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SUMMARY

Title of Dissertation:
A multicriteria analytical framework for quantifying the sustainability of concrete materials under methodological uncertainties.

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1. Introduction and Objectives

Concrete is the lifeblood of the construction industry, which creates an unprecedented vibrancy in socioeconomic development activities. Much of the advancements of the global society can be attributed to concrete. Concrete, for example, is the primary material used to build essential facilities for human habitation and protection. High-rise buildings, offices, apartments, and even most small dwellings rely on the stability provided by concrete to be a safe haven for human activities. Concrete also connects societies so that socioeconomic activities can be performed more efficiently. Our road infrastructures, railways, port systems, airports and even telecommunications systems wouldn't be possible without concrete. It is hard to imagine the modern society and the direction it is heading without concrete performing its expected task. Concrete is complexly amalgamated within the human society that it could almost be perceived as equivalent to nature.

Concrete, however, is not a flawless material. Tagged as the second widely used substance next to water, concrete is a voracious consumer of raw materials. Billions of tons of aggregates, limestones, and water are extracted annually to support the growing need of societies for a concrete-based infrastructure system. The processing and production of concrete releases huge amounts of environmentally injurious emissions, e.g., CO_2 and other greenhouse gases. The economic vitality created by the immense size of the concrete and construction industry may also encourage corruption and abuse in regard to the use of the material. Concrete is relatively a cheap and easily accessible construction material and thus its massive utilization is almost unregulated. This promotes the building of projects with dubious socioeconomic significance which drains the wealth of the society, affecting the poor and the vulnerable. Concrete with all its good benefits to the society must not continue to be a vehicle of the environmental degradation and socioeconomic decline. Therefore, as a way forward, the concrete industry must embrace sustainable decision-making practices so that concrete could continue to support socioeconomic activities, whilst being sensitive to environmental rehabilitation and preservation.

Sustainable decision-making is the consequence of the practice of sustainability. Sustainability is an innovative idea of the modern age, strongly advocated by the United Nations, which promotes the concept of continued development while assuring the balance between economy, society and the environment – the pillars of sustainable development. In other words, any development activity must not be singly motivated by any of the pillars, but they must be harmoniously considered. Sustainability has recently been conceptualized by 17 global Sustainable Development Goals (SDGs) with specific and measurable targets. The goals span a wide range of priority areas to sustainability where various industries could participate in. However, there remains significant amount of uncertainty regarding the practice of sustainability as it is still difficult for many industries to view their commercial constructs under the context of sustainable development either within the paradigm of the pillars or the SDGs. In the concrete industry, for example, there is no clear framework outlining how sustainability can be integrated and how concrete can be made into a sustainable product. Moreover, there is much uncertainty in delineating what constitutes sustainability (e.g., concrete) and what does not. As such, for the concrete industry (or any industry in general) to be a participant to these international sustainability agenda, frameworks defining the constituency of sustainable concrete must be defined.

The practice of sustainability may also require quantitative measurements, whether for the purpose of decision making or progress assessments. Since sustainability is much of a concept than a measurable entity it is difficult to underpin it in quantitative sense. There is no single value able to discriminate in absolute terms whether sustainability is achieved or not. Quantitative measurements, however, is needed for comparative decision making in regard to sustainability. This would enable, as an example, the selection of concrete material that closely represents sustainability in the context of the industry. On the other hand, quantifications would facilitate distinctive evaluations about the state of practice concerning sustainable development. However, there are still serious disagreements regarding quantitative measurements about sustainability in general. This can be attributed to the lack of a standardized measurement framework that encourages various non-equivalent ways of quantification, placing considerable uncertainty over the resulting conclusions and decisions. To facilitate, therefore, quantitative evaluations, a measurement framework sensitive to the uncertainties relevant to sustainability is essential to make robust decisions.

Considering the arguments presented above concerning concrete and sustainability, the following research objectives were devised:

1) To develop an indicator-based sustainability framework able to define the constituency of sustainable concrete material that could also be used to perform quantitative sustainability evaluations.
2) To develop a sustainability evaluation framework following the architecture of a multicriteria analysis that is able to consider the methodological uncertainties in sustainability quantification.
3) To demonstrate the practical implementation of the indicator-based framework for sustainable concrete and the sustainability evaluation framework in concrete decision-making processes.

2. Sustainability and concrete

It is clear that sustainability affects every industry and that it requires a concerted effort from everyone involved to participate in the operationalization of its targets be it from the pillars or the SDGs perspective. The focus, however, of this work is on concrete materials and its relation to sustainability. Accordingly, more than any other industry, the building sector is largely affected by the ongoing sustainability debate (Muller et al., 2014). Traditional concrete is a composite of cement, sand, coarse aggregate and water, and is used primarily for construction (Kisku et al., 2017). The statistics of concrete consumption globally is not particularly impressive when it comes to the topic of sustainable development. In this section, relevant views about the conflicts of the concept of sustainable development and the use of concrete is explicated which centers around the three pillars of sustainability.

2.1 Environmental impacts

The environmental aspect of concrete sustainability is very wide and complex. This subsection, therefore, focused only on three important issues surrounding the sustainable use and production of concrete materials: resource depletion and environmental emissions. It is estimated that concrete uses about 20 billion tonnes of raw materials every year (The Fredonia Group, 2011). This amount is expected to continue to rise for decades into the future (Opon and Henry, 2019: Mehta, 2002) if developing countries are to expand their infrastructure development to the current global average (Watts, 2019). According to an OECD report (2016), construction materials – particularly sand, gravel and crushed rock – dominate the worldwide resource consumption and this amount could double in the 2060, which has the potential to deplete natural resources. The demand for raw construction materials also requires massive extraction of sand and gravel that are now destroying rivers, lakes and ocean ecosystem (Weyler, 2018).

In terms of environmental emissions, it is estimated that about 4-8% of the world's CO_2 emissions can be attributed to concrete production (Baumert et al., 2005; Hooton and Bickley, 2014). CO_2 is the primary greenhouse gas that is directly linked to the global warming impact. Much of the CO_2

emissions from concrete can be attributed to cement production as a result of a chemical process of limestone calcination at high temperatures. Accordingly, cement alone is responsible for about 8% of the world's CO_2 emissions (Rodgers, 2018). This massive CO_2 emissions is expected to increase in the future as a direct effect of the increase in concrete production. In turn, this would affect several environmental and social issues, as global warming impact could transcend across different contextual barriers.

2.2 Economic impacts

Concrete is essentially a cheap and its constituent materials are readily accessible in most parts of the world. This is the reason why concrete remains a popular choice of building material amongst construction stakeholders and owners. Because of its unique economic quality, concrete becomes one of the primary drivers of the construction industry's economic activities. This, however, encourages many sustainability issues. On one hand, this would drive the over extraction of raw constituent materials to support the building of various socio-economic infrastructures, such as the building of roads and bridges. On the other hand, this would also lead to social issues such as labor exploitations in order to allow continuance of the economic activities relevant to the high demand for concrete production.

The massive use of concrete as a cheap construction material could also become a source of abuse and corruptions. One of the flaws is that concrete is overused in the form of dubious construction projects at staggering costs that are constructed without proper evaluations whether this would benefit the economy or the local community. In China, for example, the National Bureau of Statistics found 450 km_2 of unsold residential floor space, which is the result of excessive developments (Watts, 2019). Illegal sand mining is also pervasive in the industry due to high demands, affecting environment and ecosystem dynamics and the social stability in areas where regulations are weak.

2.3 Social impacts

Concrete could introduce various social related impacts particularly on the health and wellbeing. Negative impacts include the disturbance of landscape, dust and noise and the disruption of the local biodiversity from quarrying limestones (Narayanan, 2016). Operators in concrete production plants that come into contact with substances could face a significant health issue (Moretti et al., 2017). The cement causes many health issues as it is highly toxic, which can prompt several allergic reactions (Beech, 2019). The silica in the form of respirable crystalline silica, for example, could pose a problem as this can lead to asthma and other pulmonary disorders (Beech, 2019).

The impact on wellbeing, on the other hand, may be difficult to directly relate to concrete use as wellbeing is associated with many other environmental stimuli. Nevertheless, it is suspected that concrete use could also impact human wellbeing. The massive use of concrete, for example, has transformed substantially the landscape of cities which contributes directly to heat island effect and flood risks. Heat island effect affect communities by increasing summertime peak energy demand, air conditioning costs, air pollution and greenhouse gas emissions, heat-related illness and mortality, and water pollution (EPA, 2019). Flooding in urban areas, on the other hand, is due to the reduction of natural drainage and water storage as most areas are covered with concrete. All these issues are contributory to the deterioration of the wellbeing of the people, which are indirectly caused by massive concrete consumption.

3. The sustainable concrete material indicators framework

This objective undertakes the growing complexity of concrete material sustainability evaluation by developing an indicator framework for the quantitative development of sustainable concrete based on two contextual perspectives: the pillars of sustainability and the SDGs. Three primary points were addressed and presented following this objective that led to this development. First, is the creation of the SCMI framework, which provides a comprehensive outlook on what concrete sustainability is about. This was achieved by aggregating the multitude of indicators that represent the needs of the concrete sector to ensure both material performance and operationalize sustainability. The SCMI framework reveals the causality that exists between the indicators, which was portrayed in a causal network forming the driving force-state-impact relationship. This causality is useful in selecting the appropriate indicators for sustainability evaluation, in tracing dependencies, and in identifying focus areas necessary to effect changes in order to improve the sustainability of concrete. As a result, the SCMI framework was able to simplify the complex nature of concrete sustainability to a form that is relatively easy to communicate to the stakeholders.

The second point was the establishment of the relationships that link the SCMIs to the pillars of sustainability, as well as to the SDGs, which provided the governing contextual evaluation perspective for the efficient development of sustainable concrete. The use of indicators' descriptions, the definition of each sustainability pillars, and the different targets of the SDGs prove to be useful tools in establishing these relations. Additionally, these linkages will enable the determination of focus areas that are beneficial for the creation of target-based strategies for the improvement of the underperforming sustainability aspects. This ensures the balance between the different aspects of sustainability, which is one primary objective of sustainable development. The relations also illuminate the opportunities for the concrete sector to participate in the global sustainability agenda.

The third point was the demonstration of the practical applicability of the SCMI framework, which illustrated that the relationship between the SCMIs and the pillars of sustainability, as well as the SDGs, could be evaluated quantitatively. Therefore, the trade-offs that exist between the different aspects of sustainability could be compared unambiguously, making it easier to evaluate the feasibility of concrete mix alternatives. Finally, quantification communicates to the stakeholders their contributions toward the achievement of global sustainability, which is a fundamental input to reach robust decision and in expanding the concept of sustainable concrete.

4. Multicriteria sustainability evaluation framework under uncertainties

4.1 The uncertainties of the multicriteria analysis

Performing sustainability evaluation is one way to demonstrate that the concept of sustainable development is operationalized. Sustainability evaluations will allow decision makers to make quantitative assessments on whether their actions and proposed solutions would lead to the overall sustainability of the system. However, because of the complex nature of sustainability itself along with its several dimensions, there is no unique mathematical solution that could capture it holistically to make quantitative sustainability evaluations.

The most effective way of performing sustainability evaluations is through the use of multicriteria analysis, where the multidimensional character of sustainability could be underpinned in mathematical way. Multicriteria analysis takes the various criteria (or indicators) and aggregates them to a total score, which would indicate about the overall sustainability performance of a system. The elaborate process of the multicriteria analysis comprised of: indicator selection, data treatment, normalization, weighting and aggregation. Each of the step perform vital functions representing the various concerns about sustainability evaluation.

Indicator selection identifies the elementary components of the system relevant to sustainability. Data treatment is performed to provide resolution to indicators with missing or unreliable information. Since the indicators are expressed in various scales and unit, they need to be normalized so that they can be compared in a single multicriteria framework. The indicators also are viewed by various stakeholders to have unequal importance on the basis of their efficiency at representing of the sustainability of the system. As such, weighting process became an essential step in a multicriteria analysis so that the importance of indicators is properly reflected in the analysis. This is one area of the sustainability evaluation process that accounts for the human values of sustainable development. The last step is aggregating the normalized values and the weights of the indicators into a total score. While the sustainability evaluation using multicriteria analysis seems to be a straightforward process, it is still susceptible to various subjectivities. Each step of the MA can be performed in a number of ways; therefore, depending on the method chosen by the analyst, different conclusion about the sustainability of the system could result. This is termed as methodological uncertainty.

In indicator selection, for example, uncertainty exists by simple inclusion or exclusion of indicators on the basis of data unavailability or due to an inadvertent decision. For data treatment, the incongruency of various applicable methods cause output uncertainty. The same is true for normalization, indicator weighting and aggregation. The inequivalence of the methods undermines the validity of the sustainability evaluation process, which could be exploited to infuse bias in the analysis. The contrasting and, oftentimes, irreconcilable perspectives on what constitute sustainable development have been the catalyst of the existence of multiple evaluation methodologies, which aim to operationalize the conceptual nature of sustainability in a mathematical and scientific manner. The plurality of evaluation methodologies, however, motivates legitimate controversies, as the methods are clearly non-equivalent due to their incongruent structural assumptions. This, in turn, introduces methodological forms of uncertainty to the entire sustainability evaluation process, producing variable and, sometimes, conflicting results.

4.2 Treatment of methodological uncertainties

This section addressed the issue of methodological uncertainties in sustainability evaluation by rigorously identifying the main sources of uncertainty and their causes and proposed an uncertainty- and sensitivity-based sustainability evaluation framework to manage these uncertainties to produce homogenized results under the heterogenous sustainability environment. It has been pointed out that the main sources of uncertainty in sustainability evaluation occur at the stages of the multicriteria analysis. Uncertainties from these stages arise due to the multiplicity of methodologies with differing consequences, as well as the subjective judgments committed by the sustainability evaluator in methodological selection due to the lack of standards to guide the selection process. These uncertainties, if not objectively managed, can confuse stakeholders about the sustainability performance of the alternatives (or the system), preventing stakeholders from selecting the "best" alternative for a particular sustainability problem. This necessitated the use of unique analytical tools to scrutinize the methodological uncertainties objectively to raise the scientific rigor of the evaluation process.

The scientific tools uniquely applicable for uncertainty management are the variance-based uncertainty- and sensitivity analyses, which are the primary analytics of the proposed multicriteria framework for sustainability evaluation. The framework subjects all stages of the multicriteria analysis to uncertainty- and sensitivity analysis. Uncertainty analysis draws a picture of how uncertainties propagate from the methodological stages towards the output (i.e., ranking or sustainability score), providing stakeholders with a quantitative basis, in probabilistic form, to evaluate the volatility of their decisions. Uncertainty propagation transforms the result to a probabilistically (or approach), which proves to be valuable in facilitating the selection of the "best" alternatives or in guiding sustainability decisions for example the use of probabilistic ranking or the hierarchical exceedance probability matrix (HEPM). Moreover, a probabilistic approach provides additional insights about the practical value of the output total variance to support sustainability decision-making process, as well as helps characterize the risk involved with every sustainability decisions. With HEPM, the alternatives can be ordered in terms of the exceedance probability of a distribution of the sustainability scores from a threshold value. This ordering is associated with input uncertainty, which is beneficial in the selection of an alternative or sustainability decision. In some cases, using range ranking is also suitable than assigning a single rank to increase the stakeholder confidence over a particular alternative or decision, as range ranking utilizes cumulative probability, which might be substantially higher in magnitude than the probability of occurrence of a single rank.

Sensitivity analysis, on the other hand, affords the stakeholders quantitative measures (sensitivity indices) about the effects – both the isolated effect of an uncertain input factor, and its interactions with other factors – of each methodological sources of uncertainties to the total output variance. The calculation of the sensitivity indices is useful to determine the relative importance of each uncertain input factor, which may enable factor prioritization and fixing. Prioritization discriminates the uncertain input factors as non-influential – the precondition of factor fixing – or as influential. Influential factors guide the focus of the sustainability evaluation and support future deliberations on methodological choices. Factor fixing, on the other hand, simplifies the sustainability evaluation through the elimination of the uncertainty from the source; however, its mathematical condition is too rigid, as it requires that the factor's isolated effect to the total output variance is zero, and the factor should have no interaction with any other factors. Both factor prioritization and fixing, whenever mathematically allowable, aim to reduce the output variance so that the probabilities associated to each alternative will increase to an acceptable level pre-set by stakeholders in order to accept or choose the most credible sustainability decision. Tools such as uncertainty analysis and sensitivity analysis allow to decision- and policy-makers to select decisions that are substantiated scientifically and corroborated extensively by various legitimate perspectives.

5. Demonstration studies

The frameworks are demonstrated by comparing the sustainability performance of six distinct concrete mixes prepared by manipulating the constituent material. The mixes vary in terms of their cement type (OPC, BB, and FA) and the water-to-cement ratio (approx. 0.40 and 0.50) as the primary material variables. The analytical flow proceeds by adopting the fundamental steps of the multicriteria analysis comprised of: indicator selection, normalization, weighting and aggregation. The methodological uncertainties were characterized by varying the methodological approaches for each step of MA.

The indicator selection was varied by creating various sets of indicators from the initial set by dropping one indicator at a time. The normalization was allowed to vary between the methods: distance-to-a-reference and statistical standardization. Three weighting scenarios were considered comprised of: equal weighting, weighting by principal component analysis, and the weights from stakeholders. Lastly, linear sum and geometric mean were used as aggregation methods. The uncertainties from each step of MA were managed and captured by uncertainty and sensitivity analyses, from which the hierarchical ordering of the 6 mixes were determined by way of exceedance probabilities.

On top of the consideration of methodological uncertainties, three evaluation scenarios of similar structure have been created to represent the two important considerations for concrete sustainability: the effect of environmental conditions – captured by durability estimates – and the condition of data unavailability. The durability is measured by the initiation of steel reinforcement corrosion. Missing data, on the other hand, is expressed by case deletion – removing indicators with no data. With this, the scenarios considered are: CL – for a condition where chloride is the primary cause of corrosion and with relatively comprehensive indicator set; CB – for a condition where carbonation is the primary cause of corrosion and utilizing a comprehensive indicator set; and CL* - similar CL but with few indicators due to missing data. Methodological uncertainties were considered in each scenario.

For the CL scenario, the presence of methodological uncertainty created a variation in the sustainability scores of the mixes. According to the result of sensitivity analysis the primary cause of variability is the choice of weighting and normalization methods. The effect of indicator set inconsistency is not so prevalent, and the choice of aggregation method is the least influential in the analysis, implying that it can be fixed to either of the aggregation approach considered. KS and DKW test performed have shown that fixing the aggregation method to either linear or geometric aggregation have no significant effect on the resulting sustainability scores. The mixes were hierarchically ordered by the use of exceedance probability to capture the uncertainty in the sustainability scores. In this scenario the mixes using BB have been rank as the "most" sustainable alternative.

In the case of CB scenario, the methodological uncertainty created similar variation in the sustainability scores of the mixes. In this scenario the most influential source of uncertainty is the choice of normalization method explaining more the 60% of the total variance. In contrast the aggregation method is the least influential, accounting only 4% of the total variance, implying that the aggregation method can be fixed to either of the two approaches considered. KS and DKW statistics, however, demonstrated the opposite, as the comparison of the empirical cumulative distributions after factor fixing and the original showed statistically significant difference. The hierarchical ordering of the mixes by probability of exceedance, however, produced the same ranks as the CL scenario.

The CL* scenario, similarly showed parallel effect with CL and CB on the sustainability scores of the mixes due to methodological uncertainties. The sustainability scores of the mixes showed different magnitudes of variabilities. The most influential source of uncertainty is still the normalization method, which accounts about 67% of the total variance based on the total effects. The least influential is again the choice of aggregation method, which explains about only 2% of the total variance based on the total effects, implying that aggregation could be fixed to either LN or GM. KS and DKW statistics validates that the aggregation method could be fixed as it was demonstrated that there was no significant effect on the sustainability scores of the mixes. The hierarchical ordering of the 6 mixes by probability exceedance matrix, however, showed significant rank reversals of the alternatives, implying that the use of less indicator set could not substitute for a relatively comprehensive set as in CL.

CL, CB and CL* scenarios reflect the effect of methodological uncertainties on the sustainability scores of the alternatives. It was also demonstrated that the use of UA and SA as part of the architecture of the sustainability evaluation framework was beneficial in measuring quantitatively the influence of each methodological source of uncertainty, which discriminated each factor as influential or non-influential. The use of conditional statistics like KS and DKW further validates the condition for factor fixing, which could lead to the elimination of non-influential sources of uncertainties, making the evaluation more robust. The use of hierarchical exceedance probability matrix was also demonstrated to be effective at ordering the alternatives, leading to the identification of "best" sustainable options despite the presence of uncertainties. Therefore, the demonstrations illustrated in this Chapter have confirmed the applicability of the multicriteria analysis under methodological uncertainties for sustainability decision problems.

6. Concluding remarks

The thesis centers on to two major works: the development of an indicator framework for sustainable concrete material and the formulation of a robust sustainability evaluation framework under methodological uncertainties. The purpose of the indicator framework is to formalize in quantitative sense the idea of sustainable concrete to support decision making processes. The indicator framework helps define distinctively the constituency of sustainable concrete material. It was developed by first identifying potential indicators from various literatures. The characteristics and the inherent relationships between indicators helped in the formation of the indicator's causal framework. They were then link to the global perspectives on sustainable development to make them robust for sustainability evaluation purposes. The sustainability evaluation framework, on the other hand, is a methodological approach to make quantitative assessments of sustainability. In order for the indicator framework to be operable, it should be used together with the evaluation framework. The architecture followed in building the evaluation framework is the multicriteria analysis under methodological uncertainties. This is to account for the multiplicity of approaches applicable to perform multicriteria analysis, which could produce divergent results. To resolve this issue the analytics of the sustainability evaluation framework integrates both uncertainty and sensitivity analyses. The practical implementation of both frameworks was demonstrated in the selection problem of various sustainable concrete materials. The indicator framework and the evaluation framework together with the rich plethora of analytical methodologies presented in this research transformed in a robust way the concept of sustainable concrete into engineering terms that are actionable for various stakeholders of the industry. These outputs are expected to spur innovations in sustainable concrete material design, development of industry standards and specifications, and ultimately assists the industry stakeholders in reaching critical decisions for the sustainability of concrete material.

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