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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

32 inadequate. Similarly, Atanda (2019) employed the Analytic Hierarchy Process (AHP) to identify the social
33 indicators for green buildings assessment. However, the study fails to consider the environmental and social
34 construct of sustainable development.

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

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

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

58 Given the above gaps in the literature as regards the (i) the need for a unified sustainability assessment
59 system that encompasses the social, economic, and environmental criteria; (ii) previous studies utilized
60 additive MCDM technique which is insufficient to assess dependent and subjective criteria; and (iii) the need
61 to capture the interrelationships among these sustainability assessment criteria. The current study aims to
62 utilize an MCDM technique – the generalized Choquet fuzzy integral (GCFI) method for the evaluation of the

63 sustainability rating of green buildings based on the decision criteria of the Building Sustainability
64 Assessment Method (BSAM) scheme green rating system as well as addressed the above literature gaps.
65 The BSAM scheme is a green building rating system that took adequate and equal consideration for the
66 three pillars of sustainability (Olawumi & Chan, 2019). The BSAM scheme was developed in the course of
67 this research project, and the current study describes the development of the weighting methodology for the
68 BSAM scheme using the GCFI algorithm. The GCFI method according to extant literature (Bebčáková et al.,
69 2011; Çakır, 2017; Zhang et al., 2019) adequately addressed the issue of the interactions among dependent
70 sustainability criteria in a hierarchical structure. More so, according to Perçin (2019), using independent
71 criteria in solving MCDM problems as evident in extant literature regardless of their effect on each other will
72 limit its ability to evaluate the subject matter adequately.

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

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

81 The Choquet fuzzy integral has found its usefulness in solving numerous MCDM problems in the extant
82 literature. The GCFI technique has discussed in Section 1 and later in this section is superior to the other
83 MCDM techniques. More so, it has only been applied once to solve an MCDM problem relating to
84 sustainability issues when Ozdemir and Ozdemir (2018) employed the GCFI approach to select the best
85 alternative among five residential heating systems. In the industrial sector, Demirel et al. (2010) utilized
86 GCFI to resolve a warehouse logistic issues for a large Turkish company while in the hospitality sector,
87 Perçin (2019) used it to evaluate the quality of hospitals' websites; and Karczmarek et al. (2018) employed
88 GCFI for face recognition and classification; also, GCFI was used to evaluate equipment maintenance
89 quality (Zhang et al., 2019), hybrid image encryption (Hosseinzadeh et al., 2019), and supplier selection for
90 a steel factory (Çakır, 2017). Other applications of GCFI to solve MCDM problems include voice recognition,
91 traffic surveillance, temperature prediction (Fang et al., 2010), game theory, neural networks (Qin et al.,
92 2016), among others. The GCFI is regarded as a better alternative to the fuzzy ANP (Demirel et al., 2010).

93 **2.1 Historical development of the GCFI method**

94 The first development of the GCFI methodology was the Choquet integral introduced by Sugeno (1974) as a
95 flexible aggregator operator and the generalization of the Lebesgue integral (Demirel et al., 2010; Grabisch
96 & Roubens, 2000). It involves generalizing the “weighted average method,” the “Ordered Weighted Average”
97 (OVA) operator, and the max-min operator (Grabisch et al., 2000). It is a non-additive measure and aims at
98 representing the significance of a criterion and the interactions among dependent criteria (Demirel et al.,
99 2010; Perçin, 2019). More so, to define these fuzzy integrals, a set of values are required for the criterion,
100 and these values are in fuzzy measures; also, if these criteria have sub-sets (as seen in this study) – the
101 values of importance should be defined as well.

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

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

115 **2.2 Underlying conditions for adopting the GCFI method**

116 In the context of MCDM analysis, Krishnan et al. (2015) defined aggregation as the process of evaluating
117 the weights of a set of decision criteria under evaluation into a global score; and based on this single final
118 score, the alternatives (e.g., building projects) can be classified or ranked. Hence, before employing GCFI,
119 the decision-makers must input the importance value of the decision criteria and their subsets. An
120 aggregation operator must have two fundamental properties, which are the monotonicity and boundary
121 conditions (Cheng & Hsu, 1991; Karczmarek et al., 2018). However, the GCFI has an additional property for

122 its fuzzy measures (λ -measure), which makes the Choquet integral more robust due to the ease of usage
123 and good “degree of freedom” of the λ -measure (Krishnan et al., 2015).

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

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

141 **2.3 Advantages of the GCFI method over other MCDM techniques**

142 In a comparison of the GCFI with some other widely used MCDM techniques; unlike the GCFI, the AHP rely
143 on independent decision criteria (Zhang et al., 2019) and does not adequately capture qualitative criteria
144 (Çakır, 2017) which makes it unsuitable for resolving non-additive and dependent models. More so, Çakır
145 (2017), in analyzing an MCDM problem for a steel-producing company, carried out a comparative
146 assessment of the different MCDM techniques such as fuzzy TOPSIS, fuzzy ANP, fuzzy DEMATEL, EAM
147 and found the GCFI method to be superior. Also, fuzzy TOPSIS can handle hierarchical problems but not
148 interactive criteria (Kurt, 2014; Ozdemir & Ozdemir, 2018). Moreover, other advantages of the GCFI over the
149 other weighting methodology include:

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

- 152 ii. Its use of trapezoidal fuzzy numbers and range computations using integral provides a better result
153 (Kurt, 2014; Ozdemir & Ozdemir, 2018).
- 154 iii. Its use of signed fuzzy measure allows for an efficient approach to information aggregation (Fang et
155 al., 2010); and
- 156 iv. The usefulness of the GCFI algorithm in many information fusion and data mining problems (Yang
157 et al., 2005).

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

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

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

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

172 The set of equations that is Eq. (1) to Eq. (13), except Eq. (2) as discussed in Section 3, are based on the
173 General Choquet Fuzzy Integral (GCFI) methodology as adopted from the extant literature (see Dong et al.,
174 2016; Huang et al., 2010; Kurt, 2014; Ozdemir & Ozdemir, 2018).

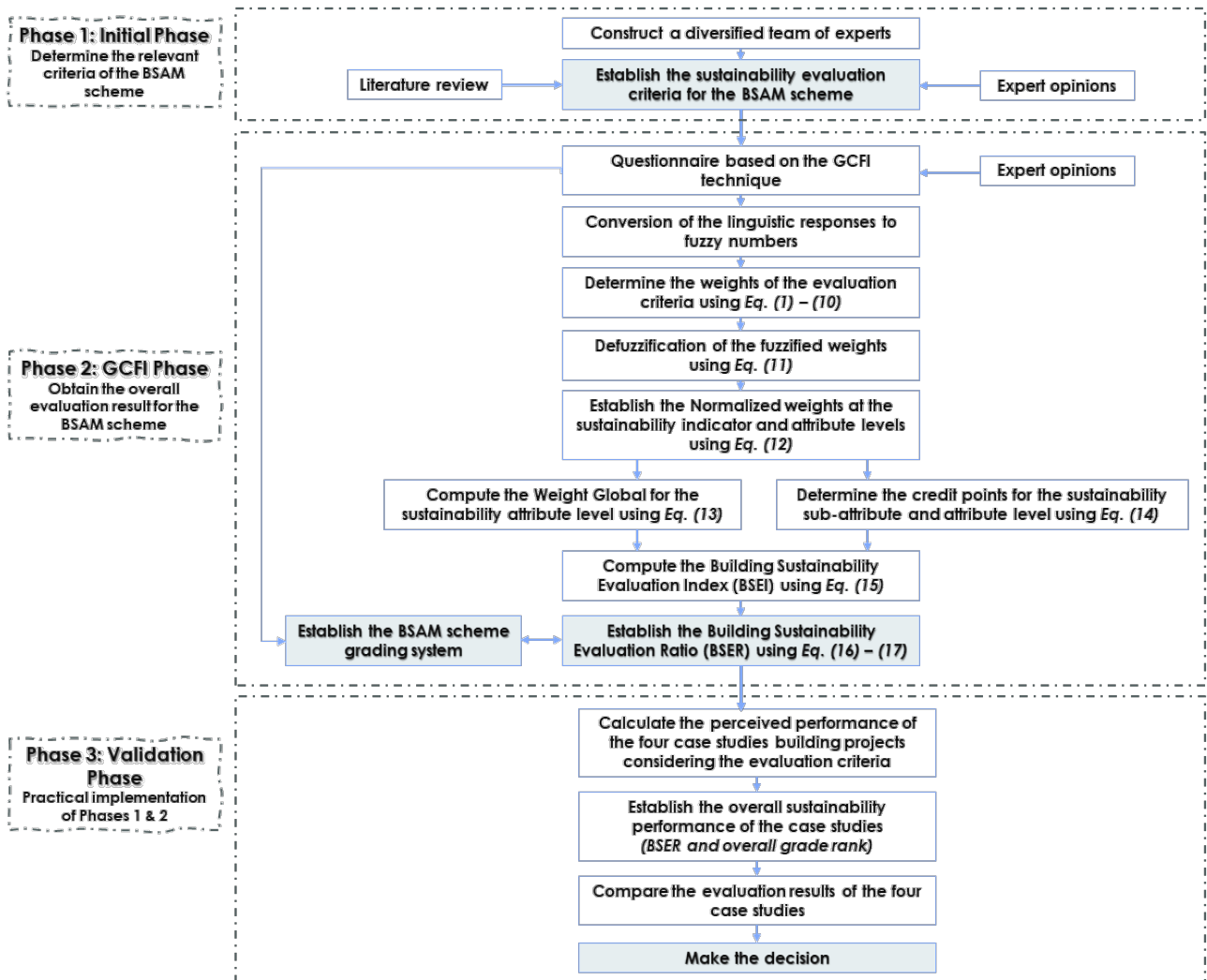
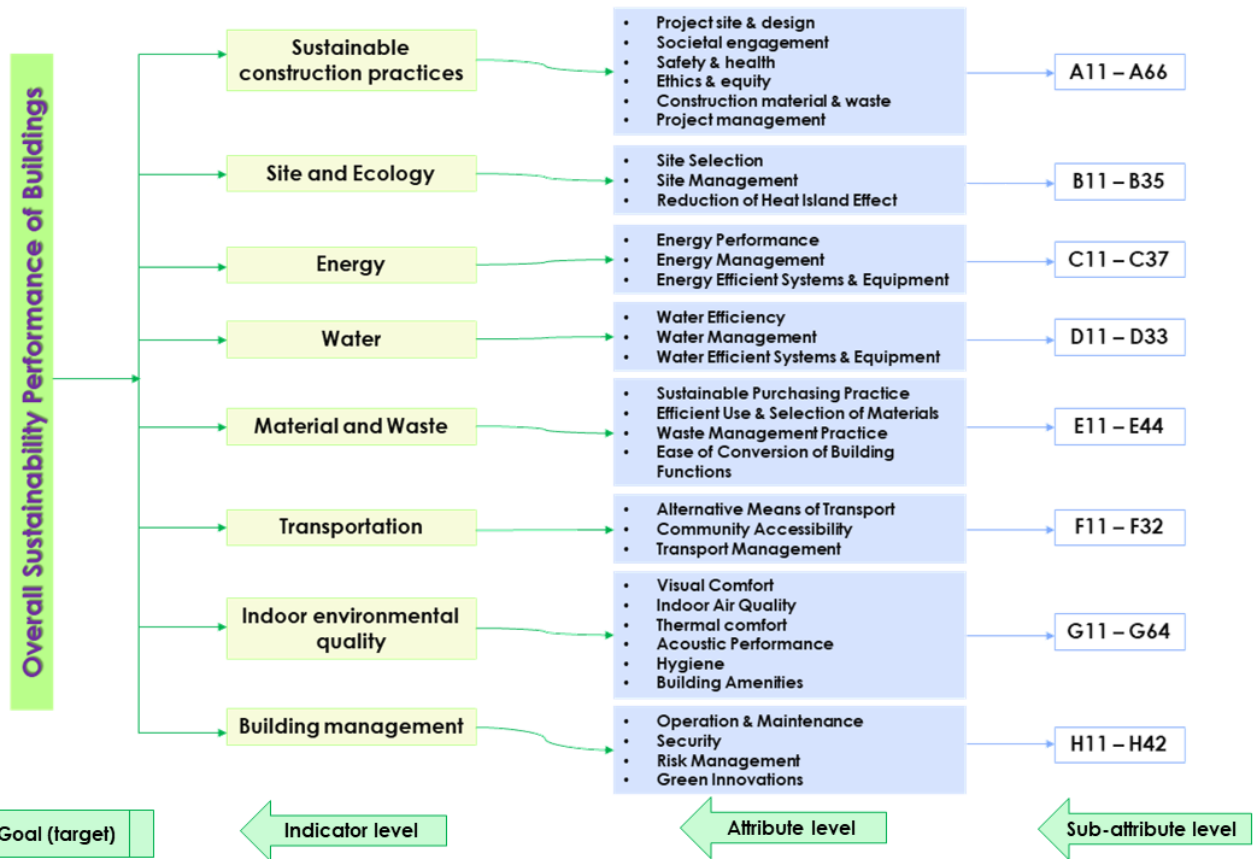


Figure 1: Overall framework of the research methodology

176 **3.1 Determination of the Building Sustainability Evaluation Index (BSEI)**

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



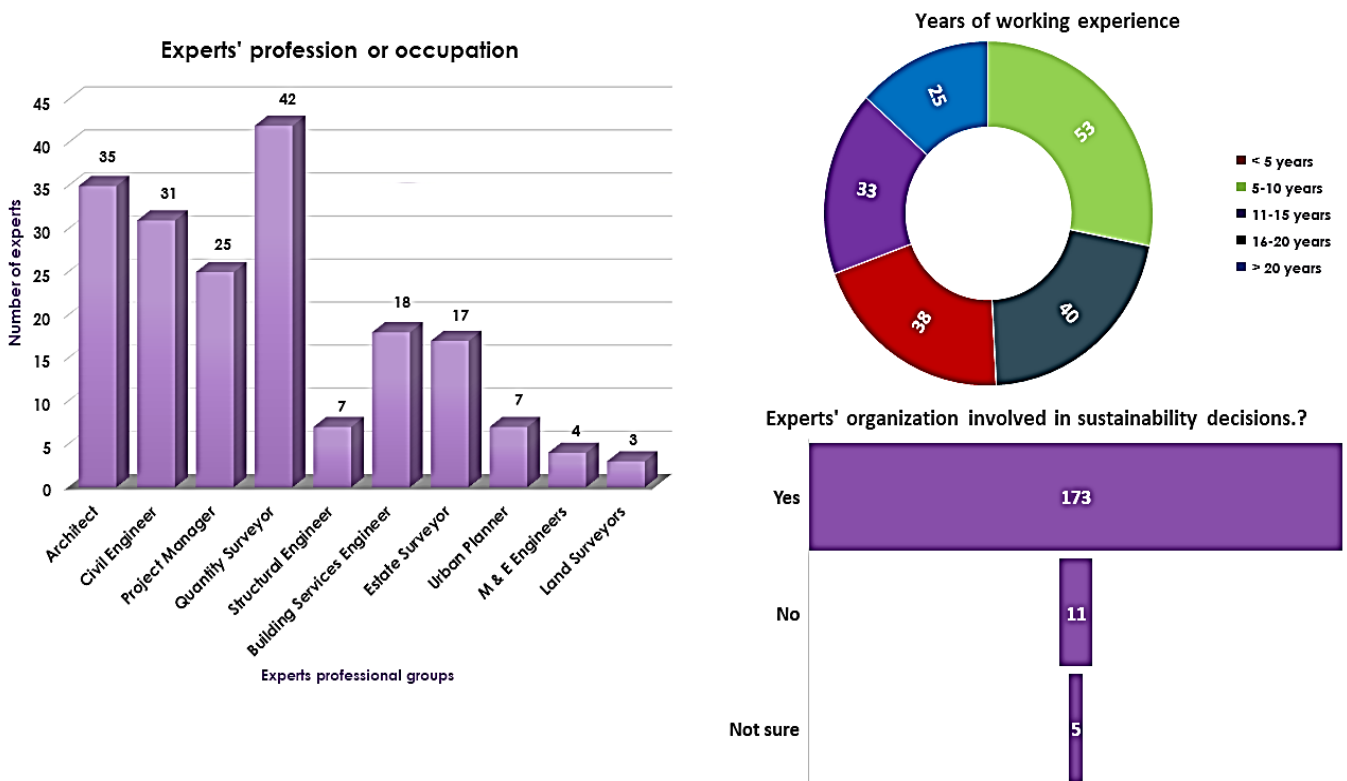
187
 188 **Figure 2: Hierarchical structure of the sustainability evaluation criteria of the BSAM scheme**

189 **3.1.1 Experts' demographics**

190 Bebčáková et al. (2011) reported that the weights of the sustainability criteria must be estimated expertly.
 191 Hence, the input data for this study is based on the responses derived from the decision-making group,
 192 which was composed of 189 experts in the built experts over six months. The experts were selected using

193 purposive and snowball sampling techniques. See Figure 3 for the analysis of the demographics of the
 194 experts. As shown in Figure 3, the invited experts are from ten distinct and varied professions; and this
 195 multi-expert consultation approach was recommended by Ali and Al Nsairat (2009) who pointed out that a
 196 diverse set of key participants should be involved in the process of developing green building assessment
 197 rating tools. Previous studies that adopt the GCFI method, such as Kurt (2014), who used the GCFI method
 198 and fuzzy TOPSIS to select the best site for a nuclear power plant, utilized three power system experts.
 199 Also, Ozdemir and Ozdemir (2018), who applied the GCFI to prioritize five residential heating systems,
 200 sought the opinion of three experts to provide the importance values of the four heating system criteria.

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



207
 208 **Figure 3: The experts' demographics**

209 **3.1.2 The fuzzification process**

210 As mentioned, the experts are invited to identify the degree of significance of each sustainability criteria that
 211 are critical to the sustainability performance of buildings. The sustainability criteria provide the right mix of

212 key criteria that satisfies the three pillars of sustainable development as it relates to building projects –
 213 social, economic, and environmental sustainability. The experts were requested to provide five sets of four
 214 numbers (trapezoidal fuzzy numbers) to express the five-linguistics variables – “very high,” “high,” “medium,”
 215 “low,” and “very low” (see Appendix A). That is, each set of linguistics variables corresponds to four
 216 numbers, which represent a trapezoidal fuzzy number that comprises a minimum threshold (lowest number
 217 in the fuzzy set), two median thresholds, and the maximum threshold (highest number in the fuzzy set).

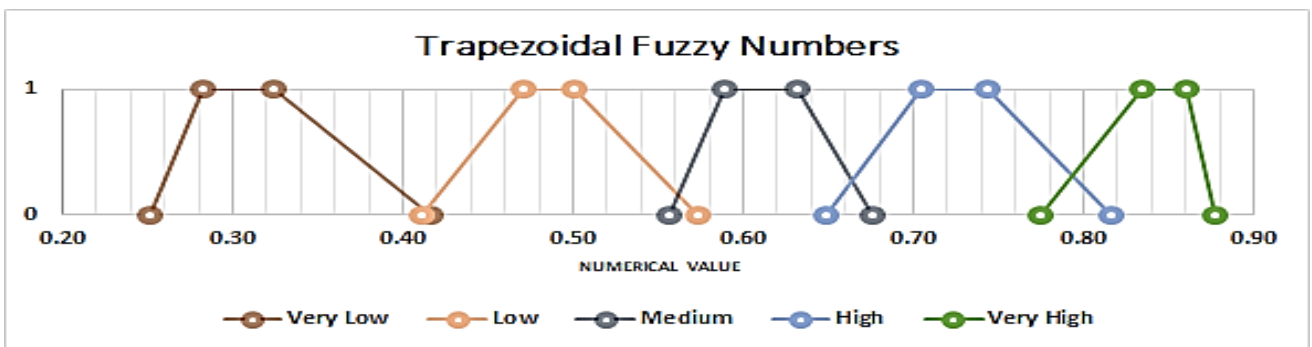
218 **Step 1: Fuzzifying the ‘degree of importance’ levels**

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

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

225
$$\tilde{P}_i, \tilde{A}_i = \frac{\sum_{t=1}^k \tilde{A}_i^t}{k} = \left(\frac{\sum_{t=1}^k \tilde{a}_{i1}^t}{k}, \frac{\sum_{t=1}^k \tilde{a}_{i2}^t}{k}, \frac{\sum_{t=1}^k \tilde{a}_{i3}^t}{k}, \frac{\sum_{t=1}^k \tilde{a}_{i4}^t}{k} \right) \quad (1)$$

226 Where k is the number of invited experts; expert t , and the linguistic terms for the “degree of importance” is
 227 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
 228 ‘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
 229 numbers of \tilde{P}_i .



230
 231 **Figure 4: Representation of the Trapezoidal Fuzzy Numbers**

232 **[Insert Table 1]**

233 **Step 2: Determination of the Tolerance Zones and perceived ‘degree of significance’ for the key**
234 **sustainability criteria**

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

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

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

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

247
$$\tilde{R}_i = \frac{\sum_{t=1}^k \tilde{R}_i^t}{n} \times \frac{1}{k} \quad (2)$$

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

252 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
253 significance’ value (*best alternative*) (\tilde{T}_i) is (0.516, 0.556, 0.574, 0.584).

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

260 The minimum (min) tolerance and the maximum (max) tolerance value is based on the lowest and highest
 261 linguistic-term scale of the sustainability criteria. Meanwhile, the tolerance zones in Table 2 are obtained by
 262 combining the first two numerical values of the ‘min tolerance value’ with the last two numerical values of the
 263 ‘max tolerance value’ for each sustainability criteria. For instance, tolerance zone [M, VH] for sustainability
 264 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,
 265 0.834, 0.860, 0.876) respectively. Hence, the combined tolerance zone (\bar{e}_i^α) for criteria A1 is (0.556, 0.589
 266 ,0.860, 0.876).

267 **[Insert Table 2]**

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

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

$$272 \quad \tilde{f} = \parallel_{\alpha \in [0,1]} \tilde{f}_i^\alpha = \parallel_{\alpha \in [0,1]} [f_{i,\alpha}^-, f_{i,\alpha}^+] \quad (3)$$

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

$$277 \quad \tilde{f}_i^\alpha = [f_{i,\alpha}^-, f_{i,\alpha}^+] = \frac{\bar{P}_i^\alpha - \bar{e}_i^\alpha + [1, 1]}{2} \quad (4)$$

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

$$281 \quad \int \tilde{f} d\tilde{g} = \parallel_{\alpha \in [0,1]} \left[(C) \int \tilde{f}_\alpha^- d\tilde{g}_\alpha^-, (C) \int \tilde{f}_\alpha^+ d\tilde{g}_\alpha^+ \right] \quad (5)$$

282 Where $\tilde{g}_i : P(S) \rightarrow I(R^+)$, $\tilde{g}_i = [g_i^-, g_i^+]$, $\tilde{g}_i^\alpha = [g_{i,\alpha}^-, g_{i,\alpha}^+]$, $\tilde{f}_i : S \rightarrow I(R^+)$ and $[\tilde{f}_i^-, \tilde{f}_i^+]$ for $i=1,2,3,\dots, n_j$.

283 Tables 3 presents the evaluation results by the GCFI algorithm for $\alpha=0$ for all the key criteria. The
 284 “individual significance” column shows the lowest and the highest value of the “average ‘degree of
 285 significance’ value” for the best alternative (\tilde{T}_i) in Table 2. For instance, the TFN for criteria “A1” in Table 2
 286 (\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

287 [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 –
 288 H4), Eq. (3) and (4) is used; while Eq. (5) is used for the S/ (A – H).

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

$$290 \quad f, \tilde{f}_{(A1)} = [\tilde{f}_{(A1),0}] = \frac{[0.516, 0.584] - [0.556, 0.876] + [1, 1]}{2} = \left[\frac{(0.516 - 0.876 + 1)}{2}, \frac{(0.584 - 0.556 + 1)}{2} \right]$$

$$291 \quad = [0.320, 0.514] \quad \text{for } (\alpha = 0)$$

292 **[Insert Table 3]**

293 More so, Table 4 gives the evaluation results by the GCFI algorithm for $\alpha = 1$ for all the key criteria. The $\alpha =$
 294 1, in this case, considers the two median values of the “average ‘degree of significance’ value” for the best
 295 alternative (\tilde{T}_i) as presented in Table 2 – as the “individual significance” column in Table 4. For criteria A1,
 296 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
 297 valence function $\tilde{f}_{i,1}$ for criteria, A1 is [0.348, 0.492] as calculated using Eq. (3) and (4) (see Table 4):

$$298 \quad f, \tilde{f}_{(A1)} = [\tilde{f}_{(A1),1}] = \frac{[0.556, 0.574] - [0.589, 0.860] + [1, 1]}{2} = [0.348, 0.492] \quad \text{for } (\alpha = 1)$$

299 **[Insert Table 4]**

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

302 Meanwhile, to calculate the location value, a λ value (for the indicators, A – H) and the fuzzy measures
 303 $g(A_{(i)})$ (for the attributes, A1 – H4), where $i=1,2,3, \dots, n$ is needed. These are derived using Eq. (6) to (8) as
 304 follows:

$$305 \quad g(A_{(n)}) = g(\{P_{(s)}\}) = g_n \quad (6)$$

$$306 \quad g(A_{(i)}) = P_i + g(A_{(i+1)}) + \lambda P_i g(A_{(i+1)}), \quad \text{for } 1 \leq i \leq n \quad (7)$$

$$307 \quad 1 = g(S) = \begin{cases} 1/\lambda \left\{ \prod_{i=1}^n [1 + \lambda g(A_i)] - 1 \right\} & \text{if } \lambda \neq 0 \\ \sum_{i=1}^n g(A_i) & \text{if } \lambda = 0 \end{cases} \quad (8)$$

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

311 For instance, as shown in Table 5, the λ for criteria A, taking $\alpha=0$ is calculated to give λ [-0.9963, -0.9997].
 312 The average 'degree of significance' value for the subset of criteria 'A' ($P_{(A),0}$) as presented in Table 2 (*that*
 313 *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],
 314 [0.597, 0.736], [0.528, 0.672], [0.660, 0.789], and [0.597, 0.736] for sustainability attributes A1 – A6
 315 respectively (taking $\alpha=0$).

$$316 \quad 1 = g(S) = \frac{1}{\lambda} \{ [(1 + 0.660\lambda)(1 + 0.597\lambda)(1 + 0.597\lambda)(1 + 0.528\lambda)(1 + 0.660\lambda)(1 + 0.597\lambda)]$$

$$317 \quad - 1 \} \quad \text{for } \alpha=0 \text{ and } \lambda^-$$

$$318 \quad 1 = g(S) = \frac{1}{\lambda} \{ [(1 + 0.789\lambda)(1 + 0.736\lambda)(1 + 0.736\lambda)(1 + 0.672\lambda)(1 + 0.789\lambda)(1 + 0.736\lambda)]$$

$$319 \quad - 1 \} \quad \text{for } \alpha=0 \text{ and } \lambda^+$$

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

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

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

$$330 \quad f_{(A4),0}^- = 0.336 > f_{(A1),0}^- = 0.320 > f_{(A6),0}^- = 0.316 > f_{(A3),0}^- = 0.313$$

$$331 \quad > f_{(A5),0}^- = 0.308 > f_{(A2),0}^- = 0.273$$

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

$$334 \quad P_{(A4),0}^- = 0.528, P_{(A1),0}^- = 0.660, P_{(A6),0}^- = 0.597, P_{(A3),0}^- = 0.597$$

$$335 \quad P_{(A5),0}^- = 0.660, P_{(A2),0}^- = 0.597$$

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

338 $\lambda^- = -0.9963$

339 $g^-(A_{(A4)}) = P_{(A4)}^- = 0.528$

340 $g^-(A_{(A1)}) = P_{(A1)}^- + g^-(A_{(A4)}) + \lambda^- P_{(A1)}^- g^-(A_{(A4)}) = 0.841$

341 $g^-(A_{(A6)}) = P_{(A6)}^- + g^-(A_{(A1)}) + \lambda^- P_{(A6)}^- g^-(A_{(A1)}) = 0.938$

342 $g^-(A_{(A3)}) = P_{(A3)}^- + g^-(A_{(A6)}) + \lambda^- P_{(A3)}^- g^-(A_{(A6)}) = 0.977$

343 $g^-(A_{(A5)}) = P_{(A5)}^- + g^-(A_{(A3)}) + \lambda^- P_{(A5)}^- g^-(A_{(A3)}) = 0.995$

344 $g^-(A_{(A2)}) = P_{(A2)}^- + g^-(A_{(A5)}) + \lambda^- P_{(A2)}^- g^-(A_{(A5)}) = 1.000$

345 **[Insert Tables 5 & 6]**

346 **3.1.3 The defuzzification process, normalization process and results**

347 Having calculated fuzzy measures $g(A_{(i)})$ as a membership function of the TFN (\tilde{P}_i) , fuzzy number \tilde{P}_i is
 348 defuzzified to \tilde{p}_i using Eq. (9) as presented in step 5 below. Where $A_i \cap A_j = \phi$ for all $i, j = 1, 2, 3, \dots, n$ and
 349 $i \neq j, \lambda \in (-1, \infty)$. Let μ be a fuzzy measure on $(I, P(I))$ and an application $f : I \rightarrow \mathfrak{R}^+$. The Choquet integral
 350 of f with respect to μ is defined by:

351
$$\int_I f d\mu = \sum_{i=1}^n (f(\sigma(i)) - f(\sigma(i-1))) \mu(A_i)$$

352 Where σ is a permutation of the indices to have $f(\sigma(i-1)) \leq \dots \leq f(\sigma(n))$, $A_i = \{\sigma(i), \dots, \sigma(n)\}$ and
 353 $xf(\sigma(0)) = 0$, by convention.

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

356 $f : S \rightarrow [0,1], 0 \leq f(s_{(1)}) \leq f(s_{(2)}) \leq \dots \leq f(s_{(n)}) \leq 1, f(s_{(0)}) = 0$ and $A_{(i)} = \{s_{(1)}, \dots, s_{(n)}\}$.

357
$$(C) \int f dg = \sum_{i=1}^n (f(s_{(i)}) - f(s_{(i-1)})) g(A_{(i)}) \quad (9)$$

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

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

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

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

$$364 \quad g^-(A_{(A2)}) = 1.000 > g^-(A_{(A3)}) = 0.977 > g^-(A_{(A5)}) = 0.995 > g^-(A_{(A6)}) = 0.938$$

$$365 \quad > g^-(A_{(A1)}) = 0.841 > g^-(A_{(A4)}) = 0.528,$$

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

$$367 \quad f_{(A2),0}^- = 0.273, f_{(A3),0}^- = 0.313, f_{(A5),0}^- = 0.308, f_{(A6),0}^- = 0.316,$$

$$368 \quad f_{(A1),0}^- = 0.320, f_{(A4),0}^- = 0.336$$

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

$$370 \quad \int \tilde{f}_0^- d\tilde{g}_0^- = \{[1.000 \times 0.273] + [0.977 \times (0.313 - 0.273)] + [0.995 \times (0.308 - 0.313)]$$

$$371 \quad + [0.938 \times (0.316 - 0.308)] + [0.841 \times (0.320 - 0.316)] + [0.528 \times (0.336 - 0.320)]\}$$

$$372 \quad = \mathbf{0.327}$$

373 Similarly,

$$374 \quad \int \tilde{f}_0^+ d\tilde{g}_0^+ = \mathbf{0.650}$$

375 Hence,

$$376 \quad \int \tilde{f} d\tilde{g} = [0.327, 0.650] \quad \text{taking } \alpha = 0; \text{ for criteria A} \quad (\text{see Table 3})$$

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

$$381 \quad \tilde{V} = (C) \int f dg \quad (10)$$

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

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

387
$$F(\tilde{A}) = \frac{v_1 + v_2 + v_3 + v_4}{4} \quad (11)$$

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

392
$$\frac{0.327 + 0.357 + 0.616 + 0.650}{4} = \mathbf{0.488}$$

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

395 After the defuzzification procedure, the normalization of the resulting defuzzified value $F(\tilde{A})$ was calculated
 396 to get the final weight of each sustainability criteria (Byun & Lee, 2005; Ertuğrul & Karakaşoğlu, 2008;
 397 Kahraman et al., 2008; Pramanik et al., 2017). Eq. (12) was utilized to normalize the $F(\tilde{A})$ for all criteria for
 398 both new and existing buildings. Note: for all computation of values for the ‘existing building’ classification –
 399 the sustainability indicator “A,” which is the “*sustainable construction practices*” and its subsets factors are
 400 excluded. The resulting value is then normalized weight $N(\tilde{A})$ for the criterion (Table 7) and the summation
 401 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.

402
$$N(\tilde{A}) = \frac{F(A_{(i)})}{\sum_{i=1}^n F(A_{(i)})} \quad (12)$$

403 Where $i = 1, 2, 3, \dots, n$

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

406
$$N(\tilde{A}_{(B1)}) = \frac{0.417}{0.417 + 0.451 + 0.446} = \mathbf{0.3170}$$

407 Similarly, for criterion “C” for existing building (EB), the $F(A_{(i)})$ of criteria B – H are aggregated as the
 408 $\sum_{i=1}^n F(A_{(B-H)})$:

409
$$N(\tilde{A}_{(C)}) = \frac{0.461}{0.449 + 0.461 + 0.413 + 0.459 + 0.466 + 0.477 + 0.442} = \mathbf{0.1469}$$

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

412 As earlier mentioned, the proposed criteria BSAM scheme consists of a three hierarchical structure of
 413 sustainability indicators (SI), sustainability attributes (SA), and sustainability sub-attributes (SSA). Having
 414 computed the normalized weights for the SI (A – H) and their respective SA (A1 – H4) as presented in step
 415 7, the global weight (WG), which is a critical variable in the sustainability assessment process can be
 416 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
 417 in Eq. (13).

418
$$WG_j = N(A)_j \times N(A)_i \quad (13)$$

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

420 $N(A)_j$ = normalized weight of the j th sustainability attribute.

421 $N(A)_i$ = corresponding normalized weight of the i th sustainability indicator for the j th sustainability
 422 attribute

423 Hence, the $WG_{(A1)}$ for criteria “A1” is:

424
$$WG_{(A1)} = N(A)_{(A1)} \times N(A)_{(A)} = 0.1591 \times 0.1345 = \mathbf{0.0214}$$

425 **[Insert Table 7]**

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

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

432
$$CP_j = \sum_{h=1}^n CP_{(h)} \quad (14)$$

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

435 3.1.4 Establishing the Building Sustainability Evaluation Index (BSEI) and BSER

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

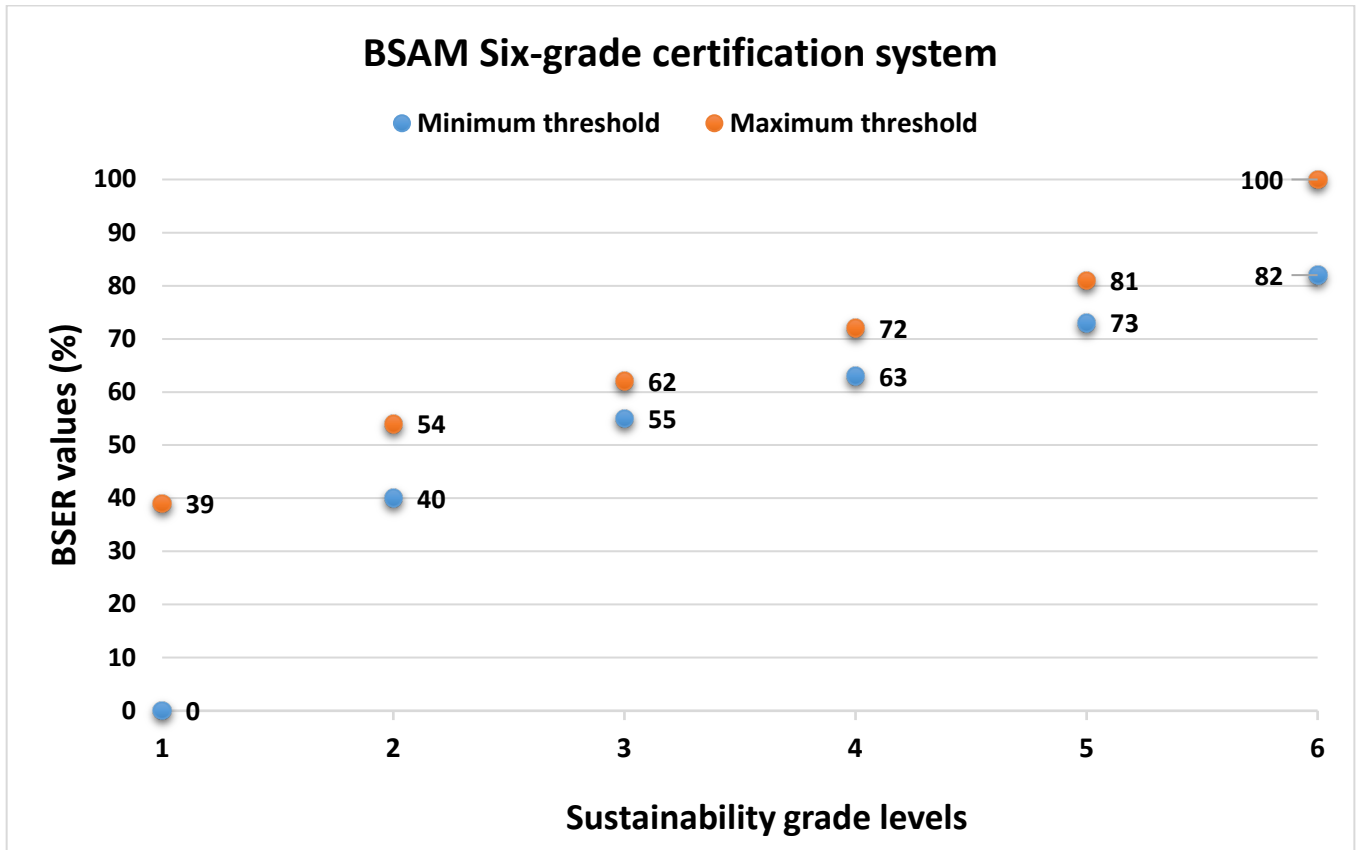
$$445 \quad BSEI = \sum_{j=1}^n CP_j \times WG_j = \sum_{j=1}^n FI_j \quad (15)$$

$$446 \quad BSER (\%) = \frac{BSEI}{BSEI_{max}} \times 100 \quad (16)$$

$$447 \quad BSER (\%) = \frac{\sum_{j=1}^n CP_j \times WG_j}{\sum_{j=1}^n (CP_j)_{max} \times WG_j} \times 100 \quad \text{OR} \quad \frac{\sum_{j=1}^n FI_j}{\sum_{j=1}^n (FI_j)_{max}} \times 100 \quad (17)$$

448 3.1.5 Building sustainability grade determination

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



458

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

461 Therefore, for a building to be green certified using the BSAM scheme, it must a minimum BSER value of
 462 40% (i.e., an ‘acceptable’ sustainability grade level).

463 **3.2 Implementation of the BSAM scheme: Case study validation**

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

467 **3.2.1 Case study projects descriptions and data**

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

472 Firstly, the NB case studies comprise of two buildings – a residential facility (CE duplex) and a commercial
 473 facility (RA labs). CE duplex is a one-story residential duplex building situated in the south-eastern region of
 474 Nigeria with a gross area of 459.820m² that accommodates seven rooms of different sizes, a stair hall, and
 475 other regular residential facilities, a gatehouse among others. It has a green area of 183.928m² (40% of the

476 GFA) and a paved area of 141.483m². More so, the RA lab is a one-story commercial facility situated in the
477 south-western part of Nigeria with a gross area of 346.784m². It includes four offices and research labs,
478 stores and other facilities on the ground floor; and two offices, meeting halls, a large conference hall, and
479 other facilities on the first floor. It has a green area of 34.581m² (10% of the GFA). Secondly, the EB case
480 studies are two residential building projects (SNN building & FT building) situated in Lagos, Nigeria. Both
481 sets of buildings are one-story buildings consisting of two units of duplex apartments. The SNN building has
482 a gross area of 896.041m² composed of sixteen rooms, two stair halls, other regular residential facilities, and
483 a gatehouse. It has a paved area of 420.064m² and a green area of 89.604m² (10% of the GFA). The FT
484 building has a gross area of 506.509m², which accommodated 14 rooms of varying sizes and purposes, two
485 stair halls, and other regular residential facilities, a gatehouse, among others. It has a paved area of
486 101.403m² and a green area of 202.581m² (40% of the GFA).

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

492 **3.2.2 Evaluation of the sustainability performance of the case study projects**

493 The weights of each *SI* and *SA*, BSEI values, BSER values and sustainability grades for the case studies
494 are determined based on (1) the collected data of the four case studies – including the BIM output and other
495 necessary simulations; (2) utilizing the sustainability evaluation equations from Eq. (13) – (17). The entire
496 sustainability evaluation process, the respective weights for each criterion, and the sustainability index
497 (BSEI) are illustrated in Table 8 for the NB case studies and Table 9 for the EB case studies. These tables
498 also present the BSER determination for the four case studies based on their BSEI, respectively. Each table
499 provides the (i) the description of the sustainability indicators and attributes; (ii) the normalized (local)
500 weights, $N(\tilde{A})$ of the *SI* and *SA*; (iii) the global weights, WG_j determination for the *SA*. (iv) credit points, CP_j
501 determination for the case studies; (v) the sustainability factor index, FI_j of each criterion. (vi) The BSEI of
502 the case studies; and (vii) the BSER of the four case studies. The credit points, CP_j and sustainability factor
503 index, FI_j of each criterion are subdivided into attained and maximum segments; the attained points and
504 indices are the current evaluation of the case study building, whereas the maximum segment represents a
505 100% score that can be awarded to the criterion.

506

[Insert Tables 8 & 9]

507 **3.3 Comparison between the BSAM scheme and other green building rating systems**

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

515

[Insert Table 10]

516 **4. Discussion of findings**

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

- 518 (i) the determined weights of the sustainability indicators (*S*) and attributes (*SA*) based on the
519 application of the generalized Choquet fuzzy integral algorithm (section 4.1).
- 520 (ii) The BSER values and sustainability grade levels of the four case studies (section 4.2) based on
521 the determination of the BSEI (model validation).

522 **4.1 Weights of the key sustainability criteria**

523 The weights of the key sustainability criteria (A – H) are presented in Table 7, which are based on the
524 application of the GCFI method on the data collected from the experts' consultations. When the weights
525 assigned to the sustainability criteria for the BSAM scheme in this study are compared to existing building
526 rating systems such as LEED, BREEAM, BEAM Plus, etc., it reveals differential weighting for the different
527 sustainability criteria. More so, this differential weighting shows a significant variation in the local context of
528 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
529 earlier mentioned, the BSAM scheme was explicitly developed for countries in the sub-Saharan region of
530 Africa. Meanwhile, as shown in Tables 5 and 6, the sets of sustainability criteria held interactive
531 characteristics (i.e. share sub-additive effect) as their fuzzy measures are $\lambda < 0$. Hence, to improve the
532 overall BSER value of a building project, efforts should be devoted to enhancing the weights of the
533 sustainability indicators, which have higher normalized weights.

534 The sustainable criterion “A” – “*sustainable construction practices*” is given the highest priority among the
535 eight criteria by the experts with a value of 0.1346. This criterion comprises several social and economic
536 sustainability sub-criteria such as “*ethics & equity*,” “*societal engagement*,” with values of 0.1948 and
537 0.1526, among others, which contributes significantly to its high weight value in comparison to other criteria.
538 Illankoon et al. (2017) reported that the existing green rating tools place very little or no emphasis on social
539 and economic sustainability issues in their assessment of the sustainability performance of building.
540 Criterion “F,” which is *transportation* receives the next highest priority among the consulted experts with the
541 value of 0.1286, and its sub-criteria of “*transport management*” and “*alternative means of transport*” receive
542 the highest weights under this criterion with values of 0.3504 and 0.3376 respectively. The Green Mark
543 green rating tool did not allocate any weights to the transportation criterion (BCA, 2015), while the IGBC
544 allocated just 3% of the total weights to the same criterion (IGBC, 2014).

545 The *energy* “C” criterion acquired the third highest weight among the sustainability criteria with a value of
546 0.1271, and its sub-criterion of “*energy management*” receives the highest weight among the sub-criteria
547 under this criterion with a value of 0.3424. However, according to Illankoon et al. (2017), LEED, BREEAM,
548 Green Star, BEAM Plus gave the highest priority to the *energy* criterion, which emphasizes the special
549 consideration given to the environmental aspect of sustainability by the existing rating tools and countries in
550 the developed world. The “*E-material and waste*” criterion receives the fourth priority among the
551 sustainability criteria with a weight value of 0.1267, and its sub-criterion “*sustainable purchasing practice*”
552 got the highest weight under this criterion with a value of 0.2575. The “*B-site and ecology*” criterion with a
553 weight value of 0.1238 is the fifth-ranked criterion, and its sub-criterion “*site management*” with a value of
554 0.3435 is the highest-ranked sub-criterion under the criterion “B.” Among existing green rating tools, these
555 criteria “B” and “E” receive consideration weights allocation (Illankoon et al., 2017).

556 Moreover, the sustainability criteria “*IEQ*,” “*building management*,” and “*water*” with weight values of 0.1232,
557 0.1219, and 0.1141 respectively received the lowest priority among the criteria as rated by the experts and
558 analyzed using the GCFI method. For the *IEQ* “G” criterion, its sub-criteria such as “*building amenities*” and
559 “*acoustic performance*” with values of 0.1803 and 0.1699 respectively receive the highest weight under the
560 *IEQ* criterion. For the “*H-building management*” criterion, its sub-criteria “*risk management*” and “*green*
561 *innovations*” with 0.2661 and 0.2544 respectively receive the highest weights. In the “*D-water*” criterion, its
562 sub-criterion of “*water efficiency*” with the value of 0.3713 gets the highest weight. An analysis of existing
563 green rating tools by Illankoon et al. (2017) reveals that LEED, Green Mark, BEAM Plus places less

564 consideration for the “*building management*” criteria, although they place a higher priority on the “*water*”
565 criterion.

566 **4.2 Assessment results of the case study projects**

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

585 More so, for the new buildings as shown in Table 8, the CE duplex and RA lab buildings have different
586 values for the sustainability factor index except for the “*energy performance*” sub-criterion, which achieved
587 the same *FI*. Similarly, for the existing buildings (Table 9), the SNN and FT buildings have similar *FI* for the
588 B1, C2, E4, G3, H3, and H4 sub-criteria. Although, for both the new and existing buildings, the summation of
589 the *FI* for each sustainability indicator differs, as shown in Tables 8 and 9. Furthermore, the BSER values for
590 each sustainability indicator – which is the percentage of the summation of the *FI* for each indicator to the
591 summation of the FI_{max} as illustrated in Eq. 17 – for the sustainability indicator A – H are 53.28%, 53.4%,
592 62.7%, 59.6%, 84.65%, 87.14%, 68.75%, 42.4% respectively for the CE duplex building while for the RA
593 labs building the values are 74.15%, 49.86, 69.04%, 71.03%, 75.8%, 53.09, 84.16, 72.53% respectively.
594 The BSER values for criteria “*site & ecology*,” “*material & waste*,” and “*transportation*” for the CE duplex

595 building are higher than the RA labs building, whereas the RA labs building achieved higher BSER values in
596 other criteria. Moreover, for the existing buildings, the SNN buildings achieved higher BSER values for
597 sustainability criteria for “energy,” “water,” “transportation,” and “building management,”; while the FT
598 buildings achieved higher values in the other four sustainability criteria.

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

609 **5. Conclusions**

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

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

622 As it is revealed in the weighting calculation for the respective eight sustainability criteria, significant priority
623 was given to criteria such as “sustainable construction practices” transportation, and energy. The
624 “sustainable construction practices” criteria contain a considerable proportion of the social and economic
625 sustainability criteria which were not considered in the existing green building rating tools. Also, the BSAM

626 scheme documentation was developed, which provides comprehensive, and details descriptions of each
627 sustainability criteria, the allocation of points to the criteria, and the various documentary evidence needed
628 to be provided before a criterion can be considered fulfilled by the assessed building project. The practical
629 contributions of the current study to the industry and theoretical standpoints include:

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

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

651

652

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 (<i>best alternative</i>)
$\tilde{p}_{i1}^t, \tilde{p}_{i2}^t, \tilde{p}_{i3}^t, \tilde{p}_{i4}^t$	TFN of \tilde{P}_i
\tilde{R}_i	RON values
n	Number of attributes
\tilde{f}	Set of fuzzy valence functions
\tilde{e}_i^α	Tolerance zone
$g(A_{(i)}), \lambda$	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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Table 1: Relationship between the trapezoidal fuzzy numbers (TFN) and degree of importance (linguistics variables) on a five-linguistic-term scale

Degree of importance		Trapezoidal fuzzy numbers
Label	Linguistic terms	
VH	Very High	(0.774, 0.834, 0.860, 0.876)
H	High	(0.649, 0.704, 0.744, 0.816)
M	Medium	(0.556, 0.589, 0.631, 0.676)
L	Low	(0.411, 0.471, 0.500, 0.574)
VL	Very Low	(0.252, 0.282, 0.324, 0.416)

Table 2: Average values of the degree of significance and tolerance zones of each criterion (SA) using TFN

Sustainability Criteria (Attributes)	Average 'degree of significance' value for each criterion (\bar{P}_i)	Min. Tolerance Value	Max. Tolerance Value	Tolerance Zone (\bar{e}_i^α)	RON values (\bar{R}_i)	Average 'degree of significance' value (Best Alternative) (\bar{T}_i)
A- Sustainable Construction Practices						
A1- Project Site and Design	(0.660, 0.709, 0.745, 0.789)	M	VH	(0.556, 0.589, 0.860, 0.876)	0.667	(0.516, 0.556, 0.574, 0.584)
A2- Societal Engagement	(0.597, 0.650, 0.684, 0.736)	L	VH	(0.411, 0.471, 0.860, 0.876)	0.547	(0.423, 0.456, 0.471, 0.479)
A3- Safety & Health	(0.597, 0.650, 0.684, 0.736)	L	VH	(0.411, 0.471, 0.860, 0.876)	0.650	(0.503, 0.542, 0.559, 0.570)
A4- Ethics & Equity	(0.528, 0.576, 0.612, 0.672)	VL	VH	(0.252, 0.282, 0.860, 0.876)	0.708	(0.548, 0.591, 0.609, 0.621)
A5- Construction Material & Waste	(0.660, 0.709, 0.745, 0.789)	M	VH	(0.556, 0.589, 0.860, 0.876)	0.638	(0.493, 0.532, 0.549, 0.559)
A6- Project Management	(0.597, 0.650, 0.684, 0.736)	L	VH	(0.411, 0.471, 0.860, 0.876)	0.657	(0.509, 0.548, 0.566, 0.576)
B- Site and Ecology						
B1- Site Selection	(0.597, 0.650, 0.684, 0.736)	L	VH	(0.411, 0.471, 0.860, 0.876)	0.583	(0.452, 0.486, 0.502, 0.511)
B2- Site Management	(0.528, 0.576, 0.612, 0.672)	VL	VH	(0.252, 0.282, 0.860, 0.876)	0.563	(0.435, 0.469, 0.484, 0.493)
B3- Reduction of Heat Island Effect	(0.528, 0.576, 0.612, 0.672)	VL	VH	(0.252, 0.282, 0.860, 0.876)	0.550	(0.426, 0.459, 0.473, 0.482)
C- Energy						
C1- Energy Performance	(0.528, 0.576, 0.612, 0.672)	VL	VH	(0.252, 0.282, 0.860, 0.876)	0.540	(0.418, 0.450, 0.464, 0.473)
C2- Energy Management	(0.528, 0.576, 0.612, 0.672)	VL	VH	(0.252, 0.282, 0.860, 0.876)	0.600	(0.464, 0.500, 0.516, 0.526)
C3- Energy Efficient Systems & Equipment	(0.528, 0.576, 0.612, 0.672)	VL	VH	(0.252, 0.282, 0.860, 0.876)	0.571	(0.442, 0.477, 0.492, 0.501)
D- Water						
D1- Water Efficiency	(0.528, 0.576, 0.612, 0.672)	VL	VH	(0.252, 0.282, 0.860, 0.876)	0.500	(0.387, 0.417, 0.430, 0.438)
D2- Water Management	(0.597, 0.650, 0.684, 0.736)	L	VH	(0.411, 0.471, 0.860, 0.876)	0.563	(0.435, 0.469, 0.484, 0.493)
D3- Water Efficient Systems & Equipment	(0.597, 0.650, 0.684, 0.736)	L	VH	(0.411, 0.471, 0.860, 0.876)	0.333	(0.258, 0.278, 0.287, 0.292)
E- Material and Waste						
E1- Sustainable Purchasing Practice	(0.528, 0.576, 0.612, 0.672)	VL	VH	(0.252, 0.282, 0.860, 0.876)	0.589	(0.456, 0.491, 0.507, 0.516)
E2- Efficient Use & Selection of Materials	(0.528, 0.576, 0.612, 0.672)	VL	VH	(0.252, 0.282, 0.860, 0.876)	0.583	(0.452, 0.486, 0.502, 0.511)
E3- Waste Management Practice	(0.528, 0.576, 0.612, 0.672)	VL	VH	(0.252, 0.282, 0.860, 0.876)	0.560	(0.434, 0.467, 0.482, 0.491)
E4- Ease of Conversion of Building Functions	(0.528, 0.576, 0.612, 0.672)	VL	VH	(0.252, 0.282, 0.860, 0.876)	0.500	(0.387, 0.417, 0.430, 0.438)
F- Transportation						
F1- Alternative Means of Transport	(0.528, 0.576, 0.612, 0.672)	VL	VH	(0.252, 0.282, 0.860, 0.876)	0.583	(0.452, 0.486, 0.502, 0.512)

Sustainability Criteria (Attributes)	Average 'degree of significance' value for each criterion (\bar{P}_i)	Min. Tolerance Value	Max. Tolerance Value	Tolerance Zone (\bar{e}_i^α)	RON values (\bar{R}_i)	Average 'degree of significance' value (Best Alternative) (\bar{T}_i)
F2- Community Accessibility	(0.528, 0.576, 0.612, 0.672)	VL	VH	(0.252, 0.282, 0.860, 0.876)	0.500	(0.387, 0.417, 0.430, 0.438)
F3- Transport Management	(0.528, 0.576, 0.612, 0.672)	VL	VH	(0.252, 0.282, 0.860, 0.876)	0.625	(0.484, 0.521, 0.538, 0.548)
G- Indoor Environmental Quality						
G1- Visual Comfort	(0.597, 0.650, 0.684, 0.736)	L	VH	(0.411, 0.471, 0.860, 0.876)	0.578	(0.447, 0.482, 0.497, 0.506)
G2- Indoor Air Quality	(0.597, 0.650, 0.684, 0.736)	L	VH	(0.411, 0.471, 0.860, 0.876)	0.583	(0.452, 0.486, 0.502, 0.511)
G3- Thermal Comfort	(0.597, 0.650, 0.684, 0.736)	L	VH	(0.411, 0.471, 0.860, 0.876)	0.500	(0.387, 0.417, 0.430, 0.438)
G4- Acoustic Performance	(0.559, 0.609, 0.662, 0.700)	VL	VH	(0.252, 0.282, 0.860, 0.876)	0.500	(0.387, 0.417, 0.430, 0.438)
G5- Hygiene	(0.597, 0.650, 0.684, 0.736)	L	VH	(0.411, 0.471, 0.860, 0.876)	0.578	(0.447, 0.482, 0.497, 0.506)
G6- Building Amenities	(0.528, 0.576, 0.612, 0.672)	VL	VH	(0.252, 0.282, 0.860, 0.876)	0.563	(0.435, 0.469, 0.484, 0.493)
H- Building Management						
H1- Operation & Maintenance	(0.597, 0.650, 0.684, 0.736)	L	VH	(0.411, 0.471, 0.860, 0.876)	0.592	(0.458, 0.493, 0.509, 0.519)
H2- Security	(0.597, 0.650, 0.684, 0.736)	L	VH	(0.411, 0.471, 0.860, 0.876)	0.500	(0.387, 0.417, 0.430, 0.438)
H3- Risk Management	(0.528, 0.576, 0.612, 0.672)	VL	VH	(0.252, 0.282, 0.860, 0.876)	0.547	(0.423, 0.456, 0.471, 0.479)
H4- Green Innovations	(0.528, 0.576, 0.612, 0.672)	VL	VH	(0.252, 0.282, 0.860, 0.876)	0.500	(0.387, 0.417, 0.430, 0.438)

Table 3: Evaluation result of the GCFI algorithm for the fuzzy valence function, \tilde{f}_i^α for $\alpha=0$

Criteria code	Individual significance (T_i^0)	\tilde{f}_i^α Value for the 'BA' [[$\tilde{f}d\tilde{g}$]/($\tilde{f}_i^-, \tilde{f}_i^+$)]	Criteria code	Individual significance (T_i^0)	\tilde{f}_i^α Value for the 'BA' [[$\tilde{f}d\tilde{g}$]/($\tilde{f}_i^-, \tilde{f}_i^+$)]
A		[0.327, 0.650]	F		[0.291, 0.639]
A1	(0.516, 0.584)	(0.320, 0.514)	F1	(0.452, 0.512)	(0.288, 0.630)
A2	(0.423, 0.479)	(0.273, 0.534)	F2	(0.387, 0.438)	(0.255, 0.593)
A3	(0.503, 0.570)	(0.313, 0.579)	F3	(0.484, 0.548)	(0.304, 0.648)
A4	(0.548, 0.621)	(0.336, 0.685)	G		[0.286, 0.607]
A5	(0.493, 0.559)	(0.308, 0.501)	G1	(0.447, 0.506)	(0.285, 0.548)
A6	(0.509, 0.576)	(0.316, 0.583)	G2	(0.452, 0.511)	(0.288, 0.550)
B		[0.284, 0.613]	G3	(0.387, 0.438)	(0.255, 0.514)
B1	(0.452, 0.511)	(0.288, 0.550)	G4	(0.387, 0.438)	(0.255, 0.593)
B2	(0.435, 0.493)	(0.279, 0.621)	G5	(0.447, 0.506)	(0.285, 0.548)
B3	(0.426, 0.482)	(0.275, 0.615)	G6	(0.435, 0.493)	(0.279, 0.621)
C		[0.287, 0.632]	H		[0.281, 0.602]
C1	(0.418, 0.473)	(0.271, 0.611)	H1	(0.458, 0.519)	(0.291, 0.554)
C2	(0.464, 0.526)	(0.294, 0.637)	H2	(0.387, 0.438)	(0.255, 0.514)
C3	(0.442, 0.501)	(0.283, 0.625)	H3	(0.423, 0.479)	(0.273, 0.614)
D		[0.260, 0.569]	H4	(0.387, 0.438)	(0.255, 0.593)
D1	(0.387, 0.438)	(0.255, 0.593)			
D2	(0.435, 0.493)	(0.279, 0.541)			
D3	(0.258, 0.292)	(0.191, 0.441)			
E		[0.285, 0.630]			
E1	(0.456, 0.516)	(0.290, 0.632)			
E2	(0.452, 0.511)	(0.288, 0.630)			
E3	(0.434, 0.491)	(0.279, 0.620)			
E4	(0.387, 0.438)	(0.255, 0.593)			

Table 4: Evaluation result of the GCFI algorithm for the fuzzy valence function, \tilde{f}_i^α for $\alpha = 1$

Criteria code	Individual significance (T_i^1)	\tilde{f}_i^α Value for the 'BA' [[$\tilde{f}d\tilde{g}$]/($\tilde{f}_i^-, \tilde{f}_i^+$)]	Criteria code	Individual significance (T_i^1)	\tilde{f}_i^α Value for the 'BA' [[$\tilde{f}d\tilde{g}$]/($\tilde{f}_i^-, \tilde{f}_i^+$)]
A		[0.357, 0.616]	F		[0.318, 0.617]
A1	(0.556, 0.574)	(0.348, 0.492)	F1	(0.486, 0.502)	(0.313, 0.610)
A2	(0.456, 0.471)	(0.298, 0.450)	F2	(0.417, 0.430)	(0.278, 0.574)
A3	(0.542, 0.559)	(0.341, 0.544)	F3	(0.521, 0.538)	(0.330, 0.628)
A4	(0.591, 0.609)	(0.365, 0.664)	G		[0.312, 0.583]
A5	(0.532, 0.549)	(0.336, 0.480)	G1	(0.482, 0.497)	(0.311, 0.513)
A6	(0.548, 0.566)	(0.344, 0.547)	G2	(0.486, 0.502)	(0.313, 0.515)
B		[0.309, 0.589]	G3	(0.417, 0.430)	(0.278, 0.480)
B1	(0.486, 0.502)	(0.313, 0.515)	G4	(0.417, 0.430)	(0.278, 0.574)
B2	(0.469, 0.484)	(0.304, 0.601)	G5	(0.482, 0.497)	(0.311, 0.513)
B3	(0.459, 0.473)	(0.299, 0.596)	G6	(0.469, 0.484)	(0.304, 0.601)
C		[0.313, 0.611]	H		[0.307, 0.577]
C1	(0.450, 0.464)	(0.295, 0.591)	H1	(0.493, 0.509)	(0.316, 0.519)
C2	(0.500, 0.516)	(0.320, 0.617)	H2	(0.417, 0.430)	(0.278, 0.480)
C3	(0.477, 0.492)	(0.308, 0.605)	H3	(0.456, 0.471)	(0.298, 0.594)
D		[0.287, 0.538]	H4	(0.417, 0.430)	(0.278, 0.574)
D1	(0.417, 0.430)	(0.278, 0.574)			
D2	(0.469, 0.484)	(0.304, 0.506)			
D3	(0.278, 0.287)	(0.209, 0.408)			
E		[0.312, 0.609]			
E1	(0.491, 0.507)	(0.315, 0.612)			
E2	(0.486, 0.502)	(0.313, 0.610)			
E3	(0.467, 0.482)	(0.303, 0.600)			
E4	(0.417, 0.430)	(0.278, 0.574)			

Table 5: For $\alpha = 0$, fuzzy measures $g(A_{(i)})$ and λ values

Criteria code	λ^-	Fuzzy measures $g^-(A_{(i)})$	λ^+	Fuzzy measures $g^+(A_{(i)})$	Criteria code	λ^-	Fuzzy measures $g^-(A_{(i)})$	λ^+	Fuzzy measures $g^+(A_{(i)})$
A	-0.9963		-0.9997		F	-0.8157		-0.9536	
A1		0.8407		0.9990	F1		0.8289		0.9132
A2		1.0000		0.9942	F2		1.0000		0.6718
A3		0.9770		0.9772	F3		0.5283		1.0000
A4		0.5283		0.6718	G	-0.9943		-0.9995	
A5		0.9945		1.0000	G1		0.9384		0.9987
A6		0.9377		0.9133	G2		0.5974		0.9744
B	-0.8511		-0.9638		G3		0.9928		1.0000
B1		0.5974		1.0000	G4		1.0000		0.9018
B2		0.8289		0.6718	G5		0.8400		0.9936
B3		1.0000		0.9086	G6		0.9738		0.6718
C	-0.8157		-0.9536		H	-0.9546		-0.9919	
C1		1.0000		1.0000	H1		0.5974		0.9779
C2		0.5283		0.6718	H2		0.8244		1.0000
C3		0.8289		0.9132	H3		0.9369		0.6718
D	-0.8793		-0.9718		H4		1.0000		0.8959
D1		0.8482		0.6718					
D2		0.5974		0.9272					
D3		1.0000		1.0000					
E	-0.9342		-0.9871						
E1		0.5283		0.6718					
E2		0.7958		0.8980					
E3		0.9314		0.9743					
E4		1.0000		1.0000					

Table 6: For $\alpha = 1$, fuzzy measures $g(A_{(i)})$ and λ values

Criteria code	λ^-	Fuzzy measures $g^-(A_{(i)})$	λ^+	Fuzzy measures $g^+(A_{(i)})$	Criteria code	λ^-	Fuzzy measures $g^-(A_{(i)})$	λ^+	Fuzzy measures $g^+(A_{(i)})$
A	-0.9984		-0.9992		F	-0.8802		-0.9146	
A1		0.8773		0.9977	F1		0.8600		0.8813
A2		1.0000		0.9885	F2		1.0000		0.6119
A3		0.9862		0.9618	F3		0.5761		1.0000
A4		0.5761		0.6119	G	-0.9974		-0.9987	
A5		0.9971		1.0000	G1		0.9588		0.9971
A6		0.9579		0.8776	G2		0.6496		0.9595
B	-0.9059		-0.9335		G3		0.9960		1.0000
B1		0.6496		1.0000	G4		1.0000		0.8693
B2		0.8866		0.6119	G5		0.8783		0.9881
B3		1.0000		0.8742	G6		0.9840		0.6119
C	-0.8802		-0.9146		H	-0.9740		-0.9829	
C1		1.0000		1.0000	H1		0.6496		0.9644
C2		0.5761		0.6119	H2		1.0000		1.0000
C3		0.8600		0.8813	H3		0.8612		0.6119
D	-0.9259		-0.9481		H4		0.6496		0.8557
D1		0.8792		0.6119					
D2		0.6496		0.8990					
D3		1.0000		1.0000					
E	-0.9601		-0.9732						
E1		0.5761		0.6119					
E2		0.8335		0.8594					
E3		0.9486		0.9595					
E4		1.0000		1.0000					

Table 7: Defuzzification and normalization results for the sustainability criteria (SI & SA) using GCFI method

Criteria code	Fuzzy numbers for the 'best alternative' (\bar{V})	Defuzzied Value $F(\bar{A})$	Normalized weights – for NB $N(\bar{A})$	Weights global (SA) – for NB WG_j	Normalized weights – for EB $N(\bar{A})$	Weights global (SA) – for EB WG_j
A	(0.327, 0.357, 0.616, 0.650)	0.488	0.1346		-	-
A1	(0.320, 0.348, 0.492, 0.514)	0.419	0.1591	0.0214	-	-
A2	(0.273, 0.298, 0.450, 0.534)	0.401	0.1526	0.0205	-	-
A3	(0.313, 0.341, 0.544, 0.579)	0.444	0.1690	0.0227	-	-
A4	(0.336, 0.365, 0.664, 0.685)	0.512	0.1948	0.0262	-	-
A5	(0.308, 0.336, 0.480, 0.501)	0.406	0.1545	0.0208	-	-
A6	(0.316, 0.344, 0.547, 0.583)	0.447	0.1701	0.0229	-	-
B	(0.284, 0.309, 0.589, 0.613)	0.449	0.1238		0.1431	
B1	(0.288, 0.313, 0.515, 0.550)	0.417	0.3170	0.0392	0.3170	0.0454
B2	(0.279, 0.304, 0.601, 0.621)	0.451	0.3435	0.0425	0.3435	0.0491
B3	(0.275, 0.299, 0.596, 0.615)	0.446	0.3395	0.0420	0.3395	0.0486
C	(0.287, 0.313, 0.611, 0.632)	0.461	0.1271		0.1469	
C1	(0.271, 0.295, 0.591, 0.611)	0.442	0.3240	0.0412	0.3240	0.0476
C2	(0.294, 0.320, 0.617, 0.637)	0.467	0.3424	0.0435	0.3424	0.0503
C3	(0.283, 0.308, 0.605, 0.625)	0.455	0.3336	0.0424	0.3336	0.0490
D	(0.260, 0.287, 0.538, 0.569)	0.413	0.1141		0.1318	
D1	(0.255, 0.278, 0.574, 0.593)	0.425	0.3713	0.0424	0.3713	0.0489
D2	(0.279, 0.304, 0.506, 0.541)	0.408	0.3562	0.0406	0.3562	0.0469
D3	(0.191, 0.209, 0.408, 0.441)	0.312	0.2725	0.0311	0.2725	0.0359
E	(0.285, 0.312, 0.609, 0.630)	0.459	0.1267		0.1463	
E1	(0.290, 0.315, 0.612, 0.632)	0.463	0.2572	0.0326	0.2572	0.0376
E2	(0.288, 0.313, 0.610, 0.630)	0.460	0.2558	0.0324	0.2558	0.0374
E3	(0.279, 0.303, 0.600, 0.620)	0.450	0.2505	0.0317	0.2505	0.0367
E4	(0.255, 0.278, 0.574, 0.593)	0.425	0.2365	0.0299	0.2365	0.0346
F	(0.291, 0.318, 0.617, 0.639)	0.466	0.1286		0.1486	
F1	(0.288, 0.313, 0.610, 0.630)	0.460	0.3376	0.0434	0.3376	0.0502
F2	(0.255, 0.278, 0.574, 0.593)	0.425	0.3120	0.0401	0.3120	0.0464
F3	(0.304, 0.330, 0.628, 0.648)	0.477	0.3504	0.0451	0.3504	0.0521
G	(0.286, 0.312, 0.583, 0.607)	0.447	0.1232		0.1425	
G1	(0.285, 0.311, 0.513, 0.548)	0.414	0.1655	0.0204	0.1655	0.0236
G2	(0.288, 0.313, 0.515, 0.550)	0.417	0.1664	0.0205	0.1664	0.0237
G3	(0.255, 0.278, 0.480, 0.514)	0.382	0.1525	0.0188	0.1525	0.0217
G4	(0.255, 0.278, 0.574, 0.593)	0.425	0.1699	0.0209	0.1699	0.0242
G5	(0.285, 0.311, 0.513, 0.548)	0.414	0.1655	0.0204	0.1655	0.0236
G6	(0.279, 0.304, 0.601, 0.621)	0.451	0.1803	0.0222	0.1803	0.0257
H	(0.281, 0.307, 0.577, 0.602)	0.442	0.1219		0.1409	
H1	(0.291, 0.316, 0.519, 0.554)	0.420	0.2512	0.0306	0.2512	0.0354
H2	(0.255, 0.278, 0.480, 0.514)	0.382	0.2283	0.0278	0.2283	0.0322
H3	(0.273, 0.298, 0.594, 0.614)	0.445	0.2661	0.0324	0.2661	0.0375
H4	(0.255, 0.278, 0.574, 0.593)	0.425	0.2544	0.0310	0.2544	0.0358

Note: Sustainability Indicator (SI) levels (bolded values); SA – Sustainability attributes levels; NB – New Buildings; EB – Existing Buildings.

Table 8: Building Sustainability Evaluation Index (BSEI) – for the two New Buildings Case Studies

Sustainability Indicators (SI)	SI Normalized Weight $N(\bar{A})$	Sustainability Attributes (SA)	SA Normalized Weight $N(\bar{A})$	SI Global Weight WG_j	CE duplex building				RA labs building			
					Attained Credit Point (CP)	Maximum Credit Point (CP)	Factor Index (FI)	Maximum Factor Index (FI) _{max}	Attained Credit Point (CP)	Maximum Credit Point (CP)	Factor Index (FI)	Maximum Factor Index (FI) _{max}
Sustainable Construction Practices (A)	0.1346	A1	0.1591	0.0214	15.5	17	0.3318	0.3640	14	17	0.2997	0.3640
		A2	0.1526	0.0205	6	8	0.1232	0.1642	5	8	0.1026	0.1642
		A3	0.1690	0.0227	4	7	0.0909	0.1591	6.5	7	0.1478	0.1591
		A4	0.1948	0.0262	5	14	0.1310	0.3669	13	14	0.3407	0.3669
		A5	0.1545	0.0208	3.5	11	0.0728	0.2286	5	11	0.1039	0.2286
		A6	0.1701	0.0229	3.5	12	0.0801	0.2747	7	12	0.1602	0.2747
Site and Ecology (B)	0.1238	B1	0.3170	0.0392	1.5	3	0.0589	0.1178	2	3	0.0785	0.1178
		B2	0.3435	0.0425	4	7	0.1701	0.2977	4.5	7	0.1914	0.2977
		B3	0.3395	0.0420	2.5	5	0.1051	0.2102	1	5	0.0420	0.2102
Energy (C)	0.1271	C1	0.3240	0.0412	6.5	10	0.2677	0.4118	6.5	10	0.2677	0.4118
		C2	0.3424	0.0435	9	10	0.3917	0.4352	10	10	0.4352	0.4352
		C3	0.3336	0.0424	4.5	12	0.1908	0.5088	5.5	12	0.2332	0.5088
Water (D)	0.1141	D1	0.3713	0.0424	3	6	0.1271	0.2542	4	6	0.1694	0.2542
		D2	0.3562	0.0406	5	6	0.2031	0.2438	5.5	6	0.2235	0.2438
		D3	0.2725	0.0311	2.5	6	0.0777	0.1865	3	6	0.0933	0.1865
Material and Waste (E)	0.1267	E1	0.2572	0.0326	5	5	0.1629	0.1629	3	5	0.0977	0.1629
		E2	0.2558	0.0324	3	4	0.0972	0.1296	1.5	4	0.0486	0.1296
		E3	0.2505	0.0317	6.5	9	0.2062	0.2855	9	9	0.2855	0.2855
		E4	0.2365	0.0299	5	5	0.1497	0.1497	4	5	0.1198	0.1497
Transportation (F)	0.1286	F1	0.3376	0.0434	5	7	0.2171	0.3039	3	7	0.1303	0.3039
		F2	0.3120	0.0401	7	7	0.2809	0.2809	4	7	0.1605	0.2809
		F3	0.3504	0.0451	2	2	0.0901	0.0901	1.5	2	0.0676	0.0901
Indoor Environmental Quality (IEQ) (G)	0.1232	G1	0.1655	0.0204	3	8	0.0612	0.1632	7	8	0.1428	0.1632
		G2	0.1664	0.0205	6.5	8	0.1334	0.1641	8	8	0.1641	0.1641
		G3	0.1525	0.0188	2.5	5	0.0470	0.0940	4	5	0.0752	0.0940
		G4	0.1699	0.0209	2.75	4	0.0576	0.0838	2.5	4	0.0524	0.0838
		G5	0.1655	0.0204	8	9	0.1632	0.1836	9	9	0.1836	0.1836
		G6	0.1803	0.0222	6	8	0.1334	0.1779	5	8	0.1112	0.1779
Building Management (H)	0.1219	H1	0.2512	0.0306	6	13	0.1838	0.3982	10	13	0.3063	0.3982
		H2	0.2283	0.0278	1	3	0.0278	0.0835	3	3	0.0835	0.0835
		H3	0.2661	0.0324	3	7	0.0973	0.2271	4	7	0.1297	0.2271
		H4	0.2544	0.0310	1	3	0.0310	0.0930	2	3	0.0620	0.0930
Building Sustainability Evaluation Index (BSEI)							4.5618	7.2944			5.1099	7.2944
Building Sustainability Evaluation Ratio (BSER)							62.54%		70.05%			

Table 9: Building Sustainability Evaluation Index (BSEI) – for the two Existing Buildings Case Studies

Sustainability Indicators (SI)	SI Normalized Weight $N(\bar{A})$	Sustainability Attributes (SA)	SA Normalized Weight $N(\bar{A})$	SI Global Weight WG_j	SNN building				FT building			
					Attained Credit Point (CP)	Maximum Credit Point (CP)	Factor Index (FI)	Maximum Factor Index (FI) _{max}	Attained Credit Point (CP)	Maximum Credit Point (CP)	Factor Index (FI)	Maximum Factor Index (FI) _{max}
					Site and Ecology (B)	0.1431	B1	0.3170	0.0454	2	3	0.0907
Energy (C)	0.1469	B2	0.3435	0.0491	5.5	7	0.2703	0.3440	4.5	7	0.2211	0.3440
		B3	0.3395	0.0486	1	5	0.0486	0.2429	2.5	5	0.1214	0.2429
		C1	0.3240	0.0476	6.5	10	0.3093	0.4758	7.5	10	0.3569	0.4758
Water (D)	0.1318	C2	0.3424	0.0503	10	10	0.5028	0.5028	10	10	0.5028	0.5028
		C3	0.3336	0.0490	6.5	12	0.3185	0.5880	5.5	12	0.2695	0.5880
		D1	0.3713	0.0489	6	6	0.2937	0.2937	3.5	6	0.1713	0.2937
Material and Waste (E)	0.1463	D2	0.3562	0.0469	5.5	6	0.2582	0.2817	5	6	0.2347	0.2817
		D3	0.2725	0.0359	5.5	6	0.1975	0.2155	5	6	0.1796	0.2155
		E1	0.2572	0.0376	4	5	0.1506	0.1882	5	5	0.1882	0.1882
Transportation (F)	0.1486	E2	0.2558	0.0374	2.5	4	0.0936	0.1498	3	4	0.1123	0.1498
		E3	0.2505	0.0367	6.5	9	0.2383	0.3299	8.5	9	0.3116	0.3299
		E4	0.2365	0.0346	5	5	0.1730	0.1730	5	5	0.1730	0.1730
Indoor Environmental Quality (IEQ) (G)	0.1425	F1	0.3376	0.0502	5	7	0.2509	0.3512	4	7	0.2007	0.3512
		F2	0.3120	0.0464	7	7	0.3246	0.3246	2.5	7	0.1159	0.3246
		F3	0.3504	0.0521	1	2	0.0521	0.1041	0.75	2	0.0391	0.1041
Building Management (H)	0.1409	G1	0.1655	0.0236	7	8	0.1650	0.1886	7.5	8	0.1768	0.1886
		G2	0.1664	0.0237	6.25	8	0.1482	0.1897	6.5	8	0.1541	0.1897
		G3	0.1525	0.0217	3.5	5	0.0760	0.1086	3.5	5	0.0760	0.1086
		G4	0.1699	0.0242	2.25	4	0.0545	0.0968	2.75	4	0.0666	0.0968
		G5	0.1655	0.0236	7.5	9	0.1768	0.2122	8	9	0.1886	0.2122
		G6	0.1803	0.0257	5	8	0.1284	0.2055	6	8	0.1541	0.2055
		H1	0.2512	0.0354	10	13	0.3539	0.4601	8.5	13	0.3008	0.4601
		H2	0.2283	0.0322	3	3	0.0965	0.0965	1	3	0.0322	0.0965
		H3	0.2661	0.0375	4	7	0.1499	0.2624	4	7	0.1499	0.2624
		H4	0.2544	0.0358	2	3	0.0717	0.1075	2	3	0.0717	0.1075
Building Sustainability Evaluation Index (BSEI)							4.9933	6.6288	4.6595	6.6288		
Building Sustainability Evaluation Ratio (BSER)							75.33%		70.29%			

Table 10: Precedence of the BSAM scheme over the existing green building rating systems

Items	Other GBRS	BSAM Scheme	Reference (inclusive of the GBRS documentations)
Inclusive of the 3 pillars of sustainable development – social, economic, and environmental sustainability criteria	Mainly environmental criteria	All	Illankoon et al. (2017); Olawumi and Chan (2019)
Key social sustainability criteria - like <i>education, awareness, stakeholder relation, inclusiveness, employment</i>	None	In detail	Liu et al. (2013); Shari (2011)
Key economic sustainability criteria - like <i>local economy, re-use etc.</i>	Little or no focus	In detail	Ali and Al Nsairat (2009); Liu et al. (2013); Wei et al. (2011)
Cultural aspect - such as <i>cultural heritage in design</i>	None except in BEAM Plus	In detail	Banani et al. (2013); Salehudin et al. (2012); Shari (2011)
“Management” criterion	Little or no focus	More focus	Illankoon et al. (2017); Olawumi and Chan (2019); Sev (2009)
“Material and waste” criterion (<i>at the construction phase</i>)	None	In detail	Olawumi and Chan (2019)
Weighting methodology – <i>robustness and capability of the method to express the interaction among the sustainability criteria</i>	“Aggregation of points” method – <i>incapable of expressing interaction</i>	GCFI method – <i>see section 2.3</i>	Mahmoud et al. (2019)

Note: GBRS – Green Building Rating System; GBRS documentations - (see BCA, 2015; GBCA, 2017; HKGBC, 2019; IBEC, 2008; IGBC, 2014; USGBC, 2017)