DEMONSTRATION STUDY OF CONCRETE SUSTAINABILITY EVALUATION USING PARTIAL LEAST SQUARES STRUCTURAL EQUATION MODELING (PLS-SEM)

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1. Introduction

The concrete industry is constantly challenged when it comes to concrete sustainability primarily because of the lack of a holistic framework of what constitutes a sustainable concrete. To address this matter, Opon and Henry [1] developed an indicator framework for quantifying the sustainability of concrete materials from the perspectives of global sustainable development to provide a clear context to underpin this concept. However, the contribution of various indicators is still not clear and thus, the need to contend this ambiguity is crucial to help understand the indicators' relationships and interpret its implications better. In this regard, this paper proposes the use of Structural Equation Modeling (SEM), particularly Partial Least Squares – Structural Equation Modeling (PLS-SEM) as a tool to tackle this problem.

SEM is a second-generation statistical technique for studying multivariate relationships among observed (manifest or indicators) and unobserved (latent or constructs) variables. PLS-SEM is a type of SEM that is primarily used to develop theories in exploratory research. Furthermore, this method works efficiently with small sample sizes, complex models and nonparametric data which makes it a suitable approach in analyzing the sustainability of concrete.

2. Methodology

2.1. PLS-SEM Framework

PLS-SEM is composed of two sub-models: the structural model and the measurement model. The structural model deals with the relationships between latent variables, while the measurement model deals with the relationships between the latent variables and its manifest variables. Moreover, the measurement model is further classified into reflective and formative models depending whether the indicators are "reflecting" the construct, or the indicators are "forming" the construct.

The core of the algorithm is the calculation of weights required to estimate the latent variables by using the measurement and structural models in an alternating manner. The measurement model estimates the constructs as a weighted sum of its indicators. The structural model estimates the latent variables by means of simple (for reflective measurement model) or multiple (for formative measurement model) linear regressions between the constructs estimated by the measurement model. This is done in an iterative manner until convergence is achieved.

2.2. Data

Opon and Henry [1] developed an indicator framework using a concrete mix data with various amounts of low-grade recycled aggregates (0%, 50% and 100% replacement ratio) having fly ash as mineral admixture at varying water-binder ratios (0.30, 0.375 and 0.45). This framework is applied by creating a certain set of indicators to understand how various choices in material design can contribute to the different aspects of concrete sustainability.

2.3. PLS-SEM using R

R is a free, open source software for data analysis. In turn, plspm is an R package dedicated for the analysis of PLS-SEM. This paper carries out a demonstration study of the use of PLS-SEM using the plspm package in R in the evaluation of concrete sustainability by clarifying and strengthening the indicator framework developed by Opon and Henry [1].

2.4. Model Specifications

Concrete sustainability is classified as a molar higher-order construct model that is viewed as composed of lower-order latent variables. In the model, the lower-order constructs are the Environment (En), Social (So) and Economic (Ec) latent variables, while the higher-order construct is Concrete Sustainability (Su). These are represented as blue circles and green circle, respectively in Figure 1. Furthermore, for the measurement model, the indicators defined to be reflecting the constucts are classified as reflective measurement model and visualized as black rectangles in Figure 1.

In PLS-SEM, all latent variables must have at least one indicator for the model to be estimated. In the case of higher-order models, the most popular approach is the repeated indicators approach wherein the indicators of all the lower-order constructs are utilized as the manifest variables of the higher-order latent variable. This approach is utilized in this paper as shown in Figure 1.

Keywords: Concrete Sustainability, Structural Equation Modeling, Partial Least Squares

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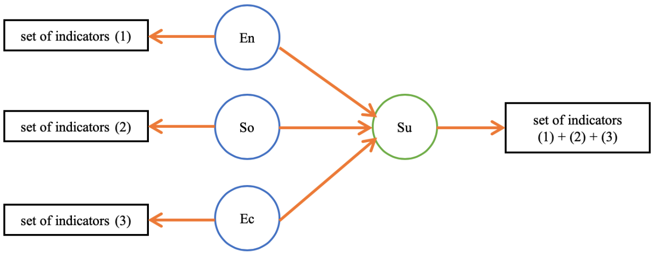

Figure 1. PLS-SEM Model

3. Results and Discussion

Having defined the full structural model and ran the analysis, the most important values calculated in PLS-SEM are the estimation of the latent variable scores and the quantification of the relationships in the model. The associated numeric value obtained represents the strength and direction of the relationship, that is, values close to +1 indicate a strong positive relationship and vice versa for negative values.

3.1. Measurement Model Assessment

The estimates of the reflective measurement model are referred to as loadings and are calculated as correlations between a latent variable and its indicators.

For the environment latent variable loadings as shown in Table 1, majority of the indicators reveal a high correlation with the environment construct having values close to 1.0. As an example, this implies that the amount of CO_2, SO_x and NO_x emissions influence the environment aspect of concrete sustainability. In contrast, PM with a loading of only 0.515 would indicate that particulate matter found in the air due to concrete production sources does not greatly impact the environment.

Table 1. Environment Latent Variable Loadings

Indicators	Loadings
water_consumption	0.878
CO_2	0.997
SO_x	0.965
NO_x	0.998
PM	0.515
GWP	0.997
photochemical_potential	0.999
acidification_potential	0.999
eutrophication_potential	0.998

Secondly, for the social latent variable loadings as shown in Table 2, all indicators exhibited a strong correlation with the social construct. This indicates that the structural safety associated with an acceptable compressive strength and the impacts to human health of toxic substances are important concerns to individuals.

Table 2. Social Latent Variable Loadings

Indicators	Loadings
compressive_strength	0.953
humantoxicity_potential	0.878
structural_safety	0.929

Thirdly, for the economic latent variable loadings as shown in Table 3, all indicators demonstrated significant relationship to economic construct. As an example, the cost of both raw and recycled materials significantly affects what comprises an economic concrete material.

Table 3. Economic Latent Variable Loadings

Indicators	Loadings
raw_materials	0.926
recycled_materials	0.938
youngs_modulus	0.962
cost_raw	0.991
cost_recycled	0.867
production_cost	0.921

3.2. Structural Model Assessment

The values of the structural model are referred to as path coefficients and are estimated by ordinary least squares regression. The estimates show that the path coefficients of the environment, social and economic constructs are 0.589, 0.168, and 0.335, respectively. This implies that among the constructs, the environment latent variable is the greatest factor that defines sustainable concrete.

4. Conclusions

The utilization of PLS-SEM as an approach in the evaluation of concrete sustainability not only validated the indicator framework by quantifying the contributions of individual indicators to a composite sustainability index, but it also proves the applicability of the approach in analyzing such multivariate relationships. In turn, these outcomes will help stakeholders have a concrete basis in policy and decision-making strategies.

References

[1] Opon, J., and Henry, M. (2018) "Understanding the Propagation of Uncertainty in Concrete Material Sustainability Evaluation", The 8th International Conference of Asian Concrete Foundation (ACF2018), Fuzhou, China, November 4-7, 2018

[2] Sanchez, G. (2013) "PLS Path Modeling with R", Trowchez Editions. Berkeley, 2013. http://www.gastonsanchez.com/PLS_Path_Modeling_with_R.pdf