Application of Generalized Choquet Fuzzy Integral Method in the Sustainability Rating of Green Buildings based on the BSAM Scheme

Abstract

The need to reduce the impact of building projects on the sustainability of the built environment and improve the use of resources necessitated several interventions such as the development of methods to assess building impacts and improve the sustainability performance of buildings. Using the BSAM scheme – a green building rating system developed specifically for the sub-Saharan region of Africa, the generalized Choquet fuzzy integral method was employed to determine the importance weights of the sustainability assessment criteria. Data collected from industry experts form the base inputs for the impact of the various sustainability criteria based on the local variations. Consequently, the building sustainability evaluation index and grading scheme were developed to measure and evaluate the sustainability performance of buildings. The developed sustainability rating model was validated in four real-world case studies to demonstrate its usefulness and robustness in practice. The findings revealed that the conventional approach of aggregation of points used by the existing green rating tools is less effective in dealing with criteria that have interactive characteristics. Also, assessment criteria such as sustainable construction practices, transportation, and energy have a significant impact on the sustainability of buildings. The study provides substantial contributions to the existing body of knowledge about green building assessment systems for built environment stakeholders, both from the theoretical and practical perspectives.

Keywords: Buildings; built environment; generalized Choquet fuzzy integral; green rating system; multi-criteria; sustainability

1. Introduction

Optimum determination of the sustainability performance or greenness of buildings and infrastructure is vital to fulfilling the objectives of sustainable development in the built environment. Assessment of the impact of the building throughout its lifecycle on the built environment involved an intricate process which includes a hierarchical structure of several variables that comprises the three pillars of sustainability – social, environmental, and economic sustainability (Mahmoud et al., 2019; Olawumi & Chan, 2018). These variables or sustainability criteria (as referred to henceforth in this study) need to be controlled or regulated to achieve the intended level of sustainability performance and reduce their harmful impacts on the building users and the environment.

Building and infrastructure projects are essential and contribute to societal wellbeing, economic development, and the safeguard of the environment. However, the design of these structures, their locations as well as the use of resources (material and energy), waste and emissions generation have a significant effect on the sustainability of the built environment. Therefore, to reverse this negative trend and ensure the prudent allocation and use of resources throughout the building lifecycle, it is essential to develop methods of assessing the impacts arising from the project as well as the building users' activities. Moreover, it is necessary to – and evaluate the efficacy of the various policies, plans, and strategies for the building project and ascertain the extent they influence the sustainability performance of the building and the overall sustainable development.

Several studies have been conducted on assessing the sustainability performance of buildings and sustainability rating tools such as the Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), BEAM Plus has been developed. However, these studies and green rating tools fail to present a unified sustainability evaluation criteria or variables, that is, only catered for 1-2 of the three sustainability pillars. Apart from these, these studies utilized aggregation of points that have many shortcomings, which have been discussed in the extant literature (*see* Ahmad & Thaheem, 2018; Illankoon et al., 2017; Mahmoud et al., 2019).

Two key shortcomings of this "aggregation of points" approach is that it does not allow for interactivity the main criteria and sub-criteria as well as does not reflect interdependence of these criteria (Kurt, 2014; Ozdemir & Ozdemir, 2018); For instance, Ahmad and Thaheem (2018) developed an economic sustainability assessment framework for residential buildings and study using normalization methods; although the study focused solely on economic sustainability criteria, it still left out some key criteria such as reuse of construction materials, local economy, etc. Also, the normalization methods adopted are inadequate. Similarly, Atanda (2019) employed the Analytic Hierarchy Process (AHP) to identify the social indicators for green buildings assessment. However, the study fails to consider the environmental and social construct of sustainable development.

The widely used green building rating systems such as LEED, BREEAM, BEAM Plus, Green Mark, etc. (BCA, 2015; BRE, 2018; HKGBC, 2018; USGBC, 2017) mainly focused on the environmental sustainability with little or no consideration for the other aspects of sustainability. More so, these green rating tools employed simple addition of points that are incapable of expressing the interactions among the sustainability criteria. Ali and Al Nsairat (2009) developed a green assessment tool for Jordan with a little more focus on the environmental and social constructs but utilized the AHP methodology, which is less effective in dealing with sustainability variables of hierarchical nature (Krishnan et al., 2015).

Mahmoud et al. (2019) utilized one of the Multi-Criteria Decision Making (MCDM) techniques – fuzzy TOPSIS to develop a green assessment tool for existing buildings for Canada and Egypt. However, the developed tool, like the other assessment frameworks in the existing literature, focused solely on environmental sustainability. Although the fuzzy TOPIS methodology aims to estimate the gaps between the expected and perceived sustainability performance in the study, it still fails to consider the interaction among the decision criteria. However, it is difficult to ignore the interactions among the sustainability criteria in a hierarchical structure. For instance, the "*thermal performance of building envelope*" consider in this study under the *energy* criterion have significant effect on the "*indoor air quality*" and "*visual comfort*" recognized under the *indoor environmental quality* (IEQ) criterion.

Tan and Chen (2010), Krishnan et al. (2015), and Perçin (2019) confirmed that in real scenarios, these criteria hold some degree of relationships that requires a robust weighting tool such as the GCFI. As emphasized by Perçin (2019), additive models such as the MCDM techniques such as AHP, TOPSIS, etc. and their fuzzy versions, as well as other existing methodologies, are insufficient to evaluate dependent and non-additive sustainability criteria as expressed in this study. Krishnan et al. (2015) present some examples to illustrate the interactive characteristics of criteria and the significance of using additive and non-additive (such as GCFI) operators.

Given the above gaps in the literature as regards the (i) the need for a unified sustainability assessment system that encompasses the social, economic, and environmental criteria; (ii) previous studies utilized additive MCDM technique which is insufficient to assess dependent and subjective criteria; and (iii) the need to capture the interrelationships among these sustainability assessment criteria. The current study aims to utilize an MCDM technique – the generalized Choquet fuzzy integral (GCFI) method for the evaluation of the sustainability rating of green buildings based on the decision criteria of the Building Sustainability Assessment Method (BSAM) scheme green rating system as well as addressed the above literature gaps. The BSAM scheme is a green building rating system that took adequate and equal consideration for the three pillars of sustainability (Olawumi & Chan, 2019). The BSAM scheme was developed in the course of this research project, and the current study describes the development of the weighting methodology for the BSAM scheme using the GCFI algorithm. The GCFI method according to extant literature (Bebčáková et al., 2011; Çakır, 2017; Zhang et al., 2019) adequately addressed the issue of the interactions among dependent sustainability criteria in a hierarchical structure. More so, according to Perçin (2019), using independent criteria in solving MCDM problems as evident in extant literature regardless of their effect on each other will limit its ability to evaluate the subject matter adequately.

The remainder of this paper is structured as follows. Section 2 presents the GCFI, its formulations, and how GCFI is a more efficient weighting technique than other MCDM tools such as fuzzy AHP, fuzzy ANP, fuzzy TOPSIS, etc. for decision-making scenario like the sustainability assessment of the building. Section 3 illustrates the steps of the GCFI methodology and how it was applied to the decision sustainability criteria. It also presents an application of the GCFI to real-life projects via case studies validation of the developed building sustainability evaluation index. Section 4 presents the discussion of the findings, and the last section summarizes the study and makes suggestions for further research.

2. State of the art: The General Choquet Fuzzy Integral (GCFI) Method

The Choquet fuzzy integral has found its usefulness in solving numerous MCDM problems in the extant literature. The GCFI technique has discussed in Section 1 and later in this section is superior to the other MCDM techniques. More so, it has only been applied once to solve an MCDM problem relating to sustainability issues when Ozdemir and Ozdemir (2018) employed the GCFI approach to select the best alternative among five residential heating systems. In the industrial sector, Demirel et al. (2010) utilized GCFI to resolve a warehouse logistic issues for a large Turkish company while in the hospitality sector, Perçin (2019) used it to evaluate the quality of hospitals' websites; and Karczmarek et al. (2018) employed GCFI for face recognition and classification; also, GCFI was used to evaluate equipment maintenance quality (Zhang et al., 2019), hybrid image encryption (Hosseinzadeh et al., 2019), and supplier selection for a steel factory (Çakır, 2017). Other applications of GCFI to solve MCDM problems include voice recognition, traffic surveillance, temperature prediction (Fang et al., 2010), game theory, neural networks (Qin et al., 2016), among others. The GCFI is regarded as a better alternative to the fuzzy ANP (Demirel et al., 2010).

2.1 Historical development of the GCFI method

The first development of the GCFI methodology was the Choquet integral introduced by Sugeno (1974) as a flexible aggregator operator and the generalization of the Lebesque integral (Demirel et al., 2010; Grabisch & Roubens, 2000). It involves generalizing the “weighted average method,” the “Ordered Weighted Average” (OVA) operator, and the max-min operator (Grabisch et al., 2000). It is a non-additive measure and aims at representing the significance of a criterion and the interactions among dependent criteria (Demirel et al., 2010; Perçin, 2019). More so, to define these fuzzy integrals, a set of values are required for the criterion, and these values are in fuzzy measures; also, if these criteria have sub-sets (as seen in this study) – the values of importance should be defined as well.

The next phase of the development of GCFI was the presentation of the generalized form of the Choquet integral by Auephanwiriyakul et al. (2002); and further improvement through the use of linguistic expressions and fusion of information among criteria, as well as the use of interval measurements by Tsai and Lu (2006). This helps to overcome the ambiguity of the questionnaire scale terms. Unlike other MCDM techniques, the GCFI adequately cater to the dependence between the decision-makers' judgments and the assessed criteria (Perçin, 2019); and this makes it differ significantly from the Sugeno integral.

The Sugeno and Choquet integral operators can deal with interactive decision criteria; however, the GCFI is better suited across many research areas (Narukawa & Torra, 2007). Furthermore, the Choquet integral is ideal for numerical and quantitative problems where cardinal aggregation is required while the Sugeno integral is best suited for qualitative problems where only the ordinal aggregation of the attributes is essential (Krishnan et al., 2015). The GCFI is a type of fuzzy set operation which depends heavily on information aggregation at hierarchical levels towards making informed decisions (Chiang, 1999), and its ability to model interactions of the decision criteria set it apart from others.

2.2 Underlying conditions for adopting the GCFI method

In the context of MCDM analysis, Krishnan et al. (2015) defined aggregation as the process of evaluating the weights of a set of decision criteria under evaluation into a global score; and based on this single final score, the alternatives (e.g., building projects) can be classified or ranked. Hence, before employing GCFI, the decision-makers must input the importance value of the decision criteria and their subsets. An aggregation operator must have two fundamental properties, which are the monotonicity and boundary conditions (Cheng & Hsu, 1991; Karczmarek et al., 2018). However, the GCFI has an additional property for its fuzzy measures (λ-measure), which makes the Choquet integral more robust due to the ease of usage and good "degree of freedom" of the λ-measure (Krishnan et al., 2015).

The λ-measure of the GCFI technique represents the "degree of additivity" the criteria hold. Hence, according to Gürbüz et al. (2012) and Hu and Chen (2010): (i) If $\lambda < 0$, it implies that the decision criteria share sub-additive (redundancy) effect. It means an increase in the overall sustainability performance of a building can be achieved by enhancing the sets of criteria which have higher weights or individual importance. (ii) If $\lambda > 0$, it implies that the decision criteria share a super-additive (synergy) effect. It means to achieve an increase in the overall sustainability of a building, all the sets of criteria must be enhanced regardless of their weights or individual importance. (iii) If $\lambda = 0$, it indicates that the sets of decision criteria have non-interactive characteristics.

Therefore, for the GCFI method to be employed for any MCDM problem, especially for a hierarchical network of decision criteria, the fuzzy measure, λ, must either be $\lambda < 0$ or $\lambda > 0$. A limitation of the fuzzy measure λ is that it requires a large quantity of information from decision-makers (Krishnan et al., 2015). Hence, as discussed in section 3.1.1, the current study utilized a sizeable number of decision-makers (experts) to determine the overall building sustainability evaluation index. Zhang et al. (2019) added that the λ-fuzzy measure has significant advantages over the other four fuzzy measures in the extant literature, and it has a relatively simple structure. Yildiz and Yayla (2017) and Qin et al. (2016) demonstrated that the classical MCDM techniques are ineffective in solving real-world decision problems, unlike the fuzzy MCDM methods, which are more suitable to cope with uncertainty issues in practical applications.

2.3 Advantages of the GCFI method over other MCDM techniques

In a comparison of the GCFI with some other widely used MCDM techniques; unlike the GCFI, the AHP rely on independent decision criteria (Zhang et al., 2019) and does not adequately capture qualitative criteria (Çakır, 2017) which makes it unsuitable for resolving non-additive and dependent models. More so, Çakır (2017), in analyzing an MCDM problem for a steel-producing company, carried out a comparative assessment of the different MCDM techniques such as fuzzy TOPSIS, fuzzy ANP, fuzzy DEMATEL, EAM and found the GCFI method to be superior. Also, fuzzy TOPSIS can handle hierarchical problems but not interactive criteria (Kurt, 2014; Ozdemir & Ozdemir, 2018). Moreover, other advantages of the GCFI over the other weighting methodology include:

i. it allows for the interactivity among the main criteria and its sub-criteria (Kurt, 2014; Ozdemir & Ozdemir, 2018).

ii. Its use of trapezoidal fuzzy numbers and range computations using integral provides a better result (Kurt, 2014; Ozdemir & Ozdemir, 2018).

iii. Its use of signed fuzzy measure allows for an efficient approach to information aggregation (Fang et al., 2010); and

iv. The usefulness of the GCFI algorithm in many information fusion and data mining problems (Yang et al., 2005).

All these make the GCFI method a more suitable and practical weighting method than the other MCDM techniques.

The steps for the GCFI algorithm (Demirel et al., 2010; Grabisch & Roubens, 2000; Kurt, 2014; Ozdemir & Ozdemir, 2018; Perçin, 2019) are summarized in section 3. Meanwhile, to minimize round-off error and ease the speed of running the GCFI algorithm in this study as illustrated in section 3, a PHP-based cloud platform was developed to record the input collated from each invited experts for each criteria and their sub-sets, analyzed the data based on the GCFI algorithm, and to output the solutions as presented in subsequent sections.

3. Application of the GCFI Method: Sustainability Rating of Green Buildings

This section discusses how an MCDM method in the form of the generalized Choquet fuzzy integral algorithm was applied to develop a sustainability evaluation index that can be employed to rate the sustainability performance of green buildings. See Figure 1 for the research methodology framework employed in this study. Further, in this section, the developed building sustainability evaluation index (BSEI) is used to evaluate four real-life case studies of building projects.

The set of equations that is Eq. (1) to Eq. (13), except Eq. (2) as discussed in Section 3, are based on the General Choquet Fuzzy Integral (GCFI) methodology as adopted from the extant literature (*see* Dong et al., 2016; Huang et al., 2010; Kurt, 2014; Ozdemir & Ozdemir, 2018).

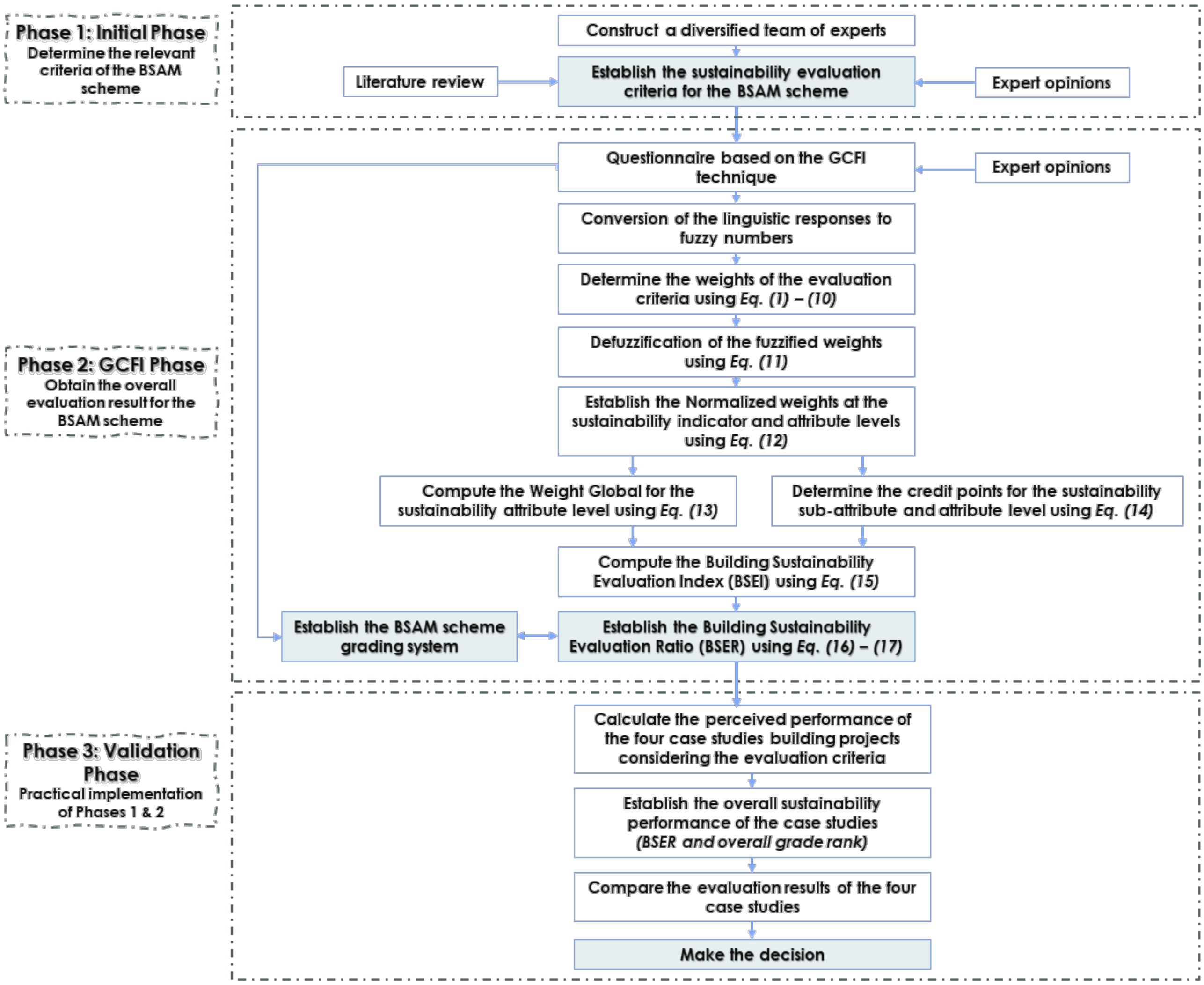

Figure 1: Overall framework of the research methodology

3.1 Determination of the Building Sustainability Evaluation Index (BSEI)

In this study, the GCFI algorithm was applied to the developed Building Sustainability Assessment Method (BSAM) scheme – a green building rating system specifically designed for countries in the sub-Saharan region of Africa (Olawumi & Chan, 2019). The structure of the BSAM scheme framework is illustrated in Figure 2. The BSAM scheme has three sustainability criteria levels in its hierarchical structure: which are sustainability indicators (SI), attributes (SA), and sub-attributes (SSA), which have 8, 32, and 136 criteria, respectively. These criteria contain both quantitative and qualitative information. The GCFI algorithm was employed to determine the weightings of these sustainability criteria (*SI, SA, & SSA*) towards establishing the overall BSEI which can then be used to (a) rate the sustainability performance of a building; and (b) select the best green building alternative or rank a set of building projects – based on their different key sustainability criteria.

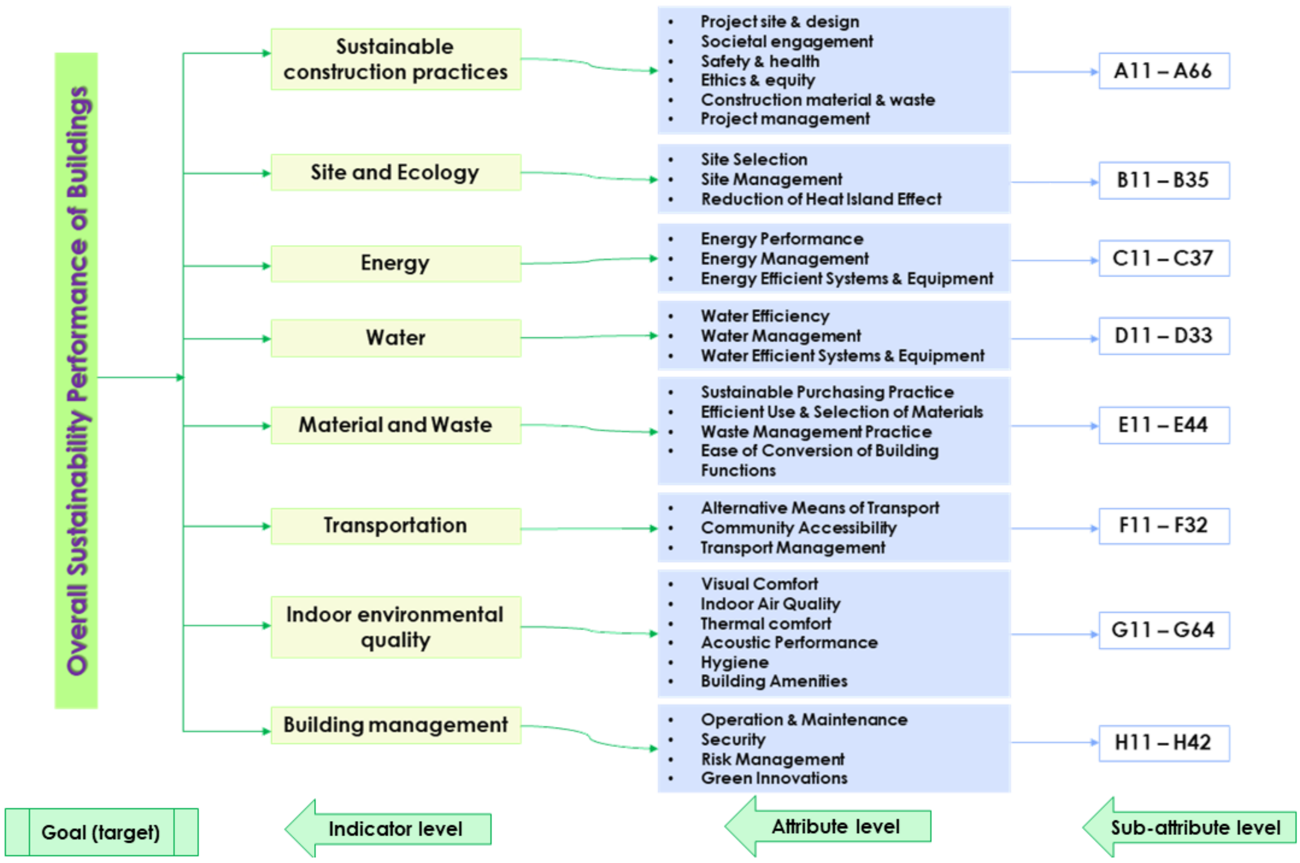

Figure 2: Hierarchical structure of the sustainability evaluation criteria of the BSAM scheme

3.1.1 Experts' demographics

Bebčáková et al. (2011) reported that the weights of the sustainability criteria must be estimated expertly. Hence, the input data for this study is based on the responses derived from the decision-making group, which was composed of 189 experts in the built experts over six months. The experts were selected using purposive and snowball sampling techniques. See Figure 3 for the analysis of the demographics of the experts. As shown in Figure 3, the invited experts are from ten distinct and varied professions; and this multi-expert consultation approach was recommended by Ali and Al Nsairat (2009) who pointed out that a diverse set of key participants should be involved in the process of developing green building assessment rating tools. Previous studies that adopt the GCFI method, such as Kurt (2014), who used the GCFI method and fuzzy TOPSIS to select the best site for a nuclear power plant, utilized three power system experts. Also, Ozdemir and Ozdemir (2018), who applied the GCFI to prioritize five residential heating systems, sought the opinion of three experts to provide the importance values of the four heating system criteria.

A comparative assessment of the statistics of the experts involved in this study and the existing literature (where the GCFI algorithm was adopted) shows that an increased number of participating experts in the decision-making. It also revealed the involvement of a highly experienced set of experts in the subject matter based on their years of working experience and participation in the implementation of sustainability practices in the built environment. Thus, this lends further credence to the input data for the development of the BSEI and its subsequent application to rate the sustainability performance of four case studies building projects.

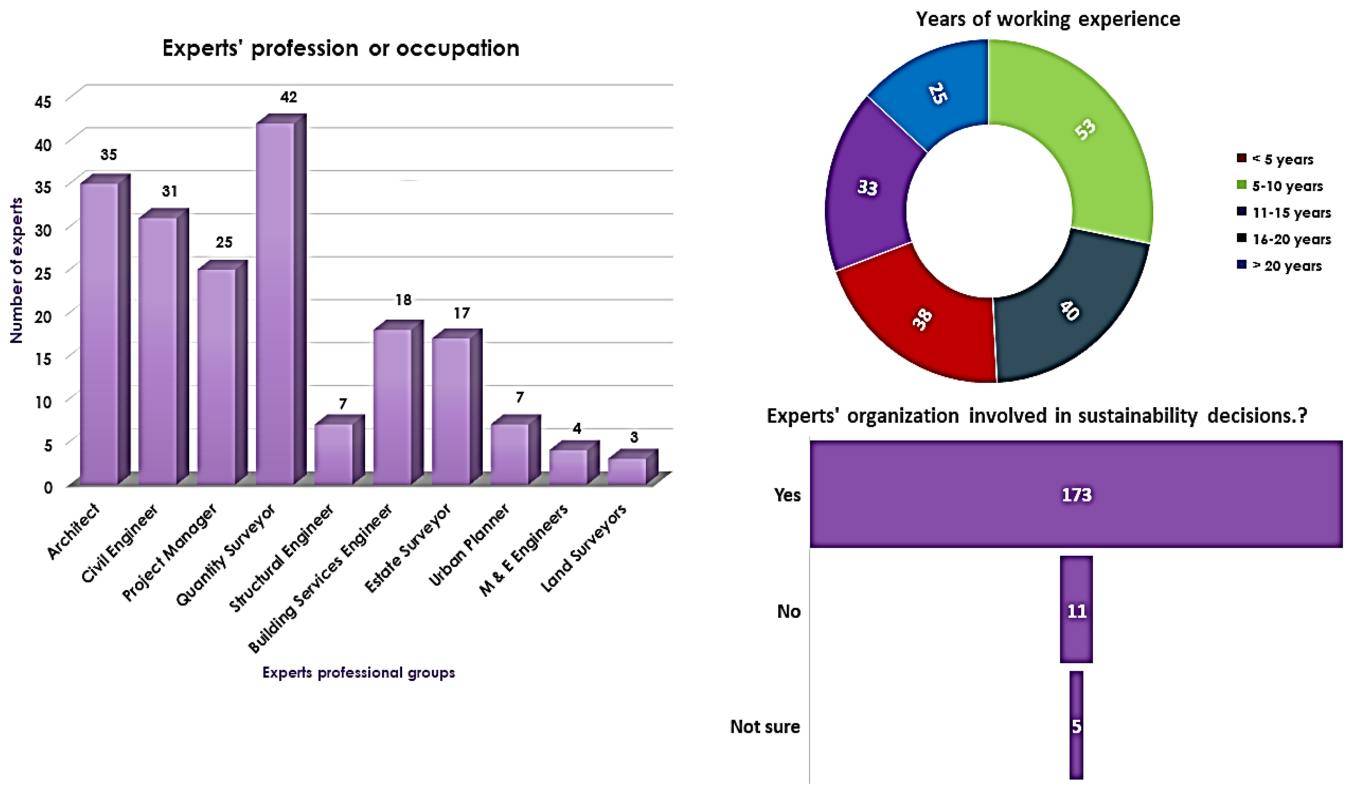

Figure 3: The experts' demographics

3.1.2 The fuzzification process

As mentioned, the experts are invited to identify the degree of significance of each sustainability criteria that are critical to the sustainability performance of buildings. The sustainability criteria provide the right mix of key criteria that satisfies the three pillars of sustainable development as it relates to building projects – social, economic, and environmental sustainability. The experts were requested to provide five sets of four numbers (trapezoidal fuzzy numbers) to express the five-linguistics variables – "*very high,*" "*high*," "*medium*," "*low*," and "*very low*" (*see Appendix A*). That is, each set of linguistics variables corresponds to four numbers, which represent a trapezoidal fuzzy number that comprises a minimum threshold (lowest number in the fuzzy set), two median thresholds, and the maximum threshold (highest number in the fuzzy set).

Step 1: Fuzzifying the 'degree of importance' levels

Given the sustainability criteria, i; the linguistics terms of the experts for the "degree of importance," the "degree of significance" of each sustainability criteria, and the tolerance zone can be quantified.

Table 1 shows the relationship between the "trapezoidal fuzzy numbers" (TFN) and degree of importance (linguistics variables) on a five-linguistic-term scale. The TFN has shown in Table 1 and, as represented in Figure 4, is the average value based on the mean of the input values for the 'degree of importance' provided by the 189 invited experts based on Eq. (1) (Ozdemir & Ozdemir, 2018).

$$\tilde{P}_i,\ \tilde{A}_i = \frac{\sum_{t=1}^{k} \tilde{A}_i^t}{k} = \left(\frac{\sum_{t=1}^{k} \tilde{a}_{i1}^t}{k}, \frac{\sum_{t=1}^{k} \tilde{a}_{i2}^t}{k}, \frac{\sum_{t=1}^{k} \tilde{a}_{i3}^t}{k}, \frac{\sum_{t=1}^{k} \tilde{a}_{i4}^t}{k}\right) \quad (1)$$

Where k is the number of invited experts; expert t, and the linguistic terms for the "degree of importance" is parameterized by $\tilde{A}_i = (\tilde{a}_{i1}^t, \tilde{a}_{i2}^t, \tilde{a}_{i3}^t, \tilde{a}_{i4}^t)$, where $\tilde{a}_{i1}^t, \tilde{a}_{i2}^t, \tilde{a}_{i3}^t, \tilde{a}_{i4}^t$ are trapezoidal fuzzy numbers of $\tilde{A}_i$; and the 'degree of significance' is parameterized by $\tilde{P}_i = (\tilde{p}_{i1}^t, \tilde{p}_{i2}^t, \tilde{p}_{i3}^t, \tilde{p}_{i4}^t)$, where $\tilde{p}_{i1}^t, \tilde{p}_{i2}^t, \tilde{p}_{i3}^t, \tilde{p}_{i4}^t$ are trapezoidal fuzzy numbers of $\tilde{P}_i$.

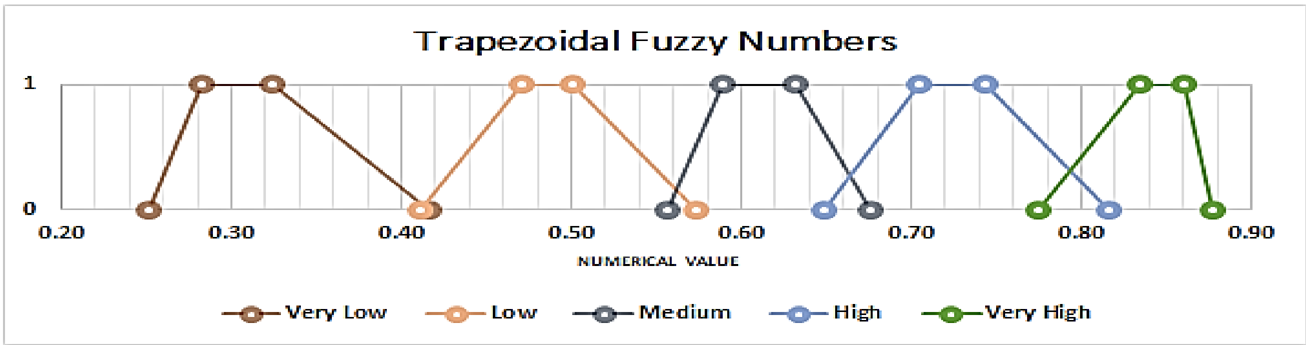

Figure 4: Representation of the Trapezoidal Fuzzy Numbers

[Insert Table 1]

Step 2: Determination of the Tolerance Zones and perceived 'degree of significance' for the key sustainability criteria

More so, considering the relationship between the perceived degree of significance and the tolerance zone of each key sustainability criteria, the TFN was used to quantify all the linguistic terms inputted by the experts (see Table 2).

Two 'degree of significance' TFN numerical values were derived. Firstly, the average 'degree of significance' value ($\tilde{P}_i$) for each sustainability criterion based on the inputs of the experts (*see Appendix B*) using the five-linguistic-term scale was calculated using Eq. (1) and as presented in Table 2.

Secondly, the average 'degree of significance' value (*best alternative*) ($\tilde{T}_i$) was calculated as follows. (i) The experts were asked to rank the sustainability sub-attributes for each criterion on a three-scale point (Required, Optional, Negligible), otherwise known as the RON scale (*see Appendix C*). (ii) The '*Required*' scale (R) was given a value of 1.0; '*Optional*' scale (O) – a value of 0.5; and '*Negligible*' scale (N) – a value of 0.0.

(iii) The mean RON values ($\tilde{R}_i$) for each criterion (attributes) is calculated by Eq. (2):

$$\tilde{R}_i = \frac{\sum_{t=1}^{k} \tilde{R}_i^t}{n} \times \frac{1}{k} \qquad (2)$$

Where k is the number of invited experts; expert t, number of *SSA* within each criterion (*SA*) n, and the RON values (see Table 2) for each criterion is represented by $\tilde{R}_i$. (iv) The individual 'degree of significance' (*best alternative*) ($\tilde{T}_i$) for each key criterion (A1 – H4) was calculated by multiplying the mean RON values ($\tilde{R}_i$, Eq. (2)) for each criterion (*SA*) with the highest numerical values of the highest linguistic-term scale (that is, VH).

For instance, in Table 2 – the $\tilde{R}_i$ of A1 is 0.667 and VH is (0.774, 0.834, 0.860, 0.876); hence, the 'degree of significance' value (*best alternative*) ($\tilde{T}_i$) is (0.516, 0.556, 0.574, 0.584).

The determination of the average 'degree of significance' (*best alternative*) ($\tilde{T}_i$) allows for the development of the BSEI and evaluating the sustainability performance of different sets of building as later seen in this study without having to repeat the entire GCFI algorithm for each new set of buildings. A similar approach was adopted by Mahmoud et al. (2019) in using fuzzy TOPSIS to develop an index. Hence, determining the average 'degree of significance' (*best alternative*) ($\tilde{T}_i$) in this study offers an improvement on existing GCFI algorithm as employed in previous studies.

The minimum (min) tolerance and the maximum (max) tolerance value is based on the lowest and highest linguistic-term scale of the sustainability criteria. Meanwhile, the tolerance zones in Table 2 are obtained by combining the first two numerical values of the 'min tolerance value' with the last two numerical values of the 'max tolerance value' for each sustainability criteria. For instance, tolerance zone [M, VH] for sustainability criteria A1; the numerical values of M and VH based on Table 1 is (0.556, 0.589, 0.631, 0.676) and (0.774, 0.834, 0.860, 0.876) respectively. Hence, the combined tolerance zone ($\bar{e}_i^{\propto}$) for criteria A1 is (0.556, 0.589 ,0.860, 0.876).

[Insert Table 2]

Step 3: Evaluation of the Fuzzy Valence Functions $[f_{i,\propto}^{-}, f_{i,\propto}^{+}]$ for the key sustainability criteria – at the SA and SI levels

Using $\tilde{f}_i \in \tilde{F}(S)$ as the fuzzy valence function (Kurt, 2014; Ozdemir & Ozdemir, 2018), the significance of the criterion for the 'best alternative (BA)' building prototype can be normalized using Eq. (3).

$$\tilde{f} = \|_{\propto\in[0,1]} \tilde{f}_i^{\propto} = \Big\|_{\propto\in[0,1]} [f_{i,\propto}^{-}, f_{i,\propto}^{+}] \quad (3)$$

Where $\tilde{f}$ is the set of fuzzy valence functions which are made to represent $\tilde{F}(S)$ for all $\propto \in [0,1]$. Hence, the $\propto$-level fragments of $\bar{P}_i^{\propto}$ ('degree of significance' for BA) and $\bar{e}_i^{\propto}$ (tolerance zone) for each sustainability criterion can be defined using Eq. 4. Eq. 4 represents the fuzzy valency functions for the sustainability criteria – that is, at the *SI's* level (A1 – H4).

$$\tilde{f}_i^{\propto} = [\tilde{f}_{i,\propto}^{-}, \tilde{f}_{i,\propto}^{+}] = \frac{\bar{P}_i^{\propto} - \bar{e}_i^{\propto} + [1,1]}{2} \quad (4)$$

More so, to calculate the fuzzy valency functions at the sustainability indicator levels (A – H), Eq. (5) is employed. Eq. (5) considers the respective $\tilde{f}_i^{\propto}$ of the *SA* (calculated in Eq. (4)) of their corresponding *SI* – that is, to calculate for A, the $\tilde{f}_i^{\propto}$ for attributes A1 – A6 is taken into account in Eq. (5).

$$\int \tilde{f}\, d\tilde{g} = \|_{\propto=[0,1]} \left[(C) \int \tilde{f}_{\propto}^{-} d\tilde{g}_{\propto}^{-} , (C) \int \tilde{f}_{\propto}^{+} d\tilde{g}_{\propto}^{+}\right] \quad (5)$$

Where $\bar{g}_i : P(S) \to I(R^{+})$, $\bar{g}_i = [g_i^{-}, g_i^{+}]$, $\bar{g}_i^{\propto} = [g_{i,\propto}^{-}, g_{i,\propto}^{+}]$, $\overline{f}_i : S \to I(R^{+})$ and $[\tilde{f}_i^{-}, \tilde{f}_i^{+}]$ for i=1,2,3,…, nj.

Tables 3 presents the evaluation results by the GCFI algorithm for $\propto = 0$ for all the key criteria. The "individual significance" column shows the lowest and the highest value of the "average 'degree of significance' value" for the best alternative ($\tilde{T}_i$) in Table 2. For instance, the TFN for criteria "A1" in Table 2 ($\tilde{T}_i$) is (0.516, 0.556, 0.574, 0.584); and the "individual significance" ($T_{i,0}$) for that criterion is obtained as

[0.516, 0.584]. Same for the tolerance zone ($e_{i,0}$) of A1 is [0.556, 0.876]. As mentioned, for the *SA* (A1 – H4), Eq. (3) and (4) is used; while Eq. (5) is used for the *SI* (A – H).

Hence, the fuzzy valence function $\tilde{f}_{i,0}$ for criteria, A1 is calculated as follows (see Table 3):

$$f,\tilde{f}_{(A1)} = \left[\tilde{f}_{(A1),0}\right] = \frac{[0.516, 0.584] - [0.556, 0.876] + [1,1]}{2} = \left[\frac{(0.516 - 0.876 + 1)}{2}, \frac{(0.584 - 0.556 + 1)}{2}\right]$$

$$= [\mathbf{0.320, 0.514}] \quad for\ (\propto = 0)$$

[Insert Table 3]

More so, Table 4 gives the evaluation results by the GCFI algorithm for $\propto = 1$ for all the key criteria. The $\propto = 1$, in this case, considers the two median values of the "average 'degree of significance' value" for the best alternative ($\tilde{T}_i$) as presented in Table 2 – as the "individual significance" column in Table 4. For criteria A1, the "individual significance" ($T_{i,1}$) is [0.556, 0.574] and the tolerance zone ($e_{i,1}$) is [0.589, 0.860]. The fuzzy valence function $\tilde{f}_{i,1}$ for criteria, A1 is [0.348, 0.492] as calculated using Eq. (3) and (4) (see Table 4):

$$f,\tilde{f}_{(A1)} = \left[\tilde{f}_{(A1),1}\right] = \frac{[0.556, 0.574] - [0.589, 0.860] + [1,1]}{2} = [\mathbf{0.348, 0.492}] \quad for\ (\propto = 1)$$

[Insert Table 4]

Step 4: Computation of the λ value (for the sustainability indicators, A – H) and the Fuzzy measures $\mathbf{g(A_{(i)})}$

Meanwhile, to calculate the location value, a λ value (*for the indicators, A – H*) and the fuzzy measures $g(A_{(i)})$ (*for the attributes, A1 – H4*), where i=1,2,3, …, n is needed. These are derived using Eq. (6) to (8) as follows:

$$g(A_{(n)}) = g(\{P_{(s)}\}) = g_n \tag{6}$$

$$g(A_{(i)}) = P_i + g(A_{(i+1)}) + \lambda P_i g(A_{(i+1)}), \qquad for\ 1 \le i \le n \tag{7}$$

$$1 = g(S) = \begin{cases} {}^{1}/_{\lambda} \left\{ \prod_{i=1}^{n} [1 + \lambda g(A_i)] - 1 \right\} & if\ \lambda \ne 0 \\ \sum_{i=1}^{n} g(A_i) & if\ \lambda = 0 \end{cases} \tag{8}$$

Eq. (8) is used for solving for λ for $\propto = [0,1]$ (see Tables 5 & 6); where $\tilde{P}_{(s)}$ is the average 'degree of significance' value for the highest-ranked fuzzy valence functions $\tilde{f}_i^{\propto}$ for each criterion, i; and P_i is the regular 'degree of significance' value for its corresponding criteria, i.

For instance, as shown in Table 5, the λ for criteria A, taking $\propto = 0$ is calculated to give λ [-0.9963, -0.9997]. The average 'degree of significance' value for the subset of criteria 'A' ($P_{(A),0}$) as presented in Table 2 (*that is, A1 – A6*) is used as the fuzzy numbers 'g' as shown in Eq. (8) which are [0.660, 0.789], [0.597, 0.736], [0.597, 0.736], [0.597, 0.736], [0.528, 0.672], [0.660, 0.789], and [0.597, 0.736] for sustainability attributes A1 – A6 respectively (taking $\propto = 0$).

$$1 = g(S) = {}^{1}\!/_{\lambda}\ \{[(1+0.660\lambda)(1+0.597\lambda)(1+0.597\lambda)(1+0.528\lambda)(1+0.660\lambda)(1+0.597\lambda)] - 1\} \qquad for\ \propto = 0 \text{ and } \lambda^{-}$$

$$1 = g(S) = {}^{1}\!/_{\lambda}\ \{[(1+0.789\lambda)(1+0.736\lambda)(1+0.736\lambda)(1+0.672\lambda)(1+0.789\lambda)(1+0.736\lambda)] - 1\} \qquad for\ \propto = 0 \text{ and } \lambda^{+}$$

The two solutions give: $\lambda = [-\mathbf{0.9963},\ -\mathbf{0.9997}] \quad for\ \propto = 0$. Hence, See Tables 5 and 6 for the λ values for the sustainability indicators (A – H) for $\propto = [0,1]$ respectively.

More so, to calculate the fuzzy measures $\mathrm{g}(\mathrm{A}_{(\mathrm{i})})$, for 1=1, 2, 3, ..., n for the sustainability attributes (A1 – H4); Eq. (6) and (7) are employed and results presented in Tables 5 and 6 for $\propto = [0,1]$ respectively. Thus, to calculate the $\mathrm{g}(\mathrm{A}_{(\mathrm{i})})$ for *SA* (A1 – A6) of its corresponding *SI* 'A' – the average 'degree of significance' value ($\tilde{P}_i$) for the *SA,* as presented in Table 2, is used as shown in Eq. (6) and (7).

However, to calculate the fuzzy measures $\mathrm{g}(\mathrm{A}_{(\mathrm{i})})$, for *SA* (A1 – A6), the fuzzy valence functions $[\mathrm{f}_{\mathrm{i},\propto}^{-}, \mathrm{f}_{\mathrm{i},\propto}^{+}]$ as calculated in Tables 3 and 4 is sorted from high to low; the same approach was adopted to evaluate for the other *SA* (i.e., B1 – H4) as presented in Tables 5 and 6. Hence, to deduce the $\mathrm{g}(\mathrm{A}_{(\mathrm{i})})$ for criteria A1 – A6 and taking ∝=0; its $\mathrm{f}_{\mathrm{i},0}^{-}$ is sorted as follows:

$$\mathrm{f}_{(\mathrm{A4}),0}^{-} = 0.336 > \mathrm{f}_{(\mathrm{A1}),0}^{-} = 0.320 > \mathrm{f}_{(\mathrm{A6}),0}^{-} = 0.316 > \mathrm{f}_{(\mathrm{A3}),0}^{-} = 0.313$$

$$> \mathrm{f}_{(\mathrm{A5}),0}^{-} = 0.308 > \mathrm{f}_{(\mathrm{A2}),0}^{-} = 0.273$$

The corresponding average 'degree of significance' value, $P_{\mathrm{i},0}^{-}$ (see Table 2) to these $f_{i,0}^{-}$ values can be given as:

$$P_{(\mathrm{A4}),0}^{-} = 0.528,\ P_{(\mathrm{A1}),0}^{-} = 0.660,\ P_{(\mathrm{A6}),0}^{-} = 0.597,\ P_{(\mathrm{A3}),0}^{-} = 0.597$$

$$P_{(\mathrm{A5}),0}^{-} = 0.660,\ P_{(\mathrm{A2}),0}^{-} = 0.597$$

The earlier calculated λ^{-} is -0.9963 using Eq. (8). Then, taking $\propto = 0$, the fuzzy measures $g^{-}(\mathrm{A}_{(\mathrm{i})})$ for A1 – A6 can be calculated (see Table 5) using Eq. (6) and (7) as follows:

$$\lambda^{-} = -0.9963$$

$$g^{-}\left(\mathrm{A}_{(\mathrm{A4})}\right) = P^{-}_{(\mathrm{A4})} = 0.528$$

$$g^{-}\left(\mathrm{A}_{(\mathrm{A1})}\right) = P^{-}_{(\mathrm{A1})} + g^{-}\left(A_{(A4)}\right) + \lambda^{-}P^{-}_{(\mathrm{A1})}g^{-}\left(A_{(A4)}\right) = 0.841$$

$$g^{-}\left(\mathrm{A}_{(\mathrm{A6})}\right) = P^{-}_{(\mathrm{A6})} + g^{-}\left(A_{(A1)}\right) + \lambda^{-}P^{-}_{(\mathrm{A6})}g^{-}\left(A_{(A1)}\right) = 0.938$$

$$g^{-}\left(\mathrm{A}_{(\mathrm{A3})}\right) = P^{-}_{(\mathrm{A3})} + g^{-}\left(A_{(A6)}\right) + \lambda^{-}P^{-}_{(\mathrm{A3})}g^{-}\left(A_{(A6)}\right) = 0.977$$

$$g^{-}\left(\mathrm{A}_{(\mathrm{A5})}\right) = P^{-}_{(\mathrm{A5})} + g^{-}\left(A_{(A3)}\right) + \lambda^{-}P^{-}_{(\mathrm{A5})}g^{-}\left(A_{(A3)}\right) = 0.995$$

$$g^{-}\left(\mathrm{A}_{(\mathrm{A2})}\right) = P^{-}_{(\mathrm{A2})} + g^{-}\left(A_{(A5)}\right) + \lambda^{-}P^{-}_{(\mathrm{A2})}g^{-}\left(A_{(A5)}\right) = 1.000$$

[Insert Tables 5 & 6]

3.1.3 The defuzzification process, normalization process and results

Having calculated fuzzy measures $\mathrm{g}\left(\mathrm{A}_{(\mathrm{i})}\right)$ as a membership function of the TFN ($\tilde{P}_i$), fuzzy number $\tilde{P}_i$ is defuzzified to $\tilde{p}_i$ using Eq. (9) as presented in step 5 below. Where $A_i \cap A_j = \phi$ for all i, j = 1,2,3, …, n and $\mathrm{i} \neq \mathrm{j}$, $\lambda \in (-1, \infty)$. Let μ be a fuzzy measure on $(I, P\,(I))$ and an application $f : I \to \Re^{+}$. The Choquet integral of f with respect to μ is defined by:

$$\int_I f d\mu = \sum_{i=1}^{n} \left(f\left(\sigma(i)\right) - \ f\left(\sigma(i-1)\right) \right) \mu(A_i)$$

Where σ is a permutation of the indices to have $f\left(\sigma(i-1)\right) \leq \cdots \leq \ f\left(\sigma(n)\right)$, $A_i = \{\sigma(i), \dots, \sigma(n)\}$ and $xf(\sigma(0)) = 0$, by convention.

Therefore, the aggregation of the mono-dimensional utility functions of the *SA* is achieved by using the generalized Choquet integral function, which is defined in terms of:

$$f : S \to [0,1], 0 \leq f\left(s_{(1)}\right) \leq f\left(s_{(2)}\right) \leq \cdots f\left(s_{(n)}\right) \leq 1, f\left(s_{(0)}\right) = 0 \text{ and } A_{(i)} = \left\{s_{(1)}, \dots, s_{(n)}\right\}.$$

$$(C) \int f dg = \sum_{i=1}^{n} \left(f\left(s_{(i)}\right) - \ f\left(s_{(i-1)}\right) \right) g\left(A_{(i)}\right) \quad (9)$$

Step 5: Evaluation of the Fuzzy Valence Functions at the SI level

The fuzzy measures $\mathrm{g}\left(\mathrm{A}_{(\mathrm{i})}\right)$ for *SA* (A1 – H4) is presented in Tables 5 and 6; and Eq. (9) is then employed to calculate the fuzzy valency functions ($\tilde{f}_i^{\propto}$) at the *SI* level (A – H); for $\propto = [0,1]$ as presented in Tables 3 and

4. The following examples show how the fuzzy valency function ($\int \tilde{f} d\tilde{g}$) of criteria 'A' and other criteria (i.e., B – H) was calculated as presented in Table 3, taking $\propto = 0$.

The $g^{-}(A_{(i)})$ for criteria A1 – A6 (see Table 5) are first sorted, as shown below:

$$g^{-}(\mathrm{A}_{(A2)}) = 1.000 > g^{-}(\mathrm{A}_{(A3)}) = 0.977 > g^{-}(\mathrm{A}_{(A5)}) = 0.995 > g^{-}(\mathrm{A}_{(A6)}) = 0.938$$

$$> g^{-}(\mathrm{A}_{(A1)}) = 0.841 > g^{-}(\mathrm{A}_{(A4)}) = 0.528,$$

Meanwhile, the corresponding fuzzy valence functions $f_{i,0}^{-}$ (see Table 3) to these $g^{-}(A_{(i)})$ values are:

$$\mathrm{f}_{(A2),0}^{-} = 0.273,\ \mathrm{f}_{(A3),0}^{-} = 0.313,\ \mathrm{f}_{(A5),0}^{-} = 0.308,\ \mathrm{f}_{(A6),0}^{-} = 0.316,$$

$$\mathrm{f}_{(A1),0}^{-} = 0.320,\ \mathrm{f}_{(A4),0}^{-} = 0.336$$

The ($\int \tilde{f} d\tilde{g}$) of criteria 'A' is given as:

$$\int \tilde{f}_0^{-} d\tilde{g}_0^{-} = \{[1.000\ X\ 0.273] + [0.977\ X\ (0.313 - 0.273)] + [0.995\ X\ (0.308 - 0.313)]$$
$$+ [0.938\ X\ (0.316 - 0.308)] + [0.841\ X\ (0.320 - 0.316)] + [0.528\ X\ (0.336 - 0.320)]\}$$
$$= \mathbf{0.327}$$

Similarly,

$$\int \tilde{f}_0^{+} d\tilde{g}_0^{+} = \mathbf{0.650}$$

Hence,

$$\int \tilde{f} d\tilde{g} = [0.327, 0.650] \qquad taking\ \propto = 0;\ \text{for criteria A} \qquad \text{(see Table 3)}$$

The respective *SA* are aggregated into their corresponding individual *SI*, using a hierarchical process by applying the two-stage aggregation process of the Choquet fuzzy integral (Eq. (9)). The resultant value at the *SI* level yields a fuzzy number, $\tilde{V}$ such that using the Choquet fuzzy integral, we have the generalized Choquet integral (Eq. (10)):

$$\tilde{V} = (C) \int f dg \tag{10}$$

Step 6: Defuzzification of the Choquet integral values ($\tilde{V}$) for the key sustainability criteria – at the SA and SI levels

Assume that the membership of $\tilde{V}$ is as defined in Eq. (10) (Kurt, 2014; Ozdemir & Ozdemir, 2018) and presented in Table 7; the fuzzy number $\tilde{V}$ can be defuzzied into a crisp value v using Eq. (11) for both levels of the SA and SI (Table 7).

$$F(\tilde{A}) = \frac{v_1 + v_2 + v_3 + v_4}{4} \tag{11}$$

In Table 7, using the calculation of the generalized Choquet integral (Eq. (10)), the weightings of each sustainability criteria (*SA* & *SI* alike) are obtained. Also, the defuzzified overall values, $F(\tilde{A})$ for the sustainability criteria using the generalized Choquet fuzzy integral is presented within the same table. For instance, the value (0.488) for criteria "A" in Table 7 is obtained in a similar way using Eq. (11).

$$\frac{0.327 + 0.357 + 0.616 + 0.650}{4} = \mathbf{0.488}$$

Step 7: Computing the Normalized Weights for the key sustainability criteria (SA and SI levels) – for the building classification types (NB & EB)

After the defuzzification procedure, the normalization of the resulting defuzzified value $F(\tilde{A})$ was calculated to get the final weight of each sustainability criteria (Byun & Lee, 2005; Ertuğrul & Karakaşoğlu, 2008; Kahraman et al., 2008; Pramanik et al., 2017). Eq. (12) was utilized to normalize the $F(\tilde{A})$ for all criteria for both new and existing buildings. Note: for all computation of values for the 'existing building' classification – the sustainability indicator "A," which is the "*sustainable construction practices*" and its subsets factors are excluded. The resulting value is then normalized weight $N(\tilde{A})$ for the criterion (Table 7) and the summation of all the $N(\tilde{A})$ for the *SI* (A – H) as well as the *SA* for each corresponding *SI* (e.g., A1 – A6) is equal to one.

$$N(\tilde{A}) = \frac{F(A_{(i)})}{\sum_{i=1}^{n} F(A_{(i)})} \tag{12}$$

Where i = 1,2,3, …, n

For instance, to calculate the $N(\tilde{A})$ for criterion "B1," which is given as 0.3170 in Table 7, using Eq. (12). We have:

$$N(\tilde{A}_{(B1)}) = \frac{0.417}{0.417 + 0.451 + 0.446} = \mathbf{0.3170}$$

Similarly, for criterion "C" for existing building (EB), the $F(A_{(i)})$ of criteria B – H are aggregated as the $\sum_{i=1}^{n} F(A_{(B-H)})$:

$$N(\tilde{A}_{(C)}) = \frac{0.461}{0.449 + 0.461 + 0.413 + 0.459 + 0.466 + 0.477 + 0.442} = \mathbf{0.1469}$$

Step 8: Determination of the Global Weights for the key sustainability criteria (SA) – for the building classification types (NB & EB)

As earlier mentioned, the proposed criteria BSAM scheme consists of a three hierarchical structure of sustainability indicators (*SI*), sustainability attributes (*SA*), and sustainability sub-attributes (*SSA*). Having computed the normalized weights for the *SI* (A – H) and their respective *SA* (A1 – H4) as presented in step 7, the global weight (WG), which is a critical variable in the sustainability assessment process can be calculated. The *WG* is the product of the $N(\tilde{A})$ of the *SA* and the $N(\tilde{A})$ of its corresponding *SI,* as illustrated in Eq. (13).

$$WG_j = N(A)_j \times N(A)_i \tag{13}$$

Where WG_j = global weight of the *j*th sustainability attribute.

$N(A)_j$ = normalized weight of the *j*th sustainability attribute.

$N(A)_i$ = corresponding normalized weight of the *i*th sustainability indicator for the *j*th sustainability attribute

Hence, the $WG_{(A1)}$ for criteria "A1" is:

$$WG_{(A1)} = N(A)_{(A1)} \times N(A)_{(A)} = 0.1591 \times 0.1345 = \mathbf{0.0214}$$

[Insert Table 7]

Step 9: Determination of the credit points for the key sustainability criteria (SSA & SA levels)

Each of the proposed sustainability attributes (*SA*) has corresponding sub-factors, which are subsets of the *SA* – the sub-attributes (*SSA*), and each of these *SSA* has a certain available credit point to be achieved. These credit points (*CP*) of the respective *SSA* was determined via the consultation with the 189 invited experts for this study. Therefore, to determine the maximum credit points (*CP*) of the respective *SA*, the *CP* of its related *SSA* is aggregated, as shown in Eq. (14) modified from Mahmoud et al. (2019).

$$CP_j = \sum_{h=1}^{n} CP_{(h)} \tag{14}$$

Where h = 1,2,3, …, n; $CP_{(h)}$ = credit points for the related *SSA* of the *j*th sustainability attribute; and CP_j = maximum credit points for the *j*th sustainability attribute.

3.1.4 Establishing the Building Sustainability Evaluation Index (BSEI) and BSER

Furthermore, the building sustainability evaluation index (BSEI), which is the aggregation of all the factor indices (*FI*) of all the sustainability attributes (*SA*), is calculated using Eq. (15) which is modified from Mahmoud et al. (2019). Moreover, the building sustainability evaluation ratio (BSER), which is the percentage between the BSEI and the maximum BSEI, is useful to determine the scale ranking of the assessed building based on the proposed BSAM certification grade system (see section 3.1.5). The maximum BSEI and the BSEI are both derived using Eq. (15); however, for the BSEI, the calculated CP_j for the *SA* varies based on the building project evaluated. Meanwhile for the maximum BSEI, its CP_j is fixed as determined during the experts' consultations – as the maximum available *CP* for each *SA*. The BSER can be deduced using either Eq. (16) or as Eq. (17).

$$BSEI = \sum_{j=1}^{n} CP_j \times WG_j = \sum_{j=1}^{n} FI_j \tag{15}$$

$$BSER\ (\%) = \frac{BSEI}{BSEI_{max}} \times 100 \tag{16}$$

$$BSER\ (\%) = \frac{\sum_{j=1}^{n} CP_j \times WG_j}{\sum_{j=1}^{n} (CP_j)_{max} \times WG_j} \times 100 \quad \boldsymbol{OR} \quad \frac{\sum_{j=1}^{n} FI_j}{\sum_{j=1}^{n} (FI_j)_{max}} \times 100 \tag{17}$$

3.1.5 Building sustainability grade determination

The final stage in the methodological approach is the developing of a grading (ranking) system for the BSAM scheme which is based on (i) the input by the experts who participated in this study; and (ii) a review of the widely used and existing green rating systems such as LEED, BREEAM, BEAM Plus, etc. The experts were asked to supply a range of values from (0) to (100) to represent the grades of sustainability performance of buildings (i.e., outstanding, excellent, very good, good, acceptable, and unclassified), see Appendix D. The proposed BSAM certification grade system is a scale from (0) to (100) which accommodates the six sustainability certification grades. Figure 5 shows the six certification grades and their respective BSER values (grade 1= unclassified; 2= acceptable; 3= good; 4= very good; 5= excellent; 6= outstanding).

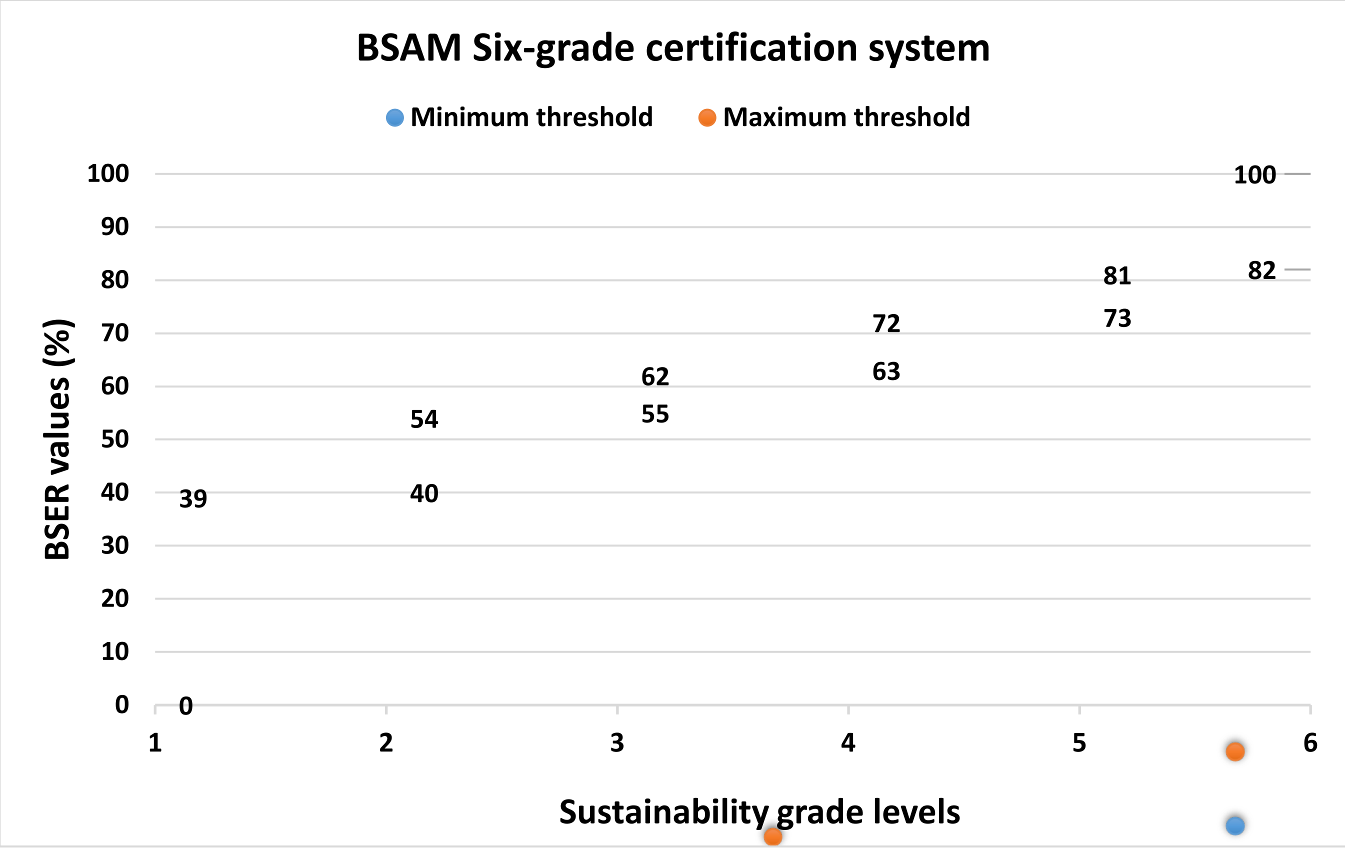

Figure 5: BSAM Six-grade certification system: showing the grade levels and corresponding BSER values

Therefore, for a building to be green certified using the BSAM scheme, it must a minimum BSER value of 40% (i.e., an 'acceptable' sustainability grade level).

3.2 Implementation of the BSAM scheme: Case study validation

The BSEI and BSER values which are computed based on the weights of the sustainability criteria – *SI, SA* & *SSA* of the BSAM scheme; as well as the proposed BSAM scheme was implemented in four case studies to demonstrate its usefulness in practice in the built environment.

3.2.1 Case study projects descriptions and data

The four case studies include two building projects that were classified as "new buildings" (NB) based on BRE (2018) classification, which defined it – buildings of less than one year of occupancy. The four case studies are situated in Nigeria. The other case studies are classified as "existing buildings" (EB), which are buildings of at least one year of occupancy (BRE, 2018).

Firstly, the NB case studies comprise of two buildings – a residential facility (CE duplex) and a commercial facility (RA labs). CE duplex is a one-story residential duplex building situated in the south-eastern region of Nigeria with a gross area of 459.820m^2 that accommodates seven rooms of different sizes, a stair hall, and other regular residential facilities, a gatehouse among others. It has a green area of 183.928m^2 (40% of the

GFA) and a paved area of 141.483m^2. More so, the RA lab is a one-story commercial facility situated in the south-western part of Nigeria with a gross area of 346.784m^2. It includes four offices and research labs, stores and other facilities on the ground floor; and two offices, meeting halls, a large conference hall, and other facilities on the first floor. It has a green area of 34.581m^2 (10% of the GFA). Secondly, the EB case studies are two residential building projects (SNN building & FT building) situated in Lagos, Nigeria. Both sets of buildings are one-story buildings consisting of two units of duplex apartments. The SNN building has a gross area of 896.041m^2 composed of sixteen rooms, two stair halls, other regular residential facilities, and a gatehouse. It has a paved area of 420.064m^2 and a green area of 89.604m^2 (10% of the GFA). The FT building has a gross area of 506.509m^2, which accommodated 14 rooms of varying sizes and purposes, two stair halls, and other regular residential facilities, a gatehouse, among others. It has a paved area of 101.403m^2 and a green area of 202.581m^2 (40% of the GFA).

Relevant data such as the BIM model and CAD drawings of the case studies were secured to assist in the sustainability assessment of the buildings. Other related documents included site maps, transportation routes, building specifications, utility records (e.g., energy, water, waste, etc.) among others. Meanwhile, necessary assumptions were made where data could not be sourced (Mahmoud, 2017). The BSAM scheme documentation (Olawumi & Chan, 2019) forms an integral part of the assessment process.

3.2.2 Evaluation of the sustainability performance of the case study projects

The weights of each *SI* and *SA*, BSEI values, BSER values and sustainability grades for the case studies are determined based on (1) the collected data of the four case studies – including the BIM output and other necessary simulations; (2) utilizing the sustainability evaluation equations from Eq. (13) – (17). The entire sustainability evaluation process, the respective weights for each criterion, and the sustainability index (BSEI) are illustrated in Table 8 for the NB case studies and Table 9 for the EB case studies. These tables also present the BSER determination for the four case studies based on their BSEI, respectively. Each table provides the (i) the description of the sustainability indicators and attributes; (ii) the normalized (local) weights, $N(\tilde{A})$ of the *SI* and *SA*; (iii) the global weights, WG_j determination for the *SA*. (iv) credit points, CP_j determination for the case studies; (v) the sustainability factor index, FI_j of each criterion. (vi) The BSEI of the case studies; and (vii) the BSER of the four case studies. The credit points, CP_j and sustainability factor index, FI_j of each criterion are subdivided into attained and maximum segments; the attained points and indices are the current evaluation of the case study building, whereas the maximum segment represents a 100% score that can be awarded to the criterion.

[Insert Tables 8 & 9]

3.3 Comparison between the BSAM scheme and other green building rating systems

This section highlights the significant improvements made in the development of the BSAM scheme as compared to the other existing green building rating systems. Previous studies (Alwisy et al., 2018; Berardi, 2012; Illankoon et al., 2017; Mahmoud et al., 2019) have reported that the existing green building rating systems such as LEED, BREEAM, etc. places more emphasis on the environmental sustainability criteria and little or no consideration of the economic and social sustainability criteria. Other improvements and precedence of the BSAM scheme over the existing green building rating systems are highlighted in Table 10 for further illustration.

[Insert Table 10]

4. Discussion of findings

This section will discuss the results of this study in two aspects:

(i) the determined weights of the sustainability indicators (*SI*) and attributes (*SA*) based on the application of the generalized Choquet fuzzy integral algorithm (section 4.1).

(ii) The BSER values and sustainability grade levels of the four case studies (section 4.2) based on the determination of the BSEI (model validation).

4.1 Weights of the key sustainability criteria

The weights of the key sustainability criteria (A – H) are presented in Table 7, which are based on the application of the GCFI method on the data collected from the experts' consultations. When the weights assigned to the sustainability criteria for the BSAM scheme in this study are compared to existing building rating systems such as LEED, BREEAM, BEAM Plus, etc., it reveals differential weighting for the different sustainability criteria. More so, this differential weighting shows a significant variation in the local context of these rating tools. As seen in Table 7, the ranking order for the criteria weights is A>F>C>E>B>G>H>D. As earlier mentioned, the BSAM scheme was explicitly developed for countries in the sub-Saharan region of Africa. Meanwhile, as shown in Tables 5 and 6, the sets of sustainability criteria held interactive characteristics (i.e. share sub-additive effect) as their fuzzy measures are $\lambda < 0$. Hence, to improve the overall BSER value of a building project, efforts should be devoted to enhancing the weights of the sustainability indicators, which have higher normalized weights.

The sustainable criterion “A” – “*sustainable construction practices*” is given the highest priority among the eight criteria by the experts with a value of 0.1346. This criterion comprises several social and economic sustainability sub-criteria such as “*ethics & equity*,” “*societal engagement,*” with values of 0.1948 and 0.1526, among others, which contributes significantly to its high weight value in comparison to other criteria. Illankoon et al. (2017) reported that the existing green rating tools place very little or no emphasis on social and economic sustainability issues in their assessment of the sustainability performance of building. Criterion “F,” which is *transportation* receives the next highest priority among the consulted experts with the value of 0.1286, and its sub-criteria of “*transport management*” and “*alternative means of transport*” receive the highest weights under this criterion with values of 0.3504 and 0.3376 respectively. The Green Mark green rating tool did not allocate any weights to the transportation criterion (BCA, 2015), while the IGBC allocated just 3% of the total weights to the same criterion (IGBC, 2014).

The *energy “C”* criterion acquired the third highest weight among the sustainability criteria with a value of 0.1271, and its sub-criterion of “*energy management*” receives the highest weight among the sub-criteria under this criterion with a value of 0.3424. However, according to Illankoon et al. (2017), LEED, BREEAM, Green Star, BEAM Plus gave the highest priority to the *energy* criterion, which emphasizes the special consideration given to the environmental aspect of sustainability by the existing rating tools and countries in the developed world. The “*E-material and waste*” criterion receives the fourth priority among the sustainability criteria with a weight value of 0.1267, and its sub-criterion “*sustainable purchasing practice*” got the highest weight under this criterion with a value of 0.2575. The “*B-site and ecology*” criterion with a weight value of 0.1238 is the fifth-ranked criterion, and its sub-criterion “*site management*” with a value of 0.3435 is the highest-ranked sub-criterion under the criterion “B.” Among existing green rating tools, these criteria “B” and “E” receive consideration weights allocation (Illankoon et al., 2017).

Moreover, the sustainability criteria “*IEQ*,” “*building management*,” and “*water*” with weight values of 0.1232, 0.1219, and 0.1141 respectively received the lowest priority among the criteria as rated by the experts and analyzed using the GCFI method. For the *IEQ “G” criterion*, its sub-criteria such as “*building amenities*” and “*acoustic performance*” with values of 0.1803 and 0.1699 respectively receive the highest weight under the *IEQ* criterion. For the “*H-building management*” criterion, its sub-criteria “*risk management*” and “*green innovations*” with 0.2661 and 0.2544 respectively receive the highest weights. In the “*D-water*” criterion, its sub-criterion of “*water efficiency*” with the value of 0.3713 gets the highest weight. An analysis of existing green rating tools by Illankoon et al. (2017) reveals that LEED, Green Mark, BEAM Plus places less consideration for the "*building management*" criteria, although they place a higher priority on the "*water*" criterion.

4.2 Assessment results of the case study projects

The results of the evaluation of the sustainability performance of the four building case studies, which include two new and existing buildings, respectively, can be classified under four aspects. The first aspect is the *attained credit point* (CP) has illustrated in Tables 8 and 9, which shows the points achieved by the four buildings under each *SI* based on its related *SA*. For instance, for sub-criterion "*G3-thermal comfort*", for the new buildings (NB), the CE duplex and RA lab buildings have a CP value of 2.5 and 4 respectively out of a maximum CP value of 5. Meanwhile, for the existing buildings (EB), the SNN and FT buildings have the same CP value of 3.5 out of 5. The second aspect is the sustainability factor index (FI) of each *SI*, for example, the FI and FI_{max} of the sub-criterion, "C2" for the CE duplex building are 0.3917 and 0.4352, respectively, as shown in Table 8. The third aspect related to the values of the $BSEI$ and $BSEI_{max}$, these values for the CE duplex building are 4.5618 and 7.2944, respectively, as shown in Table 8, and for the FT building, the values are 4.6595 and 6.6288 respectively, as presented in Table 9. Lastly, the fourth aspect under consideration is the BSER value, which is calculated based on Eq. (16). The BSER values for the CE duplex and RA lab buildings are 62.54% and 70.05%, respectively, as presented in Table 8; where for the SNN and FT buildings, the BSER values are 75.33% and 70.29% respectively as shown in Table 9. Therefore, the two new buildings such as CE duplex and RA labs buildings achieved the sustainability grades '*good'* and '*very good'* respectively; while the existing buildings – SNN and FT buildings achieved the '*excellent'* and '*very good'* sustainable grades respectively based on the BSAM certification grade system illustrated in Figure 5 and discussed in section 3.1.5.

More so, for the new buildings as shown in Table 8, the CE duplex and RA lab buildings have different values for the sustainability factor index except for the "*energy performance*" sub-criterion, which achieved the same FI. Similarly, for the existing buildings (Table 9), the SNN and FT buildings have similar FI for the B1, C2, E4, G3, H3, and H4 sub-criteria. Although, for both the new and existing buildings, the summation of the FI for each sustainability indicator differs, as shown in Tables 8 and 9. Furthermore, the BSER values for each sustainability indicator – which is the percentage of the summation of the FI for each indicator to the summation of the FI_{max} as illustrated in Eq. 17 – for the sustainability indicator A – H are 53.28%, 53.4%, 62.7%, 59.6%, 84.65%, 87.14%, 68.75%, 42.4% respectively for the CE duplex building while for the RA labs building the values are 74.15%, 49.86, 69.04%, 71.03%, 75.8%, 53.09, 84.16, 72.53% respectively. The BSER values for criteria "*site & ecology*," "*material & waste*," and "*transportation*" for the CE duplex building are higher than the RA labs building, whereas the RA labs building achieved higher BSER values in other criteria. Moreover, for the existing buildings, the SNN buildings achieved higher BSER values for sustainability criteria for "*energy*," "*water*," "*transportation*," and "*building management,*"; while the FT buildings achieved higher values in the other four sustainability criteria.

Consequently, for the new buildings, the CE duplex building has its highest BSER value for the "*transportation*" criterion, while the RA labs building achieved its highest value for the "*IEQ*" criterion. Moreover, for the existing buildings, the SNN building has its highest BSER value for the "*water*" criterion, and the FT building achieved the highest weight for the "*material & waste*" criterion. Overall, the SNN building achieved the highest sustainability certification grade based on the BSAM scheme and the calculations based on the GCFI algorithm, followed by the FT building, RA labs, and CE duplex buildings, respectively. The different percentages of the final BSER for the four building case studies can be attributed to the contrasting weights of its sustainability indicators, attributes, and sub-attributes. As pointed out by Ali and Al Nsairat (2009), Gan et al. (2017), and Illankoon et al. (2017), the weight of each sustainability criteria has a significant impact on the overall sustainability performance of a building

5. Conclusions

The current study used an MCDM technique, the generalized Choquet fuzzy integral method using TFN to develop a building sustainability evaluation index (BSEI) based on a building green rating system – the BSAM scheme. The data collected from the invited experts were analyzed using the GCFI algorithm. The resulting sustainability index and building classification system was used to assess the sustainability performance of four real-world case studies of building projects. The advantages and superiority of the GCFI over other weighting techniques were discussed in the study.

The BSAM scheme which was developed as part of broader research work and more specifically to suit the local context of the sub-Saharan region of Africa presents a more unified sustainability evaluation criteria which comprise the three pillars of sustainability; as compared to the other existing green rating tools such as BREEAM, LEED, etc. The use of the GCFI helped addressed the profound shortcomings in these existing green rating tools, which only utilize points aggregation which have been reported in the literature to be an insufficient metric.

As it is revealed in the weighting calculation for the respective eight sustainability criteria, significant priority was given to criteria such as "*sustainable construction practices*" *transportation*, and *energy*. The "*sustainable construction practices"* criteria contain a considerable proportion of the social and economic sustainability criteria which were not considered in the existing green building rating tools. Also, the BSAM scheme documentation was developed, which provides comprehensive, and details descriptions of each sustainability criteria, the allocation of points to the criteria, and the various documentary evidence needed to be provided before a criterion can be considered fulfilled by the assessed building project. The practical contributions of the current study to the industry and theoretical standpoints include:

(1) Determination of the key decision sustainability criteria which are specific to the sub-Saharan region of Africa (by incorporating the opinions of experts and literature in the selection process).
(2) Provided a generic and quantitative system that can aid decision-makers, project teams, and other relevant stakeholders in evaluating the sustainability performance of green buildings.
(3) The developed BSAM scheme and its quantitative metrics allow for the comparative assessment of building designs and models, which can help stakeholders to make informed sustainable decisions.
(4) The quantitative evaluation model developed based on the BSAM scheme can help pinpoint aspects in the sustainability performance of buildings that need improvements based on the predefined project's objectives.
(5) Implementing the developed BSAM scheme in building projects can promote greener buildings and sustainable development in the sub-Saharan region of Africa.
(6) It contributes to the existing body of knowledge in the field of sustainability – being the first attempt (*within the sub-Saharan region*) aiming at developing a quantitative green building rating system to enhance sustainability practices in the built environment.

A limitation of this study is that the developed BSER and evaluation model are based on the BSAM scheme, which is region-specific. However, the GCFI algorithm can be applied to other existing green rating tools to determine their BSER values – although these tools focused heavily on only the environmental sustainability construct. For this reason, it is recommended for these green rating tools and future development of regional tools to incorporate the social and economic aspects of sustainable development. For future studies, the GCFI method can be applied to other green rating tools or to evaluate various sustainability issues in the built environment.

Nomenclature Table	
i	Sustainability criteria
k	Number of invited experts
t	Expert
$\tilde{A}_i$	Degree of importance

Nomenclature Table	
$\tilde{a}_{i1}^{t}, \tilde{a}_{i2}^{t}, \tilde{a}_{i3}^{t}, \tilde{a}_{i4}^{t}$	Trapezoidal fuzzy numbers (TFN) of $\tilde{A}_i$
$\tilde{P}_i$	Degree of significance
$\tilde{T}_i$	Degree of significance (*best alternative*)
$\tilde{p}_{i1}^{t}, \tilde{p}_{i2}^{t}, \tilde{p}_{i3}^{t}, \tilde{p}_{i4}^{t}$	TFN of $\tilde{P}_i$
$\tilde{R}_i$	RON values
n	Number of attributes
$\tilde{f}$	Set of fuzzy valence functions
$\bar{e}_i^{\propto}$	Tolerance zone
$g(A_{(i)})$, λ	Fuzzy measures
σ	Permutation of the indices
$\tilde{V}$	Fuzzy number
v	Crisp value
$N(\tilde{A})$	Normalized weight
WG_j	Global weight of the criteria
CP_j	Credit point
SI	Sustainability indicators
SA	Sustainability attributes
SSA	Sustainability sub-attributes

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