266
BFS-NG	0.010	162.6	0.011	0.262	0.042	0.388	5679
BFS-RG	0.011	176.9	0.011	0.279	0.045	0.416	5679

TABLE 3. Mix proportions and 28-day compressive strengths of the concrete mixes.

LCA database of Leiden University (for GWP, POCP, AP, EP, HP), and constituent material costs reported by Henry et al [10]. The cost of high grade recycled aggregates was assumed the same as that of normal aggregates due to lack of data. The raw indicator values for the six mixes were calculated as shown Table 3.

The loadings of the indicators within the three pillars and SDGs concepts, as established by Opon and Henry [2], are also shown in Table 2. The environmental pillar is most represented among the three pillars, with 12 of the 14 indicators loading to the environment. Ten of the 17 goals are evaluated under the SDG concept, with SDG 11 (sustainable cities and communities) receiving the most representation with four indicators highly relevant to this goal.

2.4. NORMALIZATION METHOD

As the adopted indicators exhibit differing characteristics and behavior, their data were normalized by standardization. Standardization was carried out through a combination of z-scores, which convert the data based on a mean of zero and standard deviation of one (Eq. 1), and t-scores, which shift the data to a non-negative scale of zero to 100 (Eq. 2).

$$z = \frac{x - \mu}{s} \quad (1)$$

$$t = (z \times 10) + 50 \quad (2)$$

Where z : z-score, t : t-score, x : raw value, μ : average, and s : standard deviation,. In some cases, the t-score is divided by 100 to scale the data from zero to one.

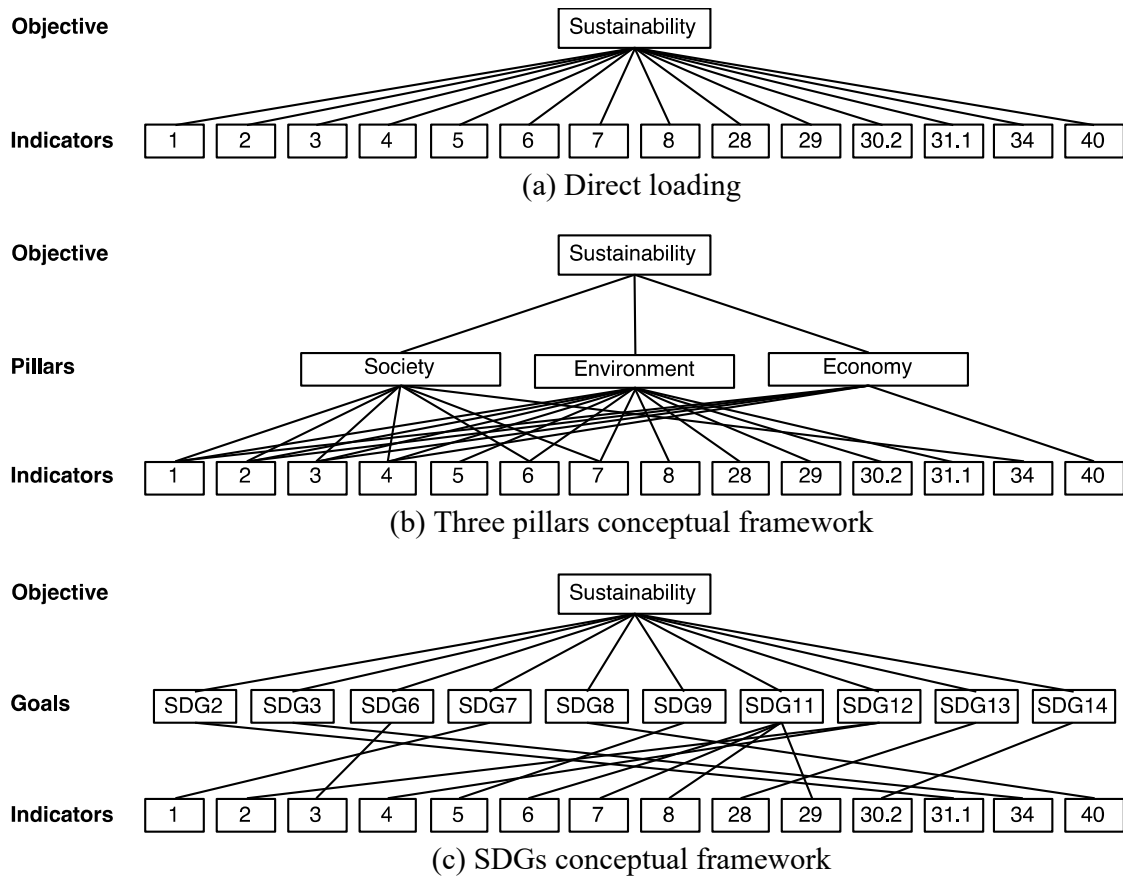


FIGURE 2. Conceptual frameworks for sustainability with indicator loadings.

2.5. CONCEPTUAL FRAMEWORKS

To represent different conceptual approaches to sustainability, three frameworks linking the individual sustainability indicators to the overall objective of concrete sustainability were constructed (Figure 2). The first framework, direct loading, assumes no priority areas or sub-categories; that is, all indicators load directly to the sustainability performance of the concrete materials. The second framework decomposes concrete sustainability into the three pillars of society, environment, and economy, and each indicator then loads to its related pillar, or pillars (for multi-dimensional indicators), following the loadings given in Table 2. The final framework sets the ten relevant SDGs as the intermediate priority areas, with each indicator loading to its respective SDG.

2.6. WEIGHTING SCHEME

As no information was available to establish the comparative importance of the indicators, pillars, and SDGs, equal weighting was applied for all loadings between levels of the conceptual framework. This is consistent with the United Nations resolution adopting the SDGs, which states that they will give "equal priority" to all goals in their implementation efforts [11].

2.7. AGGREGATION METHODS

Two aggregation methods were used to produce the sustainability scores for the concrete mixes: linear and geometric. Linear aggregation is an additive operation (Eq. 3), and is frequently the default method in MCA, whereas geometric aggregation is a multiplicative operation (Eq. 4).

$$S_{in} = \sum_{i=1}^n (w_i \times SCMI_i) \tag{3}$$

$$S_{geo} = \prod_{i=1}^n (SCMI_i)^{w_i} \tag{4}$$

Where S : sustainability score, n : total number of indicators, $SCMI_i$: sustainability indicator i , and w_i : weighting applied to indicator i .

The choice of aggregation method represents another perspective on sustainability in the evaluation process. Linear aggregation allows for full compensability between indicators; that is, an increase in one performance (such as CO₂ emissions) can be balanced by an equivalent decrease in another performance (such as cost). Geometric aggregation, however, is less compensatory [12], meaning that trade-offs between indicators have a more pronounced effect on the sustainability score. The impact of compensability on the sustainability evaluation result may differ according to the conceptual framework, so these two

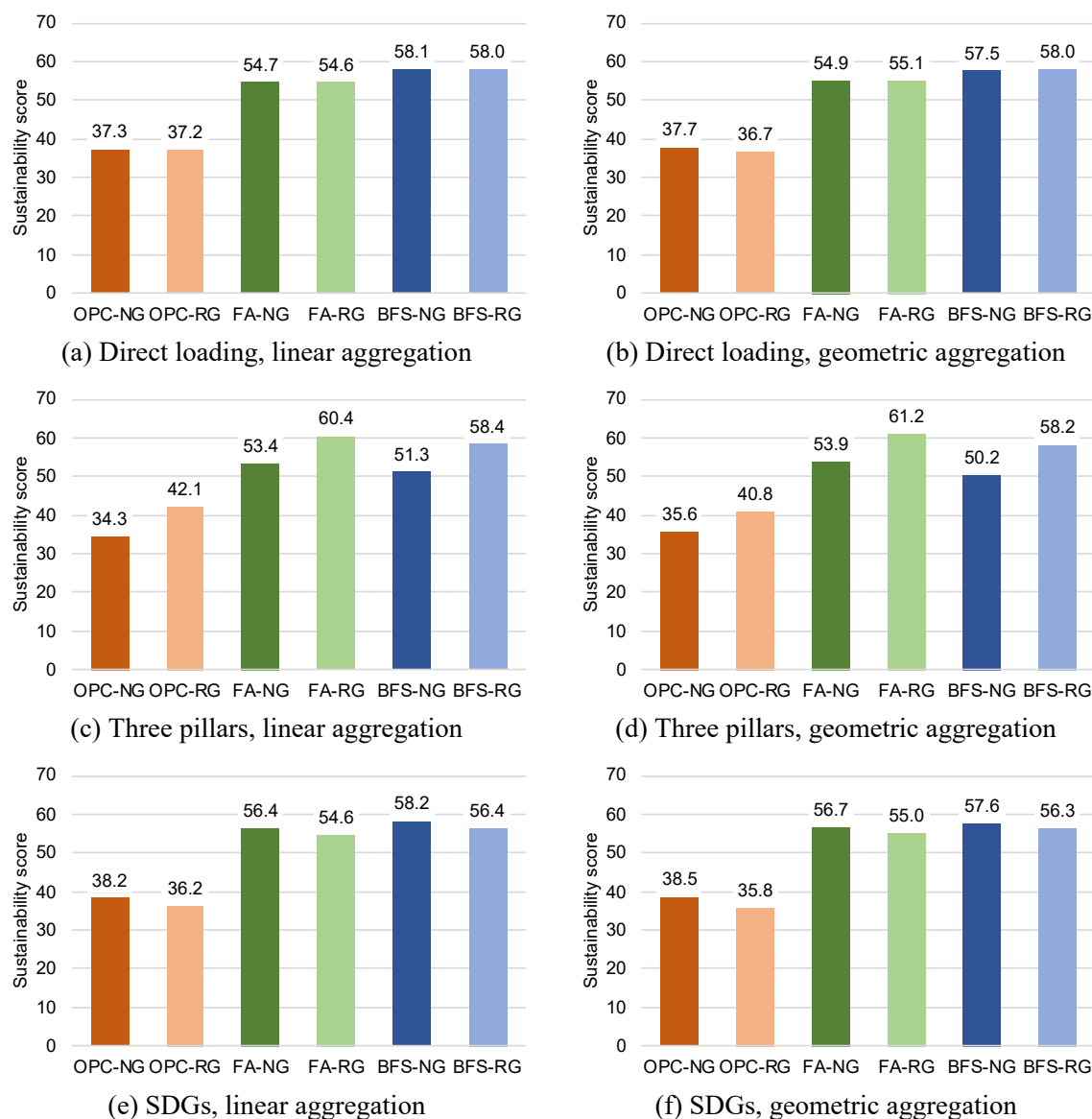


FIGURE 3. Sustainability scores by analytical scenario.

aggregation methods were included in the MCA process.

3. RESULTS AND DISCUSSION

3.1. SUSTAINABILITY SCORES

Figure 3 shows the sustainability scores for the concrete mix alternatives by analytical scenario. For direct loading, the two BFS mixes exhibited the best sustainability performance, with BFS-NG slightly higher for linear aggregation, and BFS-RG slightly higher for geometric aggregation. In the case of the three pillars, FA-RG possessed the highest sustainability score regardless of aggregation method, followed by BFS-RG. Finally, for the SDG concept, BFS-NG demonstrated the best sustainability for both aggregation methods, but the gap between the top four mixes was relatively small.

Overall, the four concrete mixes containing mineral

admixtures consistently exhibited higher sustainability scores than the two OPC mixes across all analytical scenarios. These mixes tended to have lower raw values for environment-related indicators compared to OPC; and, since 12 indicators loaded to the environment, the effect of reduced environmental impacts was amplified through the MCA process. While considering the limitations of this analysis, these results nonetheless support the general perception that the application of alternative cementitious materials to concrete construction is a critical technological solution for improving sustainability in the concrete industry.

3.2. STATISTICAL EXAMINATION

It remains unclear which concrete mix is actually the most sustainable among the alternatives, as the results of each analytical scenario may be considered as equally valid due to the lack of an established stan-

Mix	Sustainability scores					Ranks	
	Min.	Mean	Max.	Std. dev.	Variance	Mean	Variance
OPC-NG	34.3	37.0	38.5	1.6	2.2	6	3
OPC-RG	35.8	38.1	42.1	2.6	5.8	5	4
FA-NG	53.4	55.0	56.7	1.3	1.4	4	2
FA-RG	54.6	56.8	61.2	3.1	8.0	2	5
BFS-NG	50.2	55.5	58.2	3.7	11.4	3	6
BFS-RG	56.3	57.6	58.4	1.0	0.8	1	1

TABLE 4. Summary statistics of the concrete mixes sustainability performance.

Analytical scenario	(a)	(b)	(c)	(d)	(e)	(f)
(a) Direct loading, linear aggregation	1.00					
(b) Direct loading, geometric aggregation	1.00*	1.00				
(c) Three pillars, linear aggregation	0.89	0.89	1.00			
(d) Three pillars, geometric aggregation	0.88	0.89	0.99	1.00		
(e) SDGs, linear aggregation	0.99	0.99	0.86	0.86	1.00	
(f) SDGs, geometric aggregation	0.99	0.99	0.86	0.86	1.00*	1.00

*Actual coefficients were less than 1.00, but appear as 1.00 due to rounding

TABLE 5. Correlation coefficients for sustainability scores between analytical scenarios.

dard for concrete sustainability evaluation. To judge the sustainability under the uncertainty introduced by multiple concepts and aggregation methods, statistical properties of the sustainability score distributions for each material were examined (Table 4). The mix with the highest mean sustainability score was BFS-RG; however, per Figure 3, this mix was the most sustainable alternative in only one analytical scenario. On the other hand, BFS-NG was the most sustainable material in three scenarios, but its mean sustainability score was ranked third out of the six alternatives. Similarly, FARG was the most sustainable in two scenarios, but was ranked second by mean score.

This result may be explained by the variance of the sustainability scores. The variance of BFS-RG is the lowest among all alternatives, suggesting it is relatively insensitive to the uncertainty introduced by different conceptual frameworks and aggregation methods, whereas the variance of BFS-NG is the highest, and thus the alternative most affected by the choice of concept and aggregation method (and their interactions). Considering both the highest mean sustainability score and accompanying lowest variance, BFS-RG may be judged as the most sustainable material when there is no consensus on the conceptual framework or aggregation method.

Finally, the Pearson correlation coefficient matrix for the sustainability scores was calculated between analytical scenarios. It can be seen that all coefficients are equal to or greater than 0.86; in particular, the results of the linear and geometric aggregation scenarios were almost perfectly correlated for all three conceptual frameworks. This result suggests a very highly correlated set of sustainability scores

regardless of the chosen conceptual framework or aggregation method, and despite the rankings of the mix alternatives shifting between scenarios.

4. CONCLUSION

This paper examined the effect of conceptualization on the sustainability evaluation of concrete using multicriteria analysis and a set of six concrete mix alternatives with varying binder contents and aggregate types. It was found that the most sustainable concrete mix varied according to conceptual framework and aggregation method, with three different mixes achieving the highest score among six scenarios. Statistical examination of the distributions of the mixes' sustainability scores revealed that the concrete mix with the highest mean sustainability score, BFS-RG, was only ranked first in one analytical scenario. However, the variance of this mix's scores was the lowest among the alternatives, suggesting that its evaluation was comparatively less sensitive to methodological choices regarding conceptualization and aggregation. Despite the different rankings for each analytical scenario, the sustainability scores were still very highly correlated between all scenarios, indicating that different methodological choices produced closely related results.

It should be noted that the results reported here cannot simply be generalized to the greater concrete industry, as they are dependent on the sample and conditions of this specific analysis. However, it is expected that the demonstrated evaluation method will provide concrete industry stakeholders with an example of how to consider methodological uncertainties in sustainability evaluation to increase the robustness of their decision-making.

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