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DEVELOPMENT OF A BIM-ENABLED AND CLOUD-BASED SUSTAINABILITY ASSESSMENT SYSTEM FOR BUILDINGS IN SUB-SAHARAN AFRICA: THE CASE OF NIGERIA

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A thesis submitted in partial fulfilment of the requirements

for the degree of Doctor of Philosophy

February 2020

CERTIFICATE OF ORIGINALITY

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___________________________________ (Signed)

___**OLAWUMI Timothy Oluwatosin**_____ (Name of student)

DEDICATION

I dedicate this thesis to the Trinity God – God Almighty, Jesus Christ, and the Holy Spirit for the life, health, grace, and the strength to successfully complete this study. Also, to my parents – Dr. Simeon O. Olawumi and Mrs. Ireade I. Olawumi for their prayers and supports towards my education pursuits from the cradle. To my Soulmate and lovely wife, Mrs. Taiwo Oluwafunke Olawumi and my wonderful son, Master Josiah Oluwadara Olawumi, for their prayers, support, and sacrifice during my PhD study.

ABSTRACT

The increasing urbanization of the built environment has bolstered the need of promoting sustainable practices and Building Information Modelling (BIM) initiative in building and construction projects. However, there has not been a unified adoption and implementation of BIM initiative and sustainability in most countries and the built environment as a whole – most notably within the sub-Saharan region of Africa due to several factors. Moreover, based on the extant literature, the existing green rating tools have been found to be inadequate to fully address the greenness and evaluate the sustainability performance of buildings. Hence, these generate several hindrances to the current drive for a holistic implementation of sustainability practices and innovative technologies such as BIM in the construction industry.

Therefore, this research study aims to develop a green-BIM assessment model and cloud-based sustainability decision support system for evaluating buildings' compliance to sustainability principles with a view to integrating smart sustainable practices in building construction and management, improving operational efficiency, and enhancing the overall implementation of sustainable development in the built environment. The scope of study mainly focuses on developing countries located in the sub-Saharan region of Africa – using Nigeria, the largest economy in the region as a case study – with practical applications to other regions.

The following research objectives was set out in fulfilling the study's aim: (1) To identify and assess the inherent benefits, barriers, and critical success factors (drivers) associated with integrating BIM and sustainability principles in building projects. (2) To establish the relative weightings of the key sustainability indicators, sustainability attributes, and sub-attributes for buildings. (3) To develop a sustainability evaluation index for buildings using the Generalized Choquet Fuzzy Integral method. (4) To develop a cloud-based sustainability decision support system (C-SDSS) for buildings. (5) To develop a conceptual Green-BIM assessment framework as a tool for the evaluation of sustainability performance of buildings.

Objective #1 was achieved via an in-depth desktop review of extant literature, pilot and Delphi surveys, empirical questionnaire surveys, as well as the use of several statistical analysis tools such as descriptive and inferential statistical tools, factor analysis, and fuzzy synthesis evaluation method. According to the desktop literature

review, a total of 36 benefits, 38 barriers and 30 critical success factors were identified. Fourteen (14) experts from eight countries participated in the Delphi survey while 220 respondents from 21 countries were involved in the international questionnaire survey. Meanwhile, the base inputs for the data to achieve Objectives (#2 - #4) consisted of 189 diversified sets of experts in Nigeria with requisite experience in the built environment.

A holistic review of green building technical notes and guidelines, existing green building rating systems, and relevant journal articles was undertaken to fulfil Objectives (#2 - #4); and augmented by industry experts' inputs which facilitated the development of the Building Sustainability Assessment Method (BSAM) scheme. The BSAM scheme green rating system has been designed for developing countries in the sub-Saharan region of Africa. The proposed BSAM scheme is a more unified green rating tool that adequately considers the environmental, economic, and social pillars of sustainable development unlike the existing green rating tools such as LEED, BREEAM, BEAM Plus, Green Mark, etc. which focus solely on the environmental sustainability with little or no consideration of the other two sustainability pillars.

Objective #3 was actualized by employing the Generalized Choquet Fuzzy Integral (GCFI) method to establish the weightings of the 8 key sustainability indicators, 32 sustainability attributes, and 136 sustainability sub-attributes of the BSAM scheme. Data collected from industry experts form the base inputs for the impacts of various sustainability criteria based on the local variations. The GCFI approach is regarded as a more practical and robust weighting method for non-additive, dependent, and interactive criteria. Consequently, the Building Sustainability Evaluation Index (BSEI) and a six-grade certification system were developed to evaluate the sustainability performance of building projects. The key sustainability criteria with the highest weighting based on the GCFI analysis include sustainability construction practices, transportation, and energy criteria.

To ease the adoption and implementation of the proposed BSAM scheme, BSEI, and the BSAM certification system for use in the built environment, a Cloud-Based Sustainability Decision Support System (C-SDSS) was established to achieve Objective #4. PHP and Jscript, being high-level programming languages, as well as the MySQL relational database along with other web-based tools and systems were used to code, design, and deploy the C-SDSS platform. BIM models, and relevant data from four real-life building projects based in Nigeria were used during the validation exercise to demonstrate the usefulness of the developed C-SDDS and the BSAM scheme in practice for the built environment. The validation exercise was augmented with validation questionnaire surveys with industry experts.

Finally, a conceptual green-BIM assessment (GBA) framework was developed as an effective tool for the evaluation of the sustainability performance of buildings using a cloud-based system (Objective #5). The proposed GBA framework comprised of six main components is intended to provide comprehensive guidelines and algorithms that can facilitate the full and optimal integration of BIM and green building rating systems (e.g. the proposed BSAM scheme) in the assessment of the sustainability performance of buildings. The developed GBA framework was validated using expert questionnaire surveys as well.

The findings of the study have generated salient and significant contributions both from the theoretical and practical (industry) standpoints. Moreover, they have provided valuable insights, effective strategies, and recommendations that have addressed the limitations of the integration of the concepts of BIM and sustainability practices in the built environment. Overall, the research deliverables would be crucial in implementing Green-BIM both locally (in Nigeria and other sub-Saharan countries), and internationally.

LIST OF RESEARCH PUBLICATIONS AND ACHIEVEMENTS

Chapters of this thesis have been fully or partially published in the following publications which spans from September 2016 – August 2020.

Refereed Journal Papers (*published*)

1. **Olawumi, T.O.** & Chan, D.W.M. (2020). Application of Generalized Choquet Fuzzy Integral Method in the Sustainability Rating of Green Buildings Based on the BSAM Scheme. *Sustainable Cities and Society***,** 61(October), Article Number 102147. 18 Pages. https://doi.org/10.1016/j.scs.2020.102147. [*WoS Impact Factor: 5.268; Scopus CiteScore: 7.5 (top 98th percentile)*]
2. **Olawumi, T.O.**, Chan, D.W.M., Chan, A.P.C. & Wong, J.K.W. (2020). Development of a Building Sustainability Assessment Method (BSAM) for Developing Countries in Sub-Saharan Africa. *Journal of Cleaner Production*, 263 (August), Article Number 121514. 17 Pages. https://doi.org/10.1016/j.jclepro.2020.121514 [*WoS Impact Factor: 7.246; Scopus CiteScore: 10.9 (top 98th percentile)*]
3. **Olawumi, T.O.** & Chan, D.W.M. (2020). Key Drivers for Smart and Sustainable Practices in the Built Environment. *Engineering, Construction and Architectural Management*, 27(6), 1257–1281. https://doi.org/10.1108/ECAM-06-2019-0305 [*WoS Impact Factor: 2.16; Scopus CiteScore: 2.51 (top 95th percentile)*]
4. **Olawumi, T.O.** & Chan, D.W.M. (2020). Concomitant Impediments to the Implementation of Smart Sustainable Practices in the Built Environment. *Sustainable Production and Consumption,* 21(January), 239-251. https://doi.org/10.1016/j.spc.2019.09.001 [*WoS Impact Factor: 3.66; Scopus CiteScore: 5.1 (top 84th percentile)*]
5. Chan, D.W.M., **Olawumi, T.O.** & Ho, A.M.L. (2019). Critical Success Factors for Building Information Modelling (BIM) Implementation in Hong Kong. *Engineering, Construction and Architectural Management*, 26(9), 1838-1854. https://doi.org/10.1108/ECAM-05-2018-0204 [*WoS Impact Factor: 2.16; Scopus CiteScore: 2.51 (top 95th percentile)*]
6. Chan, D.W.M., **Olawumi, T.O.** & Ho, A.M.L. (2019). Perceived Benefits of and Barriers to Building Information Modelling (BIM) Implementation in Construction: The Case of Hong Kong. *Journal of Building Engineering*, 25(September), Article

Number 100764, 10 Pages. https://doi.org/10.1016/j.jobe.2019.100764 [*WoS Impact Factor: 3.379; Scopus CiteScore: 4.9 (top 97th percentile)*]

7. **Olawumi, T.O.** & Chan, D.W.M. (2019). Critical Success Factors for Implementing Building Information Modeling and Sustainability Practices in Construction Projects: A Delphi Survey. *Sustainable Development*, 27(4), 587-602. https://doi.org/10.1002/sd.1925 [*WoS Impact Factor: 4.082; Scopus CiteScore: 4.9 (top 92nd percentile)*]
8. **Olawumi, T.O.** & Chan, D.W.M. (2019). An Empirical Survey of the Perceived Benefits of Executing BIM and Sustainability Practices in the Built Environment. *Construction Innovation: Information, Process, Management*, 19(3), 321-342. https://doi.org/10.1108/CI-08-2018-0065 [*Emerging Sources Citation Index (WoS); Scopus CiteScore: 3.8 (top 93rd percentile)*]
9. **Olawumi, T.O.** & Chan, D.W.M. (2019). Development of a Benchmarking Model for BIM Implementation in Developing Countries. *Benchmarking: An International Journal*, 26(4), 1210-1232. https://doi.org/10.1108/BIJ-05-2018-0138 [*Emerging Sources Citation Index (WoS); Scopus CiteScore: 3.6 (top 81st percentile)*]
10. **Olawumi, T.O.** & Chan, D.W.M. (2019). Building Information Modelling and Project Information Management Framework for Construction Projects. *Journal of Civil Engineering and Management*, 25(1), 53-75. https://doi.org/10.3846/jcem.2019.7841 [*WoS Impact Factor: 2.338; Scopus CiteScore: 4.7 (top 83rd percentile)*]

11. **Olawumi, T.O.**, Chan, D.W.M., Wong, J.K.W. & Chan, A.P.C (2018). Barriers to the Integration of BIM and Sustainability Practices in Construction Projects: A Delphi Survey of International Experts. *Journal of Building Engineering*, 20(November), 60-71. https://doi.org/10.1016/j.jobe.2018.06.017 [*WoS Impact Factor: 3.379; Scopus CiteScore: 4.9 (top 97th percentile)*]
12. **Olawumi, T. O.** & Chan, D.W.M. (2018). Identifying and Prioritizing the Benefits of Integrating BIM and Sustainability Practices in Construction Projects: A Delphi Survey of International Experts. *Sustainable Cities and Society*, 40(July), 16-27. https://doi.org/10.1016/j.scs.2018.03.033 [*WoS Impact Factor: 5.268; Scopus CiteScore: 7.5 (top 98th percentile)*]
13. **Olawumi, T.O.** & Chan, D.W.M. (2018). A Scientometric Review of Global Research on Sustainability and Sustainable Development. *Journal of Cleaner Production*, 183(May), 231-250. https://doi.org/10.1016/j.jclepro.2018.02.162

(Top 1% "Highly Cited Paper" in the Field of Engineering – Web of Science Core Collection, 2019 & 2020) [*WoS Impact Factor: 7.246; Scopus CiteScore: 10.9 (top 98th percentile)*]

14. Ma, X., Xiong, F., **Olawumi, T.O.,** Dong, N. & Chan, A.P.C (2018). Conceptual Framework and Roadmap Approach for Integrating BIM into Lifecycle Project Management. *Journal of Management in Engineering*, ASCE, 34(6). https://doi.org/10.1061/(ASCE)ME.1943-5479.0000647 [*WoS Impact Factor: 3.269; Scopus CiteScore: 6.7 (top 95th percentile)*]

15. **Olawumi, T.O.,** Chan, D.W.M. & Wong, J.K.W. (2017). Evolution in the Intellectual Structure of BIM Research: A Bibliometric Analysis. *Journal of Civil Engineering and Management*, 23(8), 1060-1081. https://doi.org/10.3846/13923730.2017.1374301 [*WoS Impact Factor: 2.338; Scopus CiteScore: 4.7 (top 83rd percentile)*]

Refereed Journal Papers (*under review*)

1. **Olawumi, T.O.** & Chan, D.W.M. (under review). Green-BIM Assessment Framework for Evaluating Sustainability Performance of Building Projects: A Case of Nigeria. *Architectural Engineering and Design Management.* Manuscript ID: AEDM-2020-0119 (*1st round submitted on 26 August 2020*).

2. **Olawumi, T.O.** & Chan, D.W.M. (under review). Development of a Cloud-based Sustainability Decision Support System (C-SDSS): A Digitalized Automated Green Building Sustainability Assessment Tool. *Automation in Construction.* Manuscript ID: AUTCON_2019_1409 (*1st round submitted on 6 December 2019*).

3. **Olawumi, T.O**. & Chan, D.W.M. (under review). Developing Project Evaluation Models for Smart Sustainable Practices Implementation in the Construction Industry of Nigeria and Hong Kong. *Journal of Cleaner Production*. Manuscript ID: JCLEPRO-S-20-25203 (*1st round submitted on 31 August 2020*).

Refereed Conference Papers (*published*)

1. Saka, A.B., Chan, D.W.M. & **Olawumi, T.O.** (2019). A Systematic Literature Review of Building Information Modelling in the Architecture, Engineering and Construction Industry – The Case of Nigeria. In *Proceedings of the Environmental Design and Management International Conference 2019 (EDMIC 2019) on Drivers and Dynamics of Change in the Built Environment,* 20-22 May 2019, Obafemi Awolowo University, Ile-Ife, Nigeria, 728-738, ISSN 2682-6488.

2. **Olawumi, T.O**. & Chan, D.W.M. (2018). Critical Success Factors (CSFs) for Amplifying the Integration of BIM and Sustainability Principles in Construction Projects: A Delphi Study. In *Proceedings of the RICS COBRA Conference 2018*, 23-25 April 2018, London, United Kingdom. ISBN 978-1-78321-274-3, ISSN 2398-8614 (Paper #127 in electronic format). http://bit.ly/39WcqRO

3. **Olawumi, T.O**. & Chan, D.W.M. (2018). Beneficial Factors of Integrating Building Information Modelling (BIM) and Sustainability Practices in Construction Projects. In *Proceedings of the Hong Kong International Conference on Engineering and Applied Science 2018 (HKICEAS 2018)*, 24-26 January 2018, Hong Kong, 141-152, ISBN 978-986-87417-4-4 (in electronic format).

Datasets (*published*)

1. **Olawumi, T.O.** & Chan, D.W.M. (2019). Building Sustainability Assessment Method (BSAM) - for Countries in sub-Saharan region. *Mendeley Data*, 1(1). http://dx.doi.org/10.17632/jvjm5h8md3.1

2. **Olawumi, T.O.** & Chan, D.W.M. (2017). Geospatial map of the global research on sustainability and sustainable development: Generating and converting KML files to map. *Mendeley Data*, 1(1). https://doi.org/10.17632/sv23pvr252.1

<u>Book Chapter (*accepted*)</u>

1. **Olawumi, T.O.**, Saka, A.B., Chan, D.W.M. & Jayasena, N.S. (2020). Scientometric Review and Analysis: A Case Example of Smart Buildings and Smart Cities. In J.K. Akotia & E. Manu (Eds.) *Secondary Research Methods in the Built Environment.* Routledge: Taylor & Francis Group

<u>Refereed Journal Papers (*pending submission*)</u>

1. **Olawumi, T.O**. & Chan, D.W.M. Evaluating the Barriers to the Adoption of Smart Sustainable Practices: A Comparative Analysis between Hong Kong and Nigeria. *Building and Environment*.
2. **Olawumi, T.O**. & Chan, D.W.M. Comparative Study of the Benefits of implementing Smart Sustainable Practices between Nigeria and Hong Kong. *Sustainable Development*.

<u>Honors and Awards</u>

1. **Merit Award** in the Australian Institute of Building (Hong Kong Chapter) ***Professional Excellence in Building Awards 2019*** *(Category B3 - Student Achievement).* Award Certificate was presented in the AIB(HK) Dinner and Award Night 2019 held at the Sheraton Hong Kong Hotel & Towers on 21 June 2019. <u>Entry Title</u>: *BIM-based Sustainability Assessment Model for Buildings: A Choquet Fuzzy Integral Approach*.

2. **Gold Award** in the Chartered Institute of Building (Hong Kong) ***Outstanding Paper Awards 2018*** - *(Category - Research Postgraduate Students)*. Award Certificate and Cash Prize (HK$ 5,000) were presented at the CIOB Hong Kong 45th Anniversary Dinner 2018 held at the New World Millennium Hong Kong Hotel, Tsim Sha Tsui, Kowloon on 21 September 2018. <u>Paper Title</u>: *Integrating BIM and Sustainability Practices in Smart Construction Projects: Benefits, Barriers and Drivers – A Delphi Survey of International Experts.*

3. ***Certificate of Outstanding Contribution in Reviewing*** in recognition of the contributions made to the quality of the journal as a reviewer conferred by the *Journal of Cleaner Production* published by Elsevier. Awarded in September 2018.

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My profound gratitude and appreciation to my parents – Dr. Simeon Olawumi and Mrs. Ireade Olawumi for their love, prayers, constant encouragement, and supports throughout my PhD study. Sincere thanks to my siblings – Mr. Isaac Olawumi and Mr. Stephen Olawumi for their support and prayers throughout my PhD study. I owe everything I have achieved to their unfailing love. Special thanks to my in-laws, Mrs. Abosede Abe, and the Abes – Mr. Tobi, Mr. Seun, and Mr. Kehinde Abe for their prayers and encouragement to support my family and me during this period.

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lovely and wonderful son, Master Josiah Oluwadara Olawumi, thanks for your understanding and smiles.

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CHAPTER 1: INTRODUCTION[1]

1.1 Chapter Overview

This chapter presents and discusses the background of the research, states the scope of the study and the research problems that give rise to each of the research objectives, states the research aim and objectives. It also illustrates the various research approaches adopted and the contribution of the study. Also, this chapter presents the structure of the thesis to ease navigation through the chapters

1.2 Background of the Study

Green Building Information Modelling (GBIM) is an emerging trend in the built environment which is described by Wu and Issa (2014b) as a synergy between Building Information Modelling (BIM) and sustainability goals. It is a “symbiotic convergence of the two separate trends into an emerging practice” (McGraw-Hill Construction, 2013). The implementation of BIM in construction projects was categorized into two forms: (1) BIM products or technology; and (2) BIM process (Olawumi et al., 2018; Olawumi & Chan, 2019b); while sustainability is often defined

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[1] This chapter is largely based upon the following published and working papers:

Olawumi, T.O., & Chan, D.W.M. (2018d). Identifying and prioritizing the benefits of integrating BIM and sustainability practices in construction projects: A Delphi survey of international experts. *Sustainable Cities and Society*, 40, 16–27. https://doi.org/10.1016/j.scs.2018.03.033

Olawumi, T.O., & Chan, D.W.M. (2019a). An empirical survey of the perceived benefits of executing BIM and sustainability practices in the built environment. *Construction Innovation: Information, Process, Management*, 19(3), 321–342. https://doi.org/10.1108/CI-08-2018-0065

Olawumi, T.O., & Chan, D.W.M. (2020b). Concomitant Impediments to the implementation of Smart Sustainable Practices in the Built Environment. *Sustainable Production and Consumption, 21(January), 239-251*. https://doi.org/10.1016/j.spc.2019.09.001

Olawumi, T.O., Chan, D.W.M., Wong, J.K.W., & Chan, A P.C. (2018). Barriers to the Integration of BIM and Sustainability Practices in Construction Projects: A Delphi Survey of International Experts. *Journal of Building Engineering*, 20, 60–71. https://doi.org/doi.org/10.1016/j.jobe.2018.06.017

Olawumi, T.O., & Chan, D.W.M. (2020c). Key Drivers for Smart and Sustainable Practices in the Built Environment. *Engineering, Construction, and Architectural Management, 27(6), 1257–1281*. https://doi.org/10.1108/ECAM-06-2019-0305

Olawumi, T.O., Chan, D.W.M., Chan, A.P.C. & Wong, J.K.W. (2020). Development of a Building Sustainability Assessment Method (BSAM) for Developing Countries in sub-Saharan Africa. *Journal of Cleaner Production, 263(August), Article 121514.* https://doi.org/10.1016/j.jclepro.2020.121514

Olawumi, T.O., & Chan, D.W.M. Development of a Cloud-based Sustainability Decision Support System (C-SDSS): A Digitalized Automated Green Building Sustainability Assessment Tool.

Olawumi, T.O., & Chan, D.W.M. Green-BIM Assessment Framework for Evaluating Sustainability Performance of Building Projects: A Case of Nigeria.

Olawumi, T.O., & Chan, D.W.M. (2019d). Critical Success Factors of Implementing Building Information Modelling (BIM) and Sustainability Practices in Construction Projects: A Delphi Survey. *Sustainable Development*, 27(4), 587–602. https://doi.org/10.1002/sd.1925 on the basis of the holistic fulfillment of its three fundamental pillars; which are the environmental, social and economic sustainability (Olawumi & Chan, 2018a; Wong & Kuan, 2014). Moreover, to facilitate and ensure construction firms and the industry integrate green BIM into the projects, there must be a strategic plan and guidelines for its implementation (Wu & Issa, 2014b).

In recent years, the construction industry has been trying to adopt smart tools which are based on information and communication technologies (ICT) such as BIM, virtual reality, augmented reality systems, and cloud technologies among others to aid construction process and facilitate the integration of other domain knowledge like sustainability (Adamus, 2013), project management (Ahankoob et al., 2018; Ajam et al., 2010), cost control (Ahn et al., 2016), safety management (Zhang et al., 2015), etc. Bibri and Krogstie (2017) argued the importance of these smart tools to enhance and support theoretical concepts such as sustainability which according to Olawumi and Chan (2018a) has been gaining immense interest from academics, industry professional, and the government. The definition and concept of sustainability has been discussed in previous studies (Olawumi & Chan, 2018a; WCED, 1987; Wong & Zhou, 2015); while the concept of smart tools and buildings have been defined and discussed in Cugurullo (2017).

Antón and Díaz (2014) noted that the construction industry has started to embrace the concept of BIM and sustainability and suggested that the concepts should be implemented early into the project as it provides the best opportunity to impact the project effectively. The need to integrate BIM and sustainability in a project was stressed by Sun et al. (2016) who noted that for a building to be energy-sufficient, enabling software is needed to simulate and predict the energy performance. Azhar et al. (2011) pointed out that there is an increasing demand for green buildings due to the minimal environmental impact of such buildings and its relatively low lifecycle costs. However, despite the hypothetical and some few real-life evidence-based project benefits of adopting BIM and sustainability practices, Wu and Issa (2014b) observed that the potential of green BIM is yet to be explored in most construction projects, and Olawumi et al. (2017) revealed the inadequacy or lack of relevant standards on BIM and sustainability in most countries.

More so, Wu and Issa (2014b) and McGraw-Hill Construction (2010) observed stakeholders' inclinations for the adoption of green BIM had focused mostly on the technological-aspect and less on other areas such as the business process of implementing BIM and even the sustainability aspect of green BIM. Also, Cugurullo (2017) highlighted the differences and challenges in the built environment in the quest to decipher between eco-cities and smart cities and the appropriate approach to achieve the initiative. Some key attributes of BIM that can be exploited for sustainability issues to enhance smart and sustainable practices in construction projects based on the extant literature includes: 1) As a decision-making tool (Hope & Alwan, 2012); 2) Energy simulation or daylighting simulation (Olawumi et al., 2017); 3) Evaluation of the embodied CO_2 over the lifecycle of a building (Capper et al., 2012); 4) Validation of compliance with sustainability criteria (Sheth et al., 2010). Others include – 5) Storage of big data of building information that can be extracted to rating using any available green building rating systems like LEED or BREEAM (Hope & Alwan, 2012); 6) Visualization and walkthroughs for project teams especially as it relates to energy systems in buildings (Olawumi et al., 2017; Sheth et al., 2010); and 7) Improved communication and coordination of construction processes from planning to commissioning (Olawumi & Chan, 2019e).

Furthermore, a review of these smart tools shows that BIM has found more use and received the most widespread implementation in the built environment (Bradley et al., 2016; Jung & Lee, 2015; Ma et al., 2018). Hence, this study will focus solely on BIM as a smart tool to aid the sustainability of the built environment, with peculiar emphasis on the construction sector. The process of integrating these smart tools such as BIM to facilitate the implementation of sustainability practices is regarded as smart sustainable practices in this study. Olawumi et al. (2017) highlighted some BIM tools, processes, and software that has found applications in the building design analysis and simulation towards aiding the relevant stakeholders to make sound sustainability-related decisions. Another application of BIM to aid sustainability practices in the literature includes – the use of plugins in BIM software to assess some sustainability parameters in buildings by (Oti et al., 2016). Also, Tah and Abanda (2011) utilize semantic web tools to evaluate the sustainability performance of projects and energy simulation. However, despite the robustness of BIM, its interoperability and proprietary issues have limited its application to sustainability issues (Olawumi et al., 2017).

The main idea driving the concepts of a sustainable smart city in the construction industry is primarily the development of standards and the implementation of BIM and sustainable practices. Several research studies have discussed the possibilities of BIM to advance the implementation of sustainability practices in construction projects. Alsayyar and Jrade (2015) developed an innovative model which integrates BIM tools with sustainable design requirements to evaluate the cost and benefits of a proposed building in the planning and design stages. The model was developed with a database module and tested on a real-life project. Moreover, Gilkinson et al. (2015) regard BIM as a revolutionary design-based technology and process which provides considerable value to construction projects throughout the lifecycle stages (Autodesk, 2011).

BIM implementation can be considered from two aspects- (1) the use of 3D technology (software) to model and analyze building model using software such as Revit, ArchiCAD etc. (2) the process/conceptualization which enable other knowledge domain such as cost, schedule, project management, safety, sustainability parameters to be embedded in BIM software to provide one-source, central hub of information for project stakeholders. Olatunji et al. (2017b) and Olawumi and Chan (2018e) affirms BIM capability to offer both functions (application and process) which enables it to be useful for construction stakeholders and organizations in managing project data.

The integration of BIM and sustainability practices implies leveraging on BIM technologies such as software and plugins, cloud platforms to facilitate sustainability assessment of infrastructural and construction projects (Olawumi & Chan, 2018d). However, there have not been a uniform adoption and implementation of BIM initiatives and sustainability in most countries, with the United States and the United Kingdom, the leading nations in its adoption (Olawumi et al., 2017), likewise for sustainability. The five-dimensional (5-D) BIM which incorporates cost data can assist to avoid cost overrun on construction projects and facilitate substantial returns on investment for the client (Olatunji et al., 2017b).

The next phase of nD BIM is the 6D BIM which attempt to utilize BIM to address issues such as sustainability in construction projects which is consistent with the views of Bradley et al. (2016), who stressed the capacity of BIM to expand into domains such as sustainable/green buildings of which BIM was not originally conceived to address. Sustainability is a sophisticated theme in the construction field which involves a balanced play between the social, economic and environmental pillars of sustainable development (Olawumi & Chan, 2018a).

In recent years, several infrastructural projects have sprung up in urban cities across the world promoting the ideas of sustainable built environment tagged with names such as ‘smart cities’ or ‘eco-cities’ (Cugurullo, 2017). Also, several approaches have been suggested by advocates of sustainable smart cities toward ensuring the execution of construction projects with these ideas in mind. However, according to Batty (2012), Bettencourt and West (2010), the standards of these advocates of these projects for smart, sustainable cities are unclear, undefined, and often chaotic. Hence, making the drive and concept of city-making to achieve sustainability impossible.

Moreover, some cities have demonstrated possibilities in adopting smart technologies in its infrastructural development to emerge as smart cities such as Hong Kong (Cugurullo, 2017), Milano (Milano Smart City, 2017), Barcelona (Barcelona City Council, 2017) and Vienna (Smart City Wien, 2017). Also, a portrayed example of an eco-city is Masdar City envisioned as a greenprint for innovative sustainable development and a city for the future (Masdar Initiative, 2017). Although, Masdar City is often promoted as the world’s most sustainable city (Cugurullo, 2017). However, its failure makes the most use of smart technologies has weakened its ability to resolve some issues related to energy, water supply chain management and ecological impact of the settlement (Crot, 2013; Cugurullo, 2013). The above example of an eco-city (Masdar City) further strengthens the stand of this paper for a cohesive implementation of smart technologies (such as BIM) and sustainability practices in the construction industry.

For a smart city such as Hong Kong, Cugurullo (2017) argued that the smart interventions in the city are insensitive to the ideals of sustainable development with resulting environmental pollution and other urban problems. More so, Hong Kong adopted a project-based approach to smart urbanism rather than a whole system; leading to a fragmented system of different entities (Cugurullo, 2017). Hence, it is required for cohesive and strategic planning to synergy different fragmented smart projects and also integrates sustainability practices to achieve a smart, sustainable city.

There are some sustainability assessment techniques or building rating systems (such as LEED, BREEAM, etc.) that have been developed to evaluate who well a building project meet some defined criteria for such infrastructure to be considered green or sustainable. Moreover, Sala et al. (2015) highlighted some inadequacy in some of these techniques will make them unreliable and inconsistent and much of the issues are linked to the fuzziness of the sustainability concept itself. Nevertheless, there have been some application of smart technologies and sustainability practices in some projects such as BIM for sustainable material decisions (Ahmadian et al., 2017); BIM for sustainable design (Wong & Fan, 2013), GIS-based facility management (Kang & Hong, 2015); BIM-based energy analysis (Gourlis & Kovacic, 2017). A comprehensive review of the body of literature was examined by Olawumi and Chan (2018a).

Yusof et al. (2016) examined the influence of project's stakeholders' behavior on the implementation of sustainability practices which reveal a positive correlation between the firm's management practices in respect of energy efficiency and waste and the implementation of sustainability ideals during project execution. Since construction projects are people-driven, it is expected the project stakeholders are well-informed on the ideals of sustainable development. More so, Eurostat (2013) reported that 859 million tons of waste were generated from construction activities in the European Union; also, Fuertes et al. (2013) regards the construction industry as a significant source of water, noise, and air pollution.

In countries such as China and Malaysia, construction-related activities account for 45-46% of the overall energy consumption (MIGHT, 2014; Zhaojian & Yi, 2006); along with about 30% of solid waste in China (Lu & Tam, 2013); and 30% of greenhouse gas emissions in Malaysia (MIGHT, 2014). These case studies reveal the immense potential for the construction industry to embrace the ideals of sustainability (Birkeland, 2014) as well as its cohesive implementation with smart technologies. Therefore, since the construction activities involved several stakeholders such as the clients, architects, project managers, engineers among others (Olawumi & Ayegun, 2016); it is necessary for the stakeholders to well experienced in the use and implementation of smart tools such as BIM and adhere to the ideals of sustainability (Mom et al., 2014a).

1.3 Research Problems and Scope

This section discusses the knowledge and practice gaps that gives rise to the current study's aim and objectives. More so, the scope of the study is discussed within the subsections 1.3.1 – 1.3.6.

1.3.1 Benefits of BIM and sustainability practices implementation

Studies by De Boeck et al. (2015), and Chandel et al. (2016) highlighted significant research gap in research and practice on the utilization of innovative tools like BIM in sustainability practices. Accordingly, they noted that much emphasis is being placed on the analysis and optimization of energy performance on residential buildings (Chandel et al., 2016; De Boeck et al., 2015) and less on other building typologies such as commercial and industrial buildings (Ruparathna et al., 2016). Also, Abanda and Byers (2016) examined the practical use of BIM in the simulation of energy performance. Moreover, it is necessary to point out that 'energy performance' of buildings is a subset of the environmental aspect of sustainable development and green buildings; and according to Ahmad and Thaheem (2017) to achieve sustainable smart cities initiative and green buildings, there must be a balanced play between the economic, social and environmental pillars of sustainability.

Moreover, recent studies (*see* Hosseini et al., 2016; Mao et al., 2016) revealed that inadequate knowledge of the benefits of these concepts had hindered its implementation in the construction industry. Meanwhile, studies such as Mom et al. (2014b, 2014a) have examined some benefits and drivers of BIM adoption in Taiwan. However, these studies focused solely on BIM. Previous studies (*see* Abdirad, 2016; Ahmad & Thaheem, 2017; Antón & Díaz, 2014; Azhar, 2011) which employed BIM for sustainable construction practices have been limited by their scope. Some of the authors either focused on a subcategory item of sustainability such as energy or LCA, other studies were defined by being confined to a country or building typology. Although some of the benefits identified by previous authors might apply to a single application of either BIM or sustainability practices in construction projects; the study aims to fill the gap by identifying the key benefits that are obtainable when both concepts are adopted in a project as well as categorize them based on the measures of assessment- either qualitative/quantitative or both.

1.3.2 Barriers of BIM and sustainability practices implementation

Much criticism has been raised about the sole implementation of either smart initiative or sustainability practices in the built environment (Cugurullo, 2017) due to the difficulties and more problems caused by its adoption. Hence, Olawumi et al. (2018) advocated for the implementation of concepts of sustainable smart practices to facilitate a holistic sustainability development of the built environment. Meanwhile, there is still vagueness regarding what constitutes smart- and eco-initiatives (Angelidou, 2015; Olawumi & Chan, 2018b). Extant literature (*see* Olawumi et al., 2017; Olawumi & Chan, 2017, 2018a; Wong et al., 2014) have conducted reviews on the concepts of smart sustainable practices as it applies to both industry practice and teaching.

Also, previous studies (Kivits & Furneaux, 2013; Olatunji et al., 2016b, 2017b) illustrated several attempts by the construction industry to utilize BIM to implement sustainability practices in building projects. However, issues related to inadequate coordination in organization and collaboration among key stakeholders has been a bane of the built environment. Adamus (2013) and Ma et al. (2018) accentuated that a critical challenge with implementing sustainable practices in the industry is the need to balance the implementation of the three pillars of sustainable development (social, environmental and economic sustainability) in projects. More so, where there has been an implementation of sustainability practices in building projects, more emphasis has been on the environmental sustainability construct (Ali & Al Nsairat, 2009; Berardi, 2012).

More so, studies such as Chandel et al. (2016) and De Boeck et al. (2015) pointed out that there are still significant gaps in practice in the adoption of innovative tools such as BIM for the implementation of sustainability practices in the construction industry. Studies such as Hosseini et al. (2015) and Mao et al. (2016) emphasized that without sufficient knowledge on the status (such as its barriers etc.) of the implementation of these concepts in the construction industry; it would be difficult to improve track aspects of its implementation that is still lagging. Olawumi and Chan (2018a) highlighted some current application of BIM in implementing sustainability in building projects.

Apart from these, there are several smart technologies and tools employed in the construction industry which include: (i) Building Information Modelling (BIM); (ii) virtual reality; (iii) semantic web technology or ontology; (iv) augmented reality; (v) sensors; (vi) Radio-frequency identification (RFID); and (vii) Point-cloud data extraction, among others (Olawumi et al., 2017). However, the current study will discuss one of these smart tools- BIM and the challenges of utilizing it to enable the implementation of sustainable practices in the built environment. Although the other smart devices are being used in the construction industry, BIM is still the most widely employed smart tool (Jung & Lee, 2015; Olawumi et al., 2017; Wong & Zhou, 2015). Virtually every project stakeholder can also utilize BIM, and it is also a multifunctional technology.

Although some previous research studies have highlighted the profound barriers relating to BIM in the construction industry – none is yet to appraise the impediments militating against adopting both BIM and sustainability practices on the same building project. Accordingly, this study reviewed the existing literature to gather solid evidence of the challenges faced by the built environment in the implementation of sustainable smart practices.

1.3.3 Drivers of BIM and sustainability practices implementation

Meanwhile, a plethora of published literature (*see* Ali & Al Nsairat, 2009; Anthopoulos, 2017; Ilhan & Yaman, 2016; Olawumi & Chan, 2018d; Shi et al., 2013) have provided holistic reviews and undertook empirical studies to discuss and shows the different application and the use of smart tools to aid sustainability issues. However, no study has examined the drivers of implementing smart and sustainable practices across regions as undertaken in this study. Also, as seen in the previous sections and the extant literature (Jung & Lee, 2015; Malleson, 2012; Olawumi & Chan, 2018a) among others; there has been a varied adoption, implementation, and application of BIM and sustainability practices in the construction industry. The construction industry is given more focus in this study as part of the built environment because according to previous studies (Abanda & Byers, 2016; Bynum et al., 2013), buildings account for one-third of the global energy use and one-fifth of the greenhouse gases emission.

Furthermore, according to Gourlis and Kovacic (2017) and Olawumi and Chan (2020), BIM has offered encouraging promises to optimize energy consumption and reduce the carbon footprints of the building facilities. Therefore, the scope of the study is delimited to construction projects (as a subset of the built environment), BIM (a type of smart tools), and sustainability practices as it relates to the whole lifecycle of buildings. Hence, this study aims to take deeper insights by investigating and assessing the key drivers (KDs) that aid the implementation of smart and sustainable practices in the construction industry and projects.

Several attempts have been made in the extant literature to address issues related to smart and sustainable practices in the construction industry. For instance, a study by Abanda and Byers (2016) utilized BIM tools to simulate the energy performance of buildings. Although the findings are of significant value, but the focus on the 'energy' criterion limits its ability to influence building sustainability. Similar studies by Tsai et al. (2014b) and Oti et al. (2016) demonstrated the use of BIM plugins to embed some sustainability criteria to assess the greenness of building projects. However, these studies place emphasis on a single construct of sustainable development and fail to provide ways to enhance its adoption and implementation.

Meanwhile, a few studies have attempted to investigate the drivers to BIM adoption, such as Tsai et al. (2014a) and Chan et al. (2019a) who examine BIM adoption in Taiwan and Hong Kong, respectively. These studies fail to consider how BIM can help improve sustainability practices in the construction industry. Similar studies by Olawumi and Chan (2018d, 2020) have examined the benefits and barriers to the implementation of BIM and sustainability practices; hence, there is a salient need to examine the critical success factors that can drive its implementation. Furthermore, a review by previous studies (*see* Jung & Lee, 2015; Olawumi et al., 2017; Olawumi & Chan, 2018a) reviewed an uneven rate of adoption of BIM and sustainability across the various regions in the world.

These relevant knowledge gaps in the extant literature and practice will be bridged and addressed in this study. Also, the need to enhance the sustainability potential of the built environment and building projects as outlined in the sustainable development goals of the United Nations motivates and necessitates this study. The current study reiterated the need for the application of BIM and sustainability practices in construction projects as against the singularity of the adoption of either BIM or sustainability practices initiatives.

1.3.4 Why develop a Building Sustainability Assessment Method (BSAM) for Developing Countries in Sub-Saharan Africa?

A desktop review of the extant literature conducted by Olawumi and Chan (2018a) and Olawumi and Chan (2017) reveals some salient sustainable development issues in the built environment. The statistics of the construction industry regarding its energy consumption rate stand at 32% of the global consumption rate, its carbon emissions stand at 40%, it contributes about 40% of the global solid waste generation; utilizes 12% of the global freshwater and 1/3 of the global material usage (IPCC, 2007; Johansson et al., 2012; Olawumi & Chan, 2019a; UNEP, 2011; Ürge-Vorsatz et al., 2007; WEC, 2013). According to Tam et al. (2019b) and Le et al. (2018), the increase in these carbon emissions is a major contributory factor to global warming as well as the increased energy consumption due to the development of new houses (Gobbi et al., 2016).

There is an increasing focus and attention on sustainability issues in the built environment which has led to an increase in the number of certified green buildings nowadays when compared to the advent of the Building Research Establishment Environmental Assessment Method (BREEAM) in the year 1990. Green buildings have been recognized as the flagship of sustainable development in recent years with the increasing responsibility to cater to and balance the social, economic, and environmental sustainability issues (Ando et al., 2005). Green building rating systems (GBRS) have provided an effective means to assess the sustainability performance of various construction projects – be it buildings, civil engineering works, or infrastructure, as well as the integration of sustainable development objectives in such projects (Ali & Al Nsairat, 2009). Currently, there are over 400 registered software tools to assess various aspects of sustainability in buildings (Nguyen & Altan, 2011). More so, there are several green building rating systems such as BREEAM, Leadership in Energy and Environmental Design (LEED), Comprehensive Assessment System for Built Environment Efficiency (CASBEE), Green Star, BEAM Plus, Green Mark, among others, already in place worldwide. These green rating systems are used to address the quality of the building performance throughout its lifecycle as well as the impact of building on its surrounding ecosystem.

Ali and Al Nsairat (2009) argued that the use of these green rating systems in the evaluation of sustainability performance could yield significant benefits that might not be obtainable through the standard practice in the construction industry. A review of four Malaysian green rating tools by Hamid et al. (2014) revealed that these tools place emphasis on environmental sustainability and accordingly recommended the merging of these tools to better handle sustainability issues across the building lifecycle stages. Leading green rating tools such as LEED have similar disadvantages (Ismaeel, 2019; Wu et al., 2016). These figures further highlight the significance of sustainable buildings which are needed to improve the quality of life and health of its occupants, increase productivity, reduce air pollutions and CO_2 emissions, and enhance the efficiency of energy equipment among others.

However, a review of the extant literature and existing green building rating tools reveals some significant gaps in the existing body of knowledge. For instance, there are currently no available green rating systems that are suited for the local context of developing countries in sub-Saharan Africa. Although, some existing green rating tools such as BREEAM, LEED, and Green Star as discussed in Chapter 7 have been attempting to expand their respective rating tools beyond the borders of the originating countries (Ali & Al Nsairat, 2009; Banani et al., 2013; Berardi, 2012; Illankoon et al., 2017; Mahmoud et al., 2019). However, none of these existing rating tools have extended their reach and rating tool to suit the local context of countries in the sub-Saharan region.

Meanwhile, as argued by Todd and Geissler (1999) and Banani et al. (2013), the regional and local context of GBRS has a significant effect on the importance and priority given to each sustainability criterion in each rating system. A study by Hamid et al. (2014) argued the need to ensure that national and international green rating tools are tailored to the local context to drive green building forward. Hence, as reported in the extant literature (Alyami & Rezgui, 2012; Xiaoping et al., 2009), these regional variations in the priority of the key sustainable criteria hinder the direct use of the rating tool beyond the country of its origin or the local context to which it was designed for use.

Moreover, these existing GBRS place more substantial considerations on the environmental sustainability issues with little account or a total neglect of social and economic pillars of sustainable development (Ding et al., 2018; Illankoon et al., 2017;

Nguyen & Altan, 2011; Olawumi et al., 2018; Olawumi & Chan, 2018d). Also, the Green Mark rating system does not allocate credit points for the 'transportation' criterion (BCA, 2015). Hence, to provide a better evaluation of the 'greenness' or sustainability of buildings; Alwisy et al. (2018); Illankoon et al. (2017) recommended that future development of green rating tools should consider all three sustainability pillars.

Given the above, this study aims to develop a sustainability assessment tool for buildings (both new and existing buildings) to suit the local context of the sub-Saharan region as well as to establish the importance of the key sustainability criteria through their score-weighted category. The proposed Building Sustainability Assessment Method (BSAM) scheme covers the triple pillars of sustainable development and provides profound improvements to the existing green building rating systems.

1.3.5 Need for a Cloud-based Sustainability Decision Support System for the BSAM Scheme?

In recent years, there has been increased large-scale development and interventions in the built environment in Africa and around the world due to the urgency to shore up the gap in the housing deficits. Accordingly, Du Plessis (2007) argued that such interventions, especially in developing countries, must be socially and economically-centric and not just based on environmental factors alone. More so, Du Plessis (2007) outlined and suggested a number of enablers to facilitate the implementation of sustainability in developing countries, especially in Africa – one of which is the adoption and implementation of sustainable construction technologies and practices. A key challenge to implementing these suggestions according to Du Plessis (2007) and Banani et al. (2013), is the development of regional or local context strategies and technologies for its practice. More so, a review of the adoption of sustainability across regions and countries in the extant literature (Jung & Lee, 2015; Olawumi & Chan, 2017, 2018a) revealed a slow adoption and implementation of sustainability and green buildings in Africa.

Although, there have been a number of multi-million dollar infrastructural and building projects development across Africa; it is difficult to verify the sustainability credentials or performance of these building projects due to a lack of a local or regional-based green building rating system which suit the context of the regions in Africa or of a particular country (Ding et al., 2018; Mahmoud et al., 2019; Olawumi &

Chan, 2018d). Also, the existing green rating tools such as the Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED), Comprehensive Assessment System for Built Environment Efficiency (CASBEE), Green Star, BEAM Plus, Green Mark, among others places more emphasis and considerations on the environmental sustainability criteria (BCA, 2010; BRE, 2018; HKGBC, 2019; Mahmoud, 2017; USGBC, 2017).

Hence, these existing green rating tools, according to Ali and Al Nsairat (2009) and Ahmad and Thaheem (2017), are not suited to Africa's developing countries, which places more emphasis on the social and economic sustainability criteria. The social and economic sustainability (otherwise captioned as 'people' and 'profit' respectively) are related to the standard of living which is generally between very low and medium for African countries compared to other developed regions. According to the Human Development Index (HDI) of the United Nations (http://hdr.undp.org/en/composite/HDI), sub-Saharan Africa has the lowest HDI of 0.537. Hence, to improve these statistics sub-African countries tends to place more emphasis on the social and economic sustainability criteria, unlike other countries focusing on environmental sustainability criterion.

Given these limitations in these existing green rating tools, existing knowledge, and practice which include in summary – (1) the neglect of the economic and social sustainability criteria (by existing rating tools) in the sustainability assessment of building projects (Illankoon et al., 2017; Olawumi et al., 2018); (2) the unsuitability of these existing rating tools to the climate and geographically characteristics of the sub-Saharan region of Africa (Nguyen & Altan, 2011); (3) the higher priority given to some of the environmental criteria of these existing green rating tools (Alyami & Rezgui, 2012; Xiaoping et al., 2009); and (4) the lack of a wholly-developed technological tool to aid the sustainability assessment of green buildings (Du Plessis, 2007; Olawumi & Chan, 2020b), among others. A part of this study resulted in the development of the Building Sustainability Assessment Method (BSAM) scheme green rating system to suit the regional context of the countries within the sub-Saharan region of Africa (Olawumi & Chan, 2019c). Also, the BSAM scheme, unlike the other existing green rating tools, comprehensively included the three pillars of sustainable development (Olawumi & Chan, 2019c).

More so, as regards the development of a technological tool to aid the sustainability assessment of green buildings, Deakin and Reid (2018) argued the need for future internet-based (cloud) infrastructures to handle the data management, and sustainability ranking and assessment of green buildings as well as smart cities. Also, Stratigea et al. (2015) highlighted the roles and potential of enabling digitization tools and technologies to gather and process information necessary to aid the capacity decision-makers in the built environment and solve related urban sustainability issues. Meanwhile, Campbell (2016) argued the need for decision-makers and relevant stakeholders to consider a holistic consideration of the sustainability – economic, environmental, and social sustainability – in advocating and promoting green building and cities.

Therefore, with the development of the BSAM scheme green rating system in this study and to bridge the above gaps in extant literature and practice; the current study aims to develop a Cloud-based Sustainability Decision Support System (C-SDSS) platform to aid the assessment of the sustainability performance of green buildings and infrastructures as well as to promote the implementation of sustainability practices in building and real estate developments. The C-SDSS platform will be developed to facilitate the comparison of the sustainability performance of two or more buildings for sustainability decision making purposes. The C-SDSS platform was developed in this study using high-level programming languages (such as PHP, Jscript, etc.) as well as the use of relational databases such as MySQL. Also, the BSAM scheme will be integrated with the C-SDSS platform as its primary green building rating system.

1.3.6 Any necessity for the development of a Green-BIM Assessment Framework for Green Building Projects in Sub-Saharan Africa?

In recent years, there has been an increase in the adoption and implementation of sustainable development and smart tools such as BIM (Olawumi et al., 2020; Olawumi & Chan, 2020a). These developments in the built environment – especially in buildings and cities – have led to a paradigm shift that has translated to practical strategies and concepts such as smart buildings and smart cities, green buildings, among others. (Lam & Yang, 2020; Olawumi & Chan, 2020c). The Green-BIM concept is also an emerging trend in the extant literature and involves the application of BIM tools to enhance sustainability adoption (Wu & Issa, 2014b)

Several verifiable benefits of the adoption of BIM have been identified in the literature (Abdirad, 2016; Antón & Díaz, 2014; Cemesova et al., 2015); as well as its capability to allow for the integration of several other processes and concepts such as sustainability considerations, knowledge management. For instance, Oti et al. (2016) and Tsai et al. (2014b) demonstrated the capabilities of BIM tools to assess sustainability parameters of building designs and models via the development of customized plugins. Yuan et al. (2019) and Olawumi and Chan (2018b) described BIM as an innovative system that allows the digitalization of building information throughout the building project lifecycle stages.

Some buildings and cities have sprung up based solely on either the concepts of "eco," which incorporates mostly sustainability measures or smart schemes (Cugurullo, 2017). However, there have been issues of unclear and chaotic standards/road maps by project teams attempting to implement and promote smart and sustainable practices (Lobos et al., 2019). Taylor Buck and While (2017) and Sala et al. (2015) further revealed the issues behind the discordant implementation of smart buildings and sustainability in the built environment stems from several factors.

A limitation is the interoperability issues between design and energy simulation software programs (Adamus, 2013). Other potential barriers associated with the joint implementation of smart and eco-initiatives in construction projects were discussed in Olawumi et al. (2018). Conversely, there are practical benefits and positive effects of smart- and eco-initiatives, which include better occupants' comfort and productivity, less carbon footprint, real-time environmental data monitoring, better design of buildings, among others (Ali & Al Nsairat, 2009; Lee et al., 2012a).

A study by Jung and Lee (2015) shows a less than 10 percent application rate of the use of BIM for building sustainability analysis in Africa compared to about 40%, 54%, and 73% in Asia, Europe, and North America (see Figure 1.1). Another study by Olawumi et al. (2017) shows a low level of BIM adoption in Africa, which is consistent with the findings by Jung and Lee (2015). Findings in the extant literature show similar status for the adoption of sustainability practices in Africa compared to Europe and America (Olawumi & Chan, 2018a). Although steps have been taken by stakeholders in the sub-Saharan region to improve the adoption of BIM and sustainability – such as the development of the BSAM scheme (Olawumi & Chan, 2019c). However, the region is still faced with the challenge of digitalizing the sustainability assessment and other processes in the built environment (Olawumi et al., 2018; Saka & Chan, 2019).

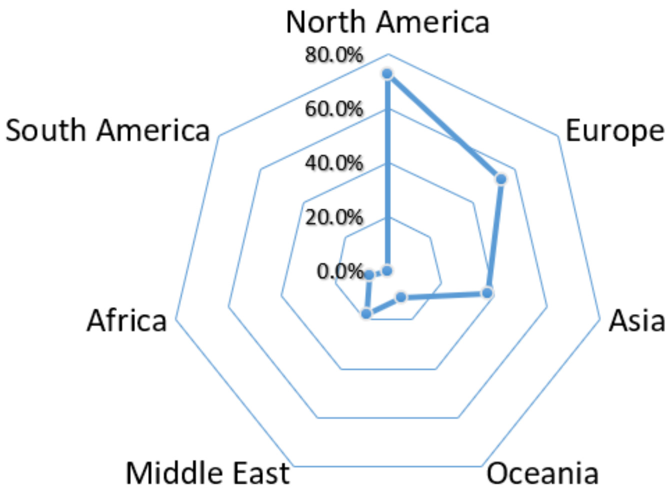

Figure 1.1: BIM usage for Building Sustainability Analysis (Jung & Lee, 2015)

Olawumi and Chan (2019a) described Green-BIM as an innovative and emerging concept; while to (Wu & Issa, 2014b), it is perceived as a synergetic initiative which bridge and break the "aura of singularity" of the sole implementation of either smart initiative (which focus mostly on BIM usage) and eco-initiatives in the built environment. However, according to extant literature (*see* Antón & Díaz, 2014; Wu & Issa, 2014b), the lack of a clear strategic framework has hindered the adoption and implementation of green-BIM in the built environment, most notably in building projects. More so, per Olawumi and Chan (2020c), the development of a digital and automated system can drive the implementation of green-BIM, especially in the sub-Saharan region of Africa where its adoption is still quite low.

Hence, the current study aims to propose and develop an integrated green-BIM assessment (GBA) framework to evaluate the sustainability performance of buildings and facilitate the implementation of smart sustainable practices in sub-Saharan Africa. Towards achieving the study's aim, firstly, the key components that make up the proposed GBA tool will be highlighted. Also, the necessary documents required for the GBA tool's components and at the different building development stages will be identified. More so, the proposed GBA tool will be validated to verify its suitability and applicability within the context of the sub-Saharan region. This study presents one of the key stages of concerted research works to digitalize the sustainability assessment process in the sub-Saharan region of Africa.

The research findings of the study are expected to have a broad range of applications and profound impacts on the knowledge and implementation of smart and sustainable practices in the built environment. The scope of the application of the proposed GBA framework is limited to the sub-Saharan region of Africa (see Figure 1.2) because one of its key components – the BSAM scheme – was designed specifically for the region as discussed in Chapters 7 and 8. More so, the sub-Saharan region based on the existing research studies (*see* Jung & Lee, 2015; Olawumi et al., 2017; Olawumi & Chan, 2017, 2018a) has been observed as one of the lowest adoption and implementation regions of smart- and eco-initiatives in the world.

More so, the current research will discuss one of the smart tools- BIM. Although the other smart devices are being used in the construction industry, BIM is still the most widely employed smart tool (Jung & Lee, 2015; Olawumi et al., 2017; Wong & Zhou, 2015).

1.4 Research Aim and Objectives

This study aims to develop a green-BIM assessment model and cloud-based sustainability decision support system for evaluating buildings' compliance to sustainability principles with a view to integrating smart sustainable practices in building construction and management, improving operational efficiency, and enhancing the overall implementation of sustainable development in the built environment. The scope of study mainly focuses on developing countries located in the sub-Saharan region of Africa – using Nigeria, the largest economy in the region as a case study – with practical applications to other regions.

The following research objectives have been set out in fulfilling the study’s aim:

1. To identify and assess the inherent benefits, barriers, and critical success factors (CSFs) associated with integrating BIM and sustainability principles in building projects.

2. To establish the relative weightings of the key sustainability indicators, sustainability attributes, and sub-attributes for buildings.

3. To develop a sustainability evaluation index for buildings using the Generalized Choquet Fuzzy Integral method.

4. To develop a cloud-based sustainability decision support system (C-SDSS) for buildings.

5. To develop a conceptual Green-BIM assessment framework as a tool for the evaluation of sustainability performance of buildings.

Figure 1.2: Map showing the sub-Saharan region of Africa

1.5 Research Approaches and Contribution to Knowledge

This section outlines briefly describes the research approaches adopted towards achieving the aim and objectives of the study as well as the intended contributions to knowledge and practice. Detailed discussion and descriptions of the research techniques and the contributions of this study to knowledge and practice are expatiated in subsequent chapters of this thesis, as illustrated in section 1.6 and Figure 1.3. The overall research methodology can be classified into four phases (sections 1.5.1 – 1.5.4):

1.5.1 Literature review – extant literature, practice, and experts' consultations

The review of the literature is often the first stage in a research endeavor and very critical towards identifying the trends and practices in the research discipline as well as relevant gaps in the knowledge and practice of the subject matter. It also helps to establish a solid theoretical base for the study. The current study is an interdisciplinary research field – involving the concepts of BIM and sustainability. It was necessary to conduct an extensive review of the literature and practice involving either BIM or sustainability adoption and implementation in the built environment as well as its joint application. The review helped in highlighting the key benefits, barriers, and drivers of the implementation of BIM and sustainability practices in the construction industry (Objective #1).

More so, since the study set out to develop a green building rating system suited to the regional context of sub-Saharan Africa. A review of existing rating systems, green building technical notes and guidelines was conducted to develop the BSAM scheme as well as establish its sustainability criteria (Objective #2). It was also useful in the comparative assessment of the BSAM scheme with other leading green rating systems such as LEED, BREEAM, BEAM Plus, etc.

Moreover, the review of the various Multi-Criteria Decision Methods (MCDM) helped to decide to use the more superior weighting methodology – the Generalized Choquet Fuzzy Integral (GCFI) to develop the sustainability evaluation index of the BSAM scheme. The GCFI helped to identify the weight of the BSAM criteria – indicators, attributes, and sub-attributes – and the other factors used in the building sustainability assessment process in this study (Objective #3). Furthermore, a review of the extant literature helped in the extraction of the six components aggregated to develop the GBA framework (Objective #5).

Meanwhile, relevant informal discussions, brainstorming sessions (with research supervisors and academic colleagues), and expert consultations were held during the study to establish the aim and objectives, methodologies, assemble research data as well as validate the study’s findings and data. The literature review stage involves retrieving, synthesizing, analyzing, and classifying information from the relevant secondary data sources.

1.5.2 Primary data collection – Questionnaire surveys and Data analysis

After the conclusion of the various aspects of the literature review phase, the second phase of the research approach, which involves the collection of relevant data via questionnaires surveys and expert consultation, was commenced. Several sets of questionnaire surveys were developed and can be categorized into (1) general surveys, (2) a GCFI-based expert surveys, and (3) validation surveys.

For the general surveys, three sets of questionnaires – pilot, Delphi, and international expert surveys – were developed to achieve Objective #1. These sets of questionnaires helped to establish and highlights the key benefits, barriers, and drivers of implementing BIM and sustainability practices. The GCFI-based expert surveys consist of five sets of questionnaire forms that were distributed to experts in the subject matter towards identifying the BSAM scheme sustainability criteria (for new and existing buildings). These questionnaires also help in determining the degree of importance for each of its sustainability criteria; establishing the BSAM scheme certification grade system as well as the trapezoidal fuzzy numbers; and an appendix showing the structure of the BSAM scheme criteria – indicators, attributes, and sub-attributes.

Based on the qualitative and quantitative data provided by the experts in the questionnaire surveys set, the building sustainability evaluation ratio (BSER) for new and existing buildings was obtained as well as the weighting of each criterion. It also helps to identify where and when to upgrade the overall BSER value of a project towards improving its sustainability performance. The data from the GCFI-based expert surveys were used to achieve Objectives #2 and #3 and as input towards achieving Objective #4.

The validation surveys were used to establish the applicability, suitability, credibility, etc. of the two models – BSAM scheme (Objective #3) and the GBA framework (Objective #5); and the C-SDSS platform developed in the study (Objective #4) within the built environment, most notably within the sub-Saharan region.

1.5.3 Case studies – Implementing the models and cloud-based platform

As highlighted in section 1.5.2, two significant models were developed in the study which is: (1) the Building Sustainability Assessment Method (BSAM) scheme, which is a regional-based green building rating system suited to the context of sub-Saharan Africa (Objective #3). (2) Green-BIM Assessment (GBA) framework intends to serve as an automated and dynamic tool to facilitate the assessment of the sustainability performance of green buildings for comparison and benchmarking purposes (Objective #3. Also, the Cloud-based Sustainability Decision Support System (C-SDSS) platform was developed (Objective #4).

Apart from using validation surveys as illustrated in section 1.5.2, real-life case study building projects were used to validate the BSAM scheme green rating system and the C-SDSS platform. These involve collecting the BIM models as well as relevant physical data and sustainability data of the buildings.

1.5.4 Cloud-based system – Coding, database management, and web development

A key deliverable of this study is the development of the Cloud-based Sustainability Decision Support System (C-SDSS) platform (Objective #4). The C-SDSS platform is designed to be a digitalized, automated green building sustainability assessment tool for green buildings projects. The key features and significance of the C-SDSS platforms are discussed in Chapter 9 of this thesis. Most of all, for its development and management, a number of high-level programming languages – mainly the PHP and Jscript – were deployed and used on Adobe Dreamweaver software. A relational database in the form of the robust MySQL databases was integrated to serve as the data storage and mining for the C-SDSS platform while the C-SDSS platform itself was hosted on a local cloud-based server.

The primary function of the C-SDSS platform which is to provide an automated and dynamic system for decision-makers and assessors to evaluate the sustainability performance of green building projects. It also provides avenues for its users to compare their building designs and projects for their sustainability potential or performance, respectively. The C-SDSS platform can also help pinpoint areas of the sustainability performance of a building that needs improvement. Also, the C-SDSS platform being an open-source project, it provides a cost-free solution to its users in the sustainability assessment of their building projects.

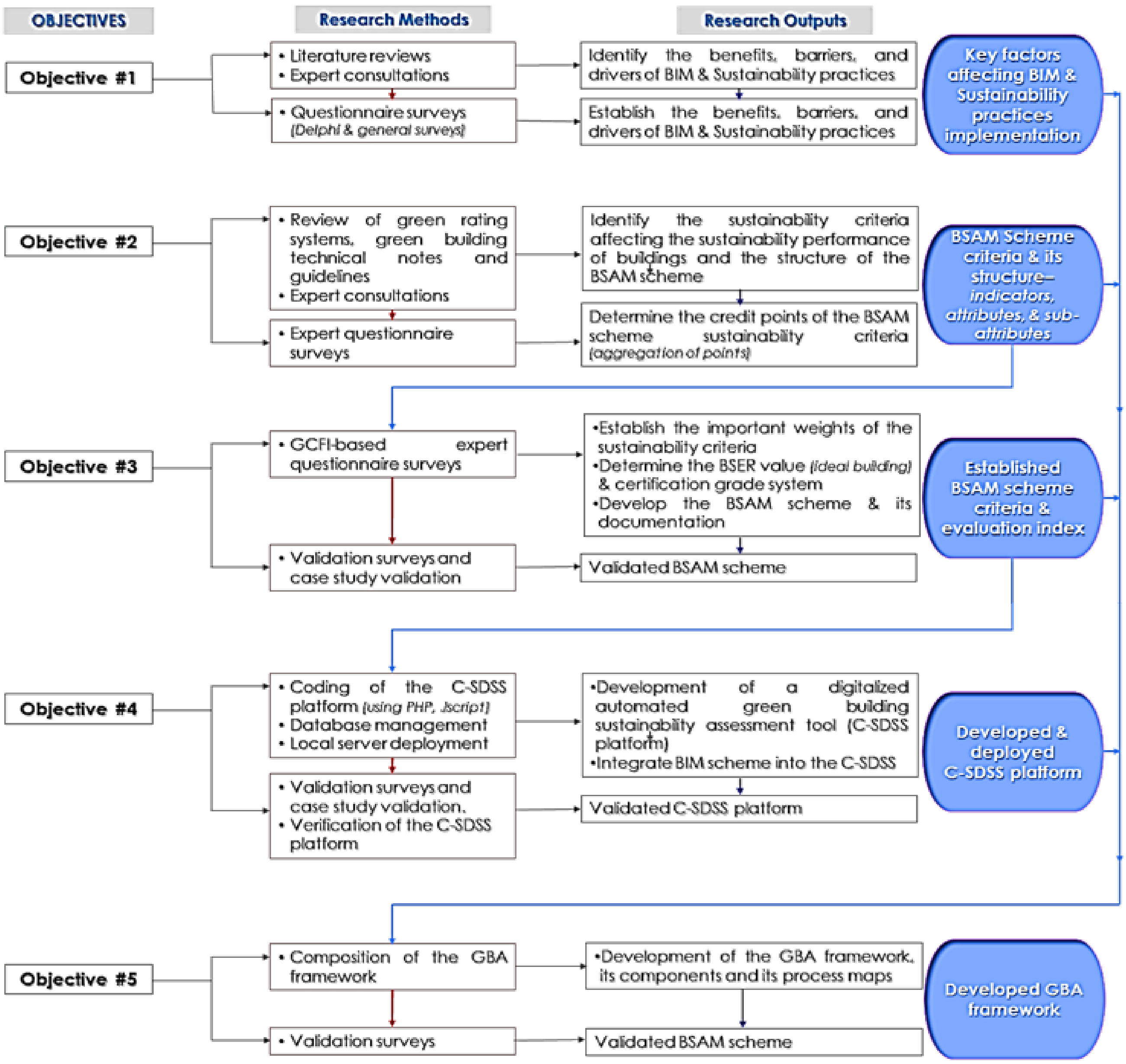

Figure 1.3: Overall research approach

1.6 Structure of the Thesis

This research study is structured into eleven chapters. Chapter 1 presents and discusses the background of the research, states the scope of the study, and the research problems that give rise to each of the research objectives, states the research aim and objectives. It also briefly discusses the various research approaches adopted in this thesis.

Chapter 2 presents a comprehensive review and a scientometric analysis of the concept of sustainability and sustainable development as it relates to the built environment. It also discusses the evolution of the research field from the definition of its concepts in the Brundtland Commission report to the recent development of models and sustainability criteria used in assessing green building projects. It also gives an extensive understanding of the salient research themes, trends and pattern of sustainability research worldwide.

Chapter 3 presents the comprehensive reviews and bibliometric analysis of BIM literature towards investigating and understanding the pattern of BIM research. Network maps that display the visualization of the structure of BIM are also presented. It also provides relevant research areas that require considerations, and the discussion of selected research areas provide an extensive understanding of salient BIM fields.

Since, the study reported in this thesis is a multi-disciplinary research work, Chapters 2 and 3 were designed to report mostly on sustainability and BIM respectively, although some sections in this chapters were designed to buttress on the linkage between these two salient concepts and how it applies to the construction industry and the built environment.

Chapters 4, 5, and 6 identify and examines the benefits, impediments (barriers) to, and drivers of the implementation of BIM and sustainability practices in building projects as well as in the built environment, respectively. Two datasets were collected namely via Delphi surveys and international surveys. These three Chapters helped to fulfill Objective #1 of this research project.

As shown in Figure 1.3, the key research outputs of objective #1 – which are the establishment of the key factors affecting BIM and sustainability practices implementation (Chapters 4 - 6) – formed and also helped in the development of some of the components of the conceptual Green-BIM assessment framework (Objective #5). Hence, Chapters 1 – 6 of this study helped in establishing the background of the research work and fulfilling Objective #1.

Chapter 7 develops a sustainability assessment method for building projects within the context of the sub-Saharan region of Africa – based on the findings and deliverables of the previous chapters. The developed Building Sustainability Assessment Method (BSAM) scheme and its weighted criteria will be validated using two real-life building case studies. The proposed BSAM scheme will be compared with six widely used green rating systems such as LEED, BREEAM, etc. in this chapter. It also provides an overview of the development of the BSAM scheme and its sustainability criteria. The findings of this chapter led to the fulfilment of Objective #2.

As shown in Figure 1.3, the key research outputs of Objective #2 presented in Chapter 7 of this thesis is the development of the relative weightings and structure for the BSAM scheme sustainability criteria which was used in Objective #3 to develop the sustainability evaluation index (using the GCFI method) for the BSAM scheme as reported in Chapter 8 (Objective #3) of this thesis.

Chapter 8 employs the MCDM technique – the generalized Choquet fuzzy integral (GCFI) method – to determine the weights of the sustainability criteria and develop the sustainability evaluation index of the BSAM scheme, while solidifying the development of the BSAM scheme. The developed sustainability rating model (BSAM scheme) will then be validated in four real-world building case studies to demonstrate its usefulness and robustness in practice. More so, the significance of the GCFI technique over other weighting methodology and MCDM tools will be discussed. The findings of this chapter led to the fulfilment of Objective #3.

The key research outputs of Objective #3 as shown in Figure 1.3 is the establishment of the sustainability evaluation index for the BSAM scheme which along with the key deliverables of Objective #2 formed the basis of the assessment of the sustainability performance of building projects on the developed Cloud-based Sustainability Decision Support System (C-SDSS) as presented in Chapter 9 (Objective #4) of this thesis. The BSAM scheme was the primary green building rating system (GBRS) on the CDSS platform.

Chapter 9 develops a C-SDSS to facilitate the assessment of the sustainability performance of green buildings. The C-SDSS platform will be developed using various high-level programming languages such as PHP, Jscript, etc. and relational databases. The primary green building rating system to be used on the C-SDSS platform is the BSAM scheme – which was developed in chapters 7 and 8. It was purposely explicitly designed for the sub-Saharan region of Africa and which holistically considered the social, economic, and environmental sustainability criteria. Also, the proposed C-SDSS platform will permit the comparison of green building projects' sustainability credentials on the cloud-based system. The findings of this chapter led to the fulfilment of Objective #4.

The key research output of Objective #4 is the development of the CSDSS platform which incorporates the BSAM scheme as its primary GBRS. The BSAM scheme incorporated within the C-SDSS platform utilizes the sustainability evaluation index earlier developed in Chapter 8 (Objective #3). The C-SDSS platform and relational database (Objective #4), and BSAM scheme (Objectives #2 & #3) formed parts of the components of the Green-BIM Assessment Framework developed as presented in Chapter 10 (Objective #5) of this thesis.

Chapter 10 combines the various deliverables and findings from the previous chapters to develop a holistic Green-BIM Assessment (GBA) Framework for green building projects in Sub-Saharan Africa. A conceptual research framework approach based on a consolidated desktop literature review forms part of the basis of the GBA framework development. The GBA framework is expected to serve as an automated and dynamic digital tool for the evaluation of the sustainability performance of green building projects for comparison and benchmarking purposes. Three of the six components of the GBA framework are based on the deliverables of chapters 7, 8, and 9, hence developed beyond the 'conceptual' level. The findings of this chapter led to the fulfilment of Objective #5.

Chapter 11 concludes this thesis by providing a review of the research objectives and highlighting the significant contributions of the study, as well as recommendations for future research, are also discussed.

1.7 Chapter Summary

This chapter has presented and discussed the background of the research, scope of the study, and the research problems, and stated the research aim and objectives. It illustrated the various research approaches adopted and the contribution of the study. This chapter also presented the structure of the thesis. The next two chapters

(Chapters 2 and 3) will introduce via a review of the extant literature the concept of sustainability and BIM respectively. The following chapter presents a comprehensive review and a scientometric analysis of the concept of sustainability and sustainable development as it relates to the built environment.

CHAPTER 2: A SCIENTOMETRIC REVIEW OF GLOBAL RESEARCH ON SUSTAINABILITY AND SUSTAINABLE DEVELOPMENT[2]

2.1 Chapter Overview

The previous chapter introduced the research and presented the aim and objectives of the study alongside the relevant gaps in knowledge and practice to be bridged in this research. It also outlined the scope of the study. The current chapter presents a comprehensive review and scientometric analysis of the concept of sustainability and sustainable development as it relates to the built environment based on 2094 corpus data. More so, this chapter discusses the evolution of the research field from the definition of its concepts in the Brundtland Commission report to the recent development of models and sustainability criteria used in assessing green building projects. It also gives an extensive understanding of the salient research themes, trends and pattern of sustainability research worldwide.

2.2 Introduction

The fulcrum for the worldwide attention being paid to the concept of sustainable development (SD) was the Brundtland Commission report of 1987 which help defined SD as seeking "to meet the needs and aspirations of the present without compromising the ability to meet those of the future" (WCED, 1987). However, there have been challenges in meeting some of the thresholds of SD due to the limitation imposed by the social issues, technological advancement and the ability of the ecosystem to accommodate human carbon footprints. Therefore, it is unrealistic to have a single SD blueprint for every country or region. Hence, each country would need to develop its SD policies and standards but with a global objective in mind.

As noted by Axelsson et al. (2011), sustainability and SD are two concepts that have gained reception at national and global levels due to challenges and risks faced in areas such as rural development, environmental conservation, energy, climate change, human wellbeing etc. Hence, in recent years there have been a shift in focus and action plans to address these problems. SD is currently adopted as a

[2] This chapter is fully published in:
Olawumi, T.O., & Chan, D.W.M. (2018a). A Scientometric Review of Global Research on Sustainability and Sustainable Development. *Journal of Cleaner Production*, 183, 231–250. https://doi.org/10.1016/j.jclepro.2018.02.162

growth strategy in the built environment. According to Sartori et al. (2014), sustainability is described as a process and mechanism to achieve the intended sustainable development; while according to Dovers and Handmer (1992), it is a process of “intentional change and improvement”.

As noted by Norton (2005), the two terms of sustainability and SD are often used interchangeably, however, Axelsson et al. (2011) argued that the two concepts are quite different. Axelsson et al. (2011) described sustainability as a policy vision of the society with primary purpose of preventing the depletion of natural resources. Clark (2002) however, observed that the issue of what sustainability means is more complex and per Parrotta et al. (2006) and Ramakrishnan (2001), it currently involves issues such as biodiversity conservation, ecological integrity etc.

In contrast, as stated by Axelsson et al. (2011), SD is more of a collective societal process that involves multiple stakeholders with differing salience level and powers. Nevertheless, Lee (1993) described both concepts as a “social learning and steering process” which involved both management and governance mechanism. The concept of sustainability is conceptual (Ekins et al., 2003) and hence easily misunderstood, although still hugely popular (Slimane, 2012). SD is however multidimensional in scope (Slimane, 2012), an integrated concept (Sartori et al., 2014) and based on the principles of sustainability (Dovers & Handmer, 1992). SD also helps to find a balance between preserving the ecosystem and meeting human needs. The three pillars of SD are environmental, social and economic sustainability; and these constructs must be harmonized to achieve a holistic SD.

Environmental sustainability is concerned with confining human activity within the carrying capacity of the ecosystem (such as materials, energy, land, and water, etc.) prevailing in the locality and places emphasis on the quality of human life (air quality, human health). Moreover, the economic sustainability considers the efficient use of resources to enhance operational profit and maximize market value. It also deals with substituting natural for manmade resources, reuse, and recycling. However, the social sustainability focuses on the social well-being of the populace, balancing the need of an individual with the need for the group (equity), public awareness and cohesion, and participation and utilization of local labors and firms. Sartori et al. (2014) acknowledged that the approach to sustainability defers based on the field of application, such as engineering, management, ecology, etc. Sala et al. (2015)

considered sustainability assessment as an appraisal method to evaluate the level of the implementation of these sustainability measures. The sustainability assessment results will be used for decision-making and policy formulation for real-world SD applications (Hacking & Guthrie, 2008).

Several studies have been published to addressed salient challenges facing sustainability in the built environment. Ahmad and Thaheem (2017) developed a social sustainability assessment framework for residential buildings using a weighted aggregation approach to improve its performance value. Also, Ahmadian et al. (2017) and Akanmu et al. (2015) utilized a Building Information Modelling (BIM)-based approach to address sustainability issues regarding material selection and supply decisions. Moreover, Damtoft et al. (2008) discussed issues relating to climate change initiatives and SD. Meanwhile, studies (*see* Akinade et al., 2015; Althobaiti, 2009; Forsberg & von Malmborg, 2004; Gao et al., 2015; Huang et al., 2010b; Wang et al., 2015a); attempted to integrate technological and innovative tools to advance the concept of sustainability and SD.

2.2.1 Knowledge gap, research objectives, and value

Sustainability is a wide and complex research field which several applications in different disciplines and industries. However, previous review papers on sustainability in the built environment have focused mainly on environmental sustainability, a gap which the current study tends to bridge. For instance, Wong and Zhou (2015) examined the concept of green BIM and sustainability across the various stages of building development. The authors examined the research frontiers of green BIM and proposed a 'one-stop-shop' BIM for environmental sustainability. Also, Darko et al. (2017) classified the drivers of green building and categorize them into five (5) sub-levels such as external drivers, property-level drivers, corporate-level drivers, project-level drivers, and individual-level drivers. Both Wong and Zhou (2015) and Darko et al. (2017) used the Scopus database.

Similarly, Falkenbach et al. (2010) reviewed the drivers for sustainable building by examining the perspective of various stakeholders in the real estate market. Aarseth et al. (2016) carried out a systematic literature review (SLR) and highlighted several project sustainability strategies that could be employed in project organizations to enhance project performance. Lele (1991) carried out a critical review of the concept of SD and discusses the idea in relation to issues such as economic growth, environmental degradation, community participation, and international grade. However, the review didn't include discussions of extant literature as sustainability was still a relatively new concept as of the time.

Also, the previous studies such as Wong and Zhou (2015), Aarseth et al. (2016) and Darko et al. (2017) analyzed 84, 68 and 42 journal papers respectively as compared to a relatively higher corpus of papers in this study (2094 articles). Moreover, no previous review of the sustainability research corpus mapped out the linkage or working relationships among the clusters of sustainability researchers and their institutions. Also, no previous studies have analyzed its research corpus to such depth to include aspects such as co-citation clusters, keywords, or research clusters.

Given the above, this study aims to bridge these gaps in extant literature by undertaking an in-depth scientometric review of the global on the sustainability and SD; with a view to providing researchers and practitioners with a comprehensive understanding of the status quo and research trend in its research, with a focus on the three pillars of sustainable development. Therefore, to achieve the study aim, five scientometric techniques will be employed as discussed under section 9.2.3 which will be used to (i) track the evolution of the sustainability research field, (ii) identify the key researchers and institutions. Also, part of the objectives of this study is to (iii) identify the key subject categories, (iv) research keywords and co-citation clusters as well as (v) deduce the salient and emerging research themes.

Meanwhile, a large corpus of journal articles (2094 bibliographic records) would be analyzed, which is a significantly high volume of articles than previous reviews on sustainability or elsewhere. The findings of the study are expected to contribute to the existing body of knowledge by highlighting the trend and pattern of sustainability research field, establishing its research themes and clusters, mapping the network of key sustainability researchers and institutions and recommending areas for future studies. It will also serve as a consultation toolkit for policy making for government agencies.

2.3 Research Methodology

The study carried out a scientometric review, analyses, and visualization to achieve the predefined research objectives of providing the academics and industry practitioners an in-depth understanding of the structure (clusters), research areas and trending topics in sustainability's studies in the built environment aided with illustrative diagrams and maps. The scientometric analysis is described as one of the most used methods to evaluate and examine the research development and performance of academics, faculties, colleges, countries and even journals in an identified research field (Konur, 2012).

The scientometric analysis is a technique that allows for a broader yet concise capturing and mapping of a scientific knowledge area by identifying structural patterns and tracing salient research frontiers using mathematical formulae and visualization. Moreover, other scientific methods such as bibliometric technique (Albort-Morant et al., 2017; Olawumi et al., 2017; Santos et al., 2017); content analysis (Park & Cai, 2017); literature reviews (Wong & Zhou, 2015); latent semantic analysis (LSA) (Yalcinkaya & Singh, 2015); and scientometric analysis (Montoya et al., 2014; Zhao, 2017); have been used by several authors across research areas such as green building and innovation, building information modelling (BIM), public-private partnerships (PPPs), energy, and sustainability.

Five scientometric techniques would be adopted in this study. (1) Co-Author analysis: This includes co-occurrences of authors, countries/regions and faculties/institutions in the indexed corpus of journal articles. (2) Co-Word analysis: This identifies co-occurring keywords or terms and co-occurring Web of Science (WoS) subject. (3) Co-Citation analysis: This analysis includes co-cited authors, co-cited articles/documents, and co-cited journals. (4) Clusters analysis: This includes burst detection analysis and silhouette metric analysis. (5) Geospatial analysis: Geospatial network visualization (animated maps) of journal articles and authors' origin and generation of Keyhole Markup Language (KML) files for use in using Google Earths.

The above five (5) scientometric analysis and its visualization could be performed using a software package "CiteSpace" developed by Chaomei Chen. CiteSpace version 5.0.R7 (32bit) was used to analyze the indexed corpus articles because per Chen (2016), CiteSpace is very useful in mapping knowledge domains and aiding its illustration with graphical maps. More information on how to utilize the software "CiteSpace" for scientometric reviews of a research field are available in the literature (*see* Chen, 2016, 2014, 2005a; Chen and Morris, 2003). Figure 2.1 depicts the study's research design.

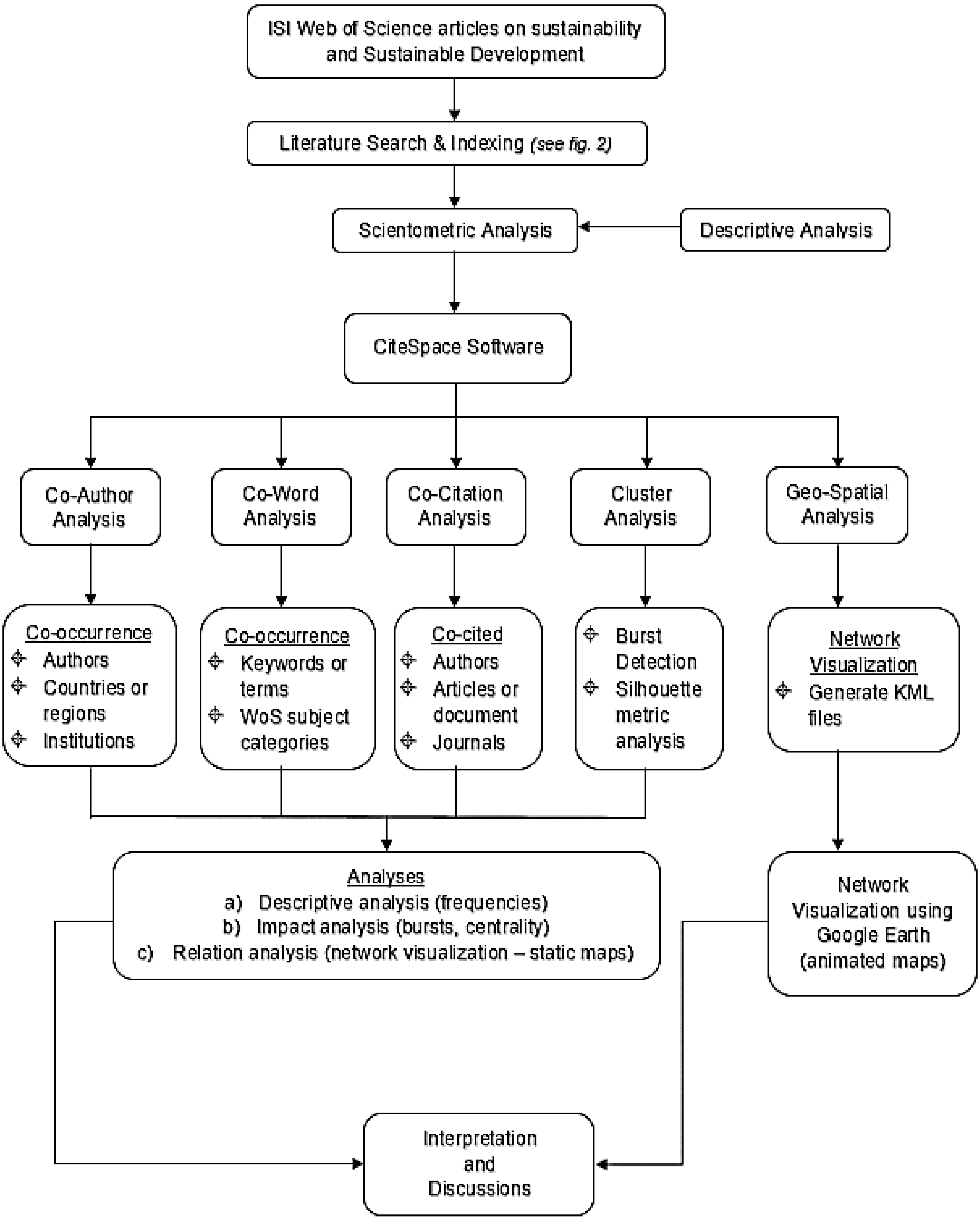

Figure 2.1: Outline of Research Design

2.3.1 Literature search strategy and Research data

One of the decisions to make in undertaking an analysis of a knowledge domain such as in this study is for the researcher(s) to identify scientific databases to use. The three primary scientific databases are Scopus, ISI Web of Science and Google Scholar, Olawumi et al. (2017) provided a comparative assessment of strength and weakness of these three databases. Similarly, several core journals publishing houses have their databases such as those of Elsevier- Science Direct, ASCE Library, Emerald, Wiley Online Library, ProQuest, EBSCO, Taylor & Francis, Springer Link, IEEE Explore among several others available for journal search and retrieval (JSR). Nevertheless, based on the submission of previous authors (Marsilio et al., 2011; Neto et al., 2016; Olawumi et al., 2017; Zhao, 2017); Web of Science core collection database was adopted for this study's JSR. It is because WoS is regarded as the most comprehensive and it also contains the most relevant and influential journals in its record combined with WoS scientific robustness.

A comprehensive literature search, retrieval, and indexing were carried out on WoS core collection using the search string- "*sustainability* and sustainable development**" as seen in Figure 2.2. A fuzzy search is denoted with a "*" and the selected time-span ranges from 1991 – 2016 (26 years).The search results were refined to include only journal articles and articles written in the English language because published journal articles would have undergone a thorough peer review process and most authors do republish their conference papers and thesis in scholarly journals afterward (Olawumi et al., 2017). Journal articles are regarded as more reputable sources and also classified as "certified knowledge" (Ramos-Rodríguez & Ruíz-Navarro, 2004) and are more comprehensive than other sources (Ke et al., 2009; Yi & Chan, 2013; Zheng et al., 2016). CiteSpace meanwhile uses several databases as its source of data such as WoS, Scopus, PubMed among others but do convert such data from other sources to WoS format before processing the data. Hence, Chen (2016) advise the use of WoS database for use in JSR to prevent loss of data during the conversion process and reduce the processing time.

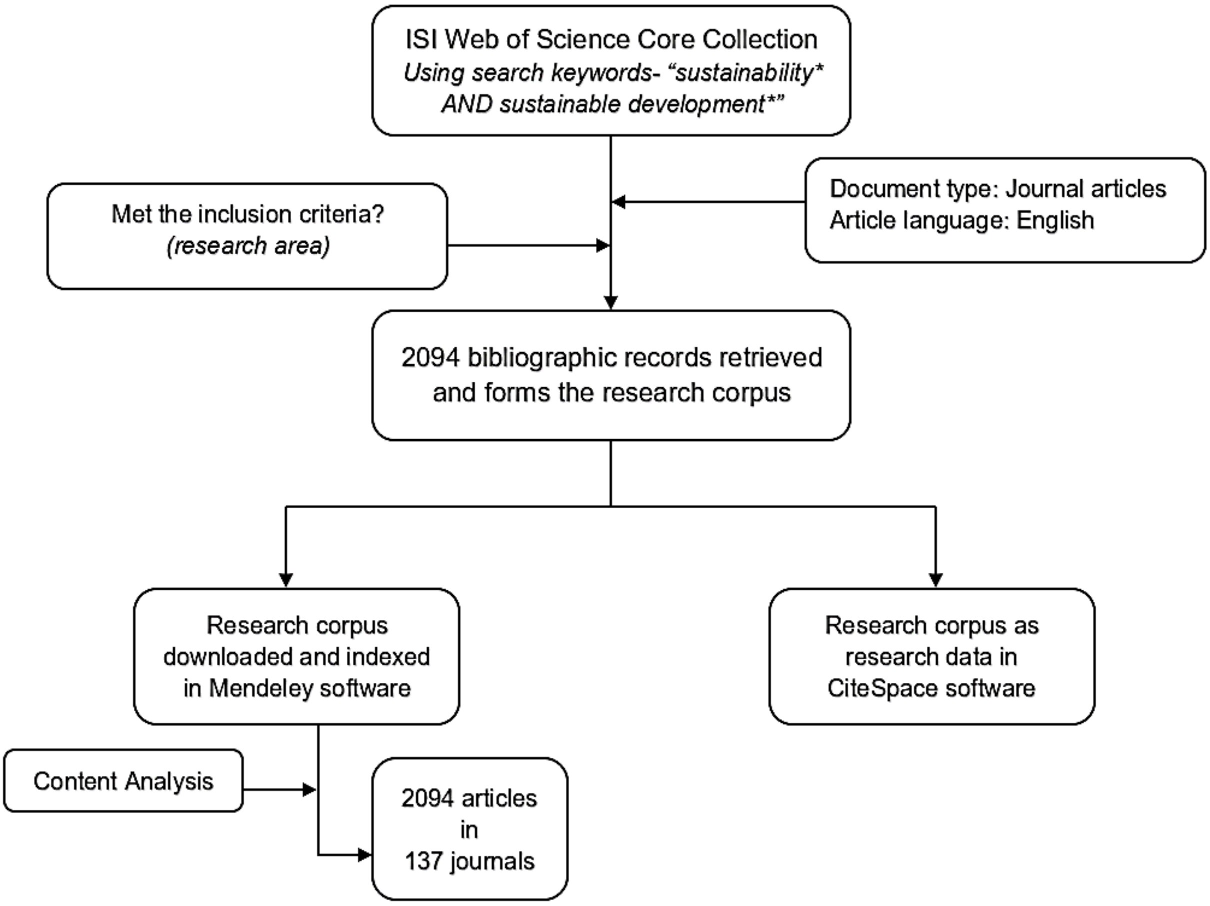

Figure 2.2: Literature search and indexing strategy

Moreover, sustainability research areas which are not relevant to the built environment were excluded from the search results. Mainly research areas such as "Environmental Science Ecology" "Engineering," and "Construction Building Technology" were retained. A total of 2094 bibliographic records were collected in September 2017, and the articles were then downloaded and indexed into Mendeley reference manager. Also, the CiteSpace software was installed, and the WoS records captured, saved in WoS "Marked List" and downloaded and inputted as research data for use as explained in the CiteSpace manual (Chen, 2014). The first paper on sustainability was in 1991 which focused on developing legislation and standards to control wood processing in Australia (Gifford & McFarlane, 1991) which has two citations so far and focused on the environmental aspect of sustainability. Figure 2.3 shows the distribution of the 2094 bibliographic records from the year 1991 to 2016.

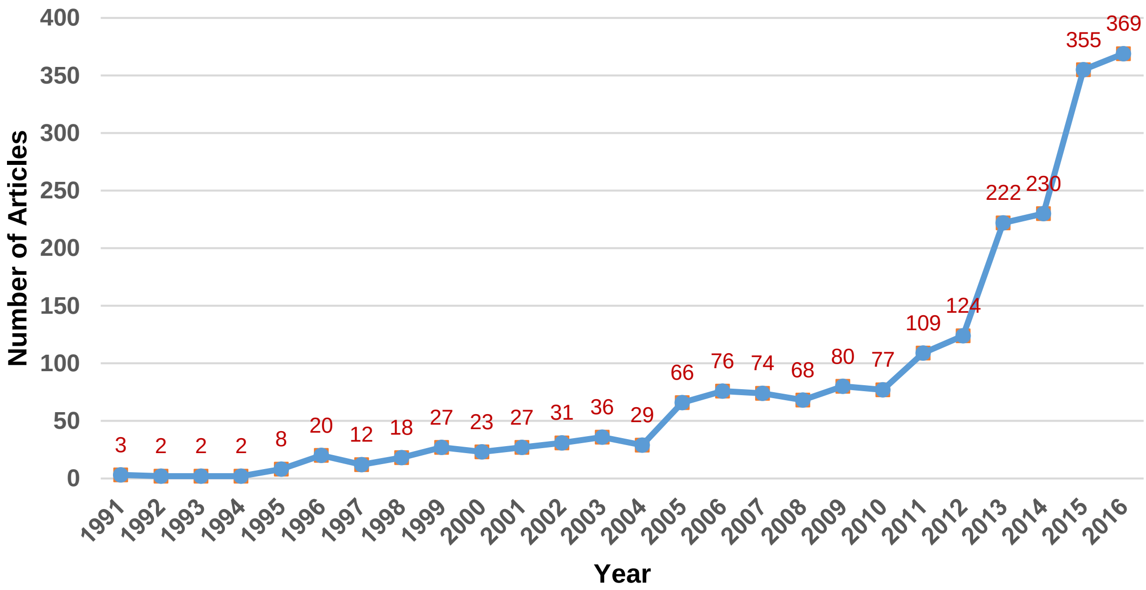

Figure 2.3: Distribution of the indexed research corpus from 1991 – 2016

The number of articles on sustainability increased significantly between 2011- 2016 and it crossed the 100 articles per year threshold in the year 2011 and subsequently crossed the 200 articles and 300 articles per year thresholds in 2013 and 2015 (2-year intervals).

2.4 Scientometric Analysis, Results and Discussion

This section discusses the facets and results of this study’s scientometric analysis as described in the research design (Figure 2.1). The following sections entail the co-author analysis, co-word analysis, co-citation analysis, clusters analysis and geospatial analysis. Since the study is examining a lengthy period of research (1991 – 2016), time slicing was employed. According to Chen (2005b), time slicing is a “divide-and-conquer strategy that divides a period into a series of smaller windows.” A 2-year per slice was used for co-author analysis, co-word analysis, co-citation analysis and clusters analysis while a 1-year per slice was used for the geospatial analysis.

The Pathfinder utility in CiteSpace was used to prune the network to remove redundant links through the process otherwise known as ‘network pruning.' Moreover, among the pruning utilities in CiteSpace, Pathfinder is regarded as the better choice (Chen, 2014) and details of its pros and cons are explained in Chen and Morris (2003).

2.4.1 Co-author analysis

Information available from the WoS records in this research field contains relevant details about the authors which are useful in establishing prolific authors, institutions or faculties and countries. Hence, such data can be extended to evaluate networks of co-authors, a network of countries or regions and those of institutions.

2.4.1.1 Co-Authorship Network

An analysis of the most productive authors (see Table 2.1) reveals Donald Huisingh (University of Tennessee, Knoxville), Rodrigo Lozano (University of Gävle) and Yong Geng (Shanghai Jiao Tong University) as the three researchers with most publications in the field.

Table 2.1: Top 13 most productive authors with their h-index

Authors	Institution	Country	Counts	h-index
Donald Huisingh	University of Tennessee, Knoxville	USA	25	29*
Rodrigo Lozano	University of Gävle	Sweden	16	29
Yong Geng	Shanghai Jiao Tong University	China	10	49
Per Angelstam	Swedish University of Agricultural Sciences	Sweden	7	54
Roland Scholz	Swiss Federal Institute of Technology, Zurich	Switzerland	7	53
Adisa Azapagic	University of Manchester	UK	7	42
James Mihelcic	University of South Florida	USA	7	37
Sekar Vinodh	National Institute Technology Tiruchirappalli	India	7	26
Xiaoling Zhang	City University of Hong Kong	Hong Kong SAR	7	22
Tomas Ramos	Universidade Nova de Lisboa, Lisbon	Portugal	7	21
Marine Elbakidze	Swedish University of Agricultural Sciences	Sweden	7	20
Robert Axelsson	Swedish University of Agricultural Sciences	Sweden	7	19*
Rebeka Lukman	University of Maribor	Slovenia	7	10*

Note: * - the h-index of the authors are based on ResearchGate.net calculation while the other authors h-index are based on Google Scholar.

A co-authorship network was generated as shown in Figure 2.4 identify the network of authors represented by nodes and links. Each representative node represents each author while each link represents the pattern of collaboration established in the publications (Zhao, 2017). The network was pruned as before described resulting in 144 nodes and 99 links in the co-authorship network. The node size corresponds to the number of publications by each author while the thickness of the links represents the strengths of ‘cooperative relationships’ among the author. The co-authorship network has a Modularity, Q= 0.942 and a mean Silhouette, S= 0.470. The modularity (Q) and the mean silhouette values (S) reveals the “overall structural properties” of the network, that is a very high Q value (say Q>0.70) denotes loosely assembled clusters while the S-metric measures the homogeneity of the clusters (Chen, 2014). Hence, the dispersed nature of the clusters of authors within the network as seen in Figure 2.4.

Meanwhile, the color of the links (e.g., blue, green, yellow and red) corresponds to the color encoding of the different time span in a 2-year slice as seen above the co-authorship networks. Moreover, regarding collaborative relationships and workings in the field, the network established several research communities constituted by central authors of the research community and other authors in the community. Three main research communities with robust collaboration among the authors include the highly productive research circuit of Donald Huisingh and Rodrigo Lozano as the central authors and other researchers such as Maik Adomssent, Liyin Shen, Jana Dlouha, Gyula Zilahy, and Kunhui Ye. Another research community with Yong Geng and Tsuyoshi Fujita as the central authors of the circuit including Huijuan Dong, Zhe Liu, Jingzheng Ren, and Liang Dong. Lastly, Robert Axelsson and Per Angelstam as the central authors of a research community which includes Kjell Andersson and Marine Elbakidze as authors within the circuit.

2.4.1.1.1 Citation bursts and centrality scores

The impact of the authors and collaboration was analyzed using the citation burst and betweenness centrality. The citation burst is based on Kleinberg’s algorithm (Kleinberg, 2002) and it measures the increase in citations within a short time span. Two authors have citation bursts, which are Donald Huisingh (burst strength= 3.43, 2013–2016) and John Cairns (burst strength= 3.42, 1991–2000). Also, the betweenness centrality which is based on Freeman's work (Freeman, 1977) is defined as the degree to which "a point [or node] falls on the shortest path between others and therefore has a potential for control of communication."

Centrality scores in CiteSpace are normalized in the unit interval between 0 and 1 (Chen, 2014), and a node of high centrality score is one that connects two or more large groups of nodes in the network with the node itself in-between and it is denoted by purple trims in the network. Such nodes with high betweenness centrality form the basis of separating clusters (Girvan & Newman, 2002) and helps to identify pivotal and salient scientific publications over time. In Figure 2.4, Donald Huisingh (centrality = 0.02), Rodrigo Lozano (centrality = 0.01), Xiaoling Zhang (centrality = 0.01), Kim Ceulemans (centrality = 0.01), Andrew Barton (centrality = 0.01) and Heloise Buckland (centrality = 0.01) are the nodes with purple trims and they serve as links between different authors and research communities. It is noteworthy that Donald Huisingh is also the most productive author in the field, with the strongest citation burst and more connections and collaborative relationships with several researchers in the field.

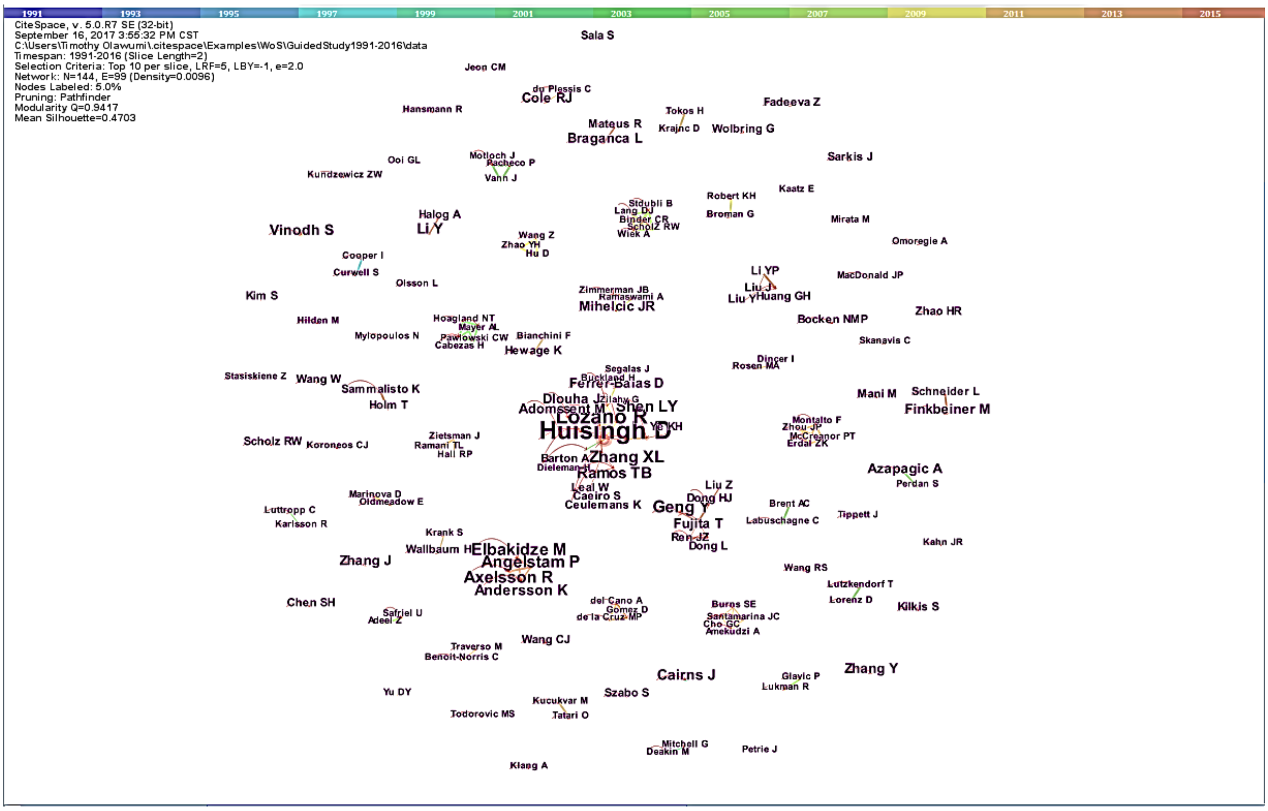

Figure 2.4: Co-authorship network

2.4.1.2 Network of institutions/faculties and countries/regions

This section explores the contribution of institutions and countries to the body of knowledge in the field. The network generated 49 nodes and 99 links with modularity, Q=0.466 and a mean Silhouette, S= 0.589. Since the Q-value of the network is below average, the nodes within the network are densely packed (see Figure 2.5). Eight (8) countries were identified in the network (Figure 2.5) with a greater contribution (*more than 100 articles*) to the research area of sustainability and SD. These include the USA (428 articles, 20.44%); China (275 articles, 13.13%); United Kingdom (258 articles, 12.32%); Canada (157 articles, 7.50%); Germany (132 articles, 6.30%); Netherlands (131 articles, 6.26%); Australia (128 articles, 6.11%), and Sweden (124 articles, 5.92%). These results revealed the advanced level of research and development in sustainability studies in these countries and with most of the counties being European countries. It is noteworthy that countries such as the USA, the origin of the world-renowned building rating system (LEED- Leadership in Energy and Environmental Design) have the most articles on sustainability field and several building energy simulation software and devices originated from the US. In the United Kingdom, we have another building rating system (BREEAM-Building Research Establishment Environmental Assessment Method) while in Australia, we have the Green STAR building rating system. In respect to collaborative research, authors from countries such as the USA, China, the UK, Canada, Sweden, South Korea, Netherlands, Australia, Switzerland have strong international collaborations.

Furthermore, in terms of institutions and faculties research outputs. The research on sustainability has progressed significantly in several universities among which are Chinese Academy of Sciences, China PR (67 articles), Delft University of Technology, Netherlands (37 articles), University of British Columbia, Canada (30 articles) Wageningen University Research, Netherlands (28 articles). The University of Tennessee Knoxville and the University of Tennessee System, both in the USA (25 articles each); ETH Zurich, Switzerland and Lund University, Sweden (24 articles); the United States Environmental Protection Agency, USA and the University of Leeds, United Kingdom (23 articles). Also, we have the Hong Kong Polytechnic University, Hong Kong SAR and the State University System of Florida, USA (22 articles) and the University of California, USA (20 articles). These institutions are unique in their outputs of research in the field of sustainability.

2.4.1.2.1 Citation bursts and centrality scores

Moreover, significant citation bursts were identified in some countries as shown in Table 2.2. While for institutions, we have Chinese Academy of Science (burst strength= 5.40, 2009–2010), University of British Columbia (burst strength= 4.66, 1999–2006) and Lund University (burst strength= 4.37, 2005–2006). It is evidently clear from the citation burst analysis that there was no citation burst between 2015–2016 for both countries and institutions; which is consistent to the fact that sustainability studies have garnered worldwide attention and consideration in recent years; one of which culminated in the signing of the Paris climate change which was signed by 166 countries. Hence, it would be difficult for a country or institutions to receive high citations in that period.

Table 2.2: Countries' citation burst

Countries	**Burst strength**	**Span**
Japan	9.66	2011 – 2014
Brazil	8.16	2009 – 2014
Switzerland	5.71	1999 – 2012
Greece	5.15	2003 – 2008
United Kingdom	5.03	1991 – 2002
South Africa	4.66	1999 – 2006
Spain	4.30	2009 – 2010
Malaysia	4.13	2011 – 2012
Sweden	4.03	2005 – 2006
Denmark	3.44	1997 – 2008

More so, in terms of high between centrality as identified by purple trims in the network (Figure 2.5). The network revealed countries such as United Kingdom (centrality = 0.54), Sweden (0.49), the USA (0.47), Netherlands (0.40), Canada (0.18), China (0.12), Germany (0.12) and France (0.10). For institutions, we have the Imperial College London (centrality = 0.08), University of Oxford (0.03), University of Salford (0.02) and Lund University (0.01) with strong connections and acting as key exchange platforms between the countries and institutions.

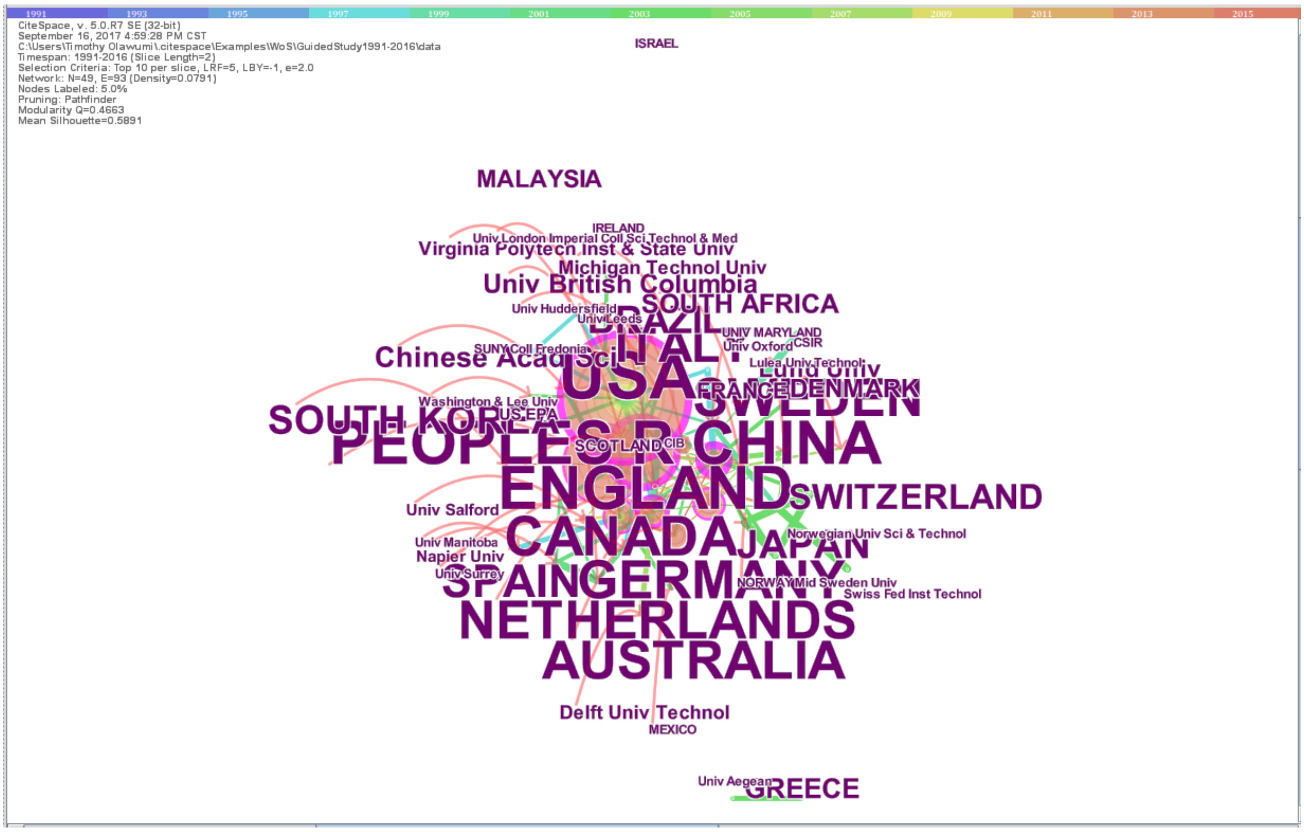

Figure 2.5: Network of Countries and Institutions

2.4.2 Co-word analysis

Several research topics and themes have merged and evolved in sustainability research over the decades which represents the trends and frontiers in the field. Data from the WoS bibliographic records are evaluated to develop the network of co-occurring keywords and subject categories in the sustainability field.

2.4.2.1 Network of co-occurring keywords

Keywords are descriptive and significant words and serve as a reference point in finding and understanding the concepts and contents of research articles. It also reveals the development of the research field over time (Zhao, 2017). Two kinds of keywords are obtainable from the WoS bibliographic records which are the (i) author keywords and the (ii) keywords plus. The former is provided by the authors in their articles while the other is based on the journal's classification of the research output. The two kinds are utilized in developing the network of co-occurring keywords in CiteSpace, and the software has a utility to merge similar keywords. A research network of co-occurring keywords as shown in Figure 2.6 with 71 nodes and 136 links. Also, the network has a modularity (Q = 0.523) and mean silhouette, S= 0.769. The node size for each keyword is a representative of the frequency of the keyword in the record.

Meanwhile, the co-word analysis reveals high-frequency keywords (Figure 2.6) in the dataset which are “sustainability” (frequency = 778), “sustainable development” (frequency = 472), “management” (frequency = 212), “system” (frequency = 193), “indicator” (frequency = 141), “framework” (frequency = 112). Other high-frequency keywords include “China” (frequency = 89), “model” (frequency = 89), “energy” (frequency = 88), “performance” (frequency = 84), “impact” (frequency = 82), “climate change” (frequency = 53), “environment” (frequency = 44) and “design” (frequency = 43).

3.2.1.1 Citation bursts and centrality scores

Fourteen (14) keywords were identified from the network with citation bursts as shown in Table 2.3.

Table 2.3: Keywords' citation bursts

Keywords	Burst strength	Span
Environment	14.15	2004 – 2012
Climate change	13.82	2009 – 2014
Design	13.01	2013 – 2014
City	11.82	2013 – 2014
Policy	10.34	2013 – 2014
Sustainable development	8.88	1999 – 2006
Impact	7.40	2013 – 2016
Construction	6.95	2005 – 2008
Sustainability indicator	5.40	2003 – 2006
Industrial ecology	5.34	1998 – 2008
Innovation	5.10	2007 – 2008
Energy	4.42	2009 – 2012
LCA	4.26	2003 – 2010
Sustainable building	3.81	2005 – 2006

All these keywords with citation bursts represent the salient topics and themes in sustainability studies and research. It is noteworthy that keywords such as “climate change,” “design,” “energy,” “sustainable development,” “sustainability indicator,” “environment” and “policy/framework” have both high frequencies and citation bursts. It is consistent with the fact that more efforts are devoted to these critical research themes which are pivotal in achieving a sustainable urban development.

Several keywords also have high betweenness centrality scores and these include: “sustainability” (centrality = 0.80), “sustainable development” (0.64), “indicator” (0.25), “system” (0.21), “China” (0.20), “management” (0.19), and “environment” (0.17). Other keyword with high betweenness centrality are “public policy” (0.16), “framework” (0.12), “research policy” (0.11), “natural capital” (0.08), “decision making” (0.08), “energy” (0.07), “city” (0.06) and “ecological footprint” (0.06). These keywords and themes have greatly influenced the development of the sustainability research field and help connect several research topics.

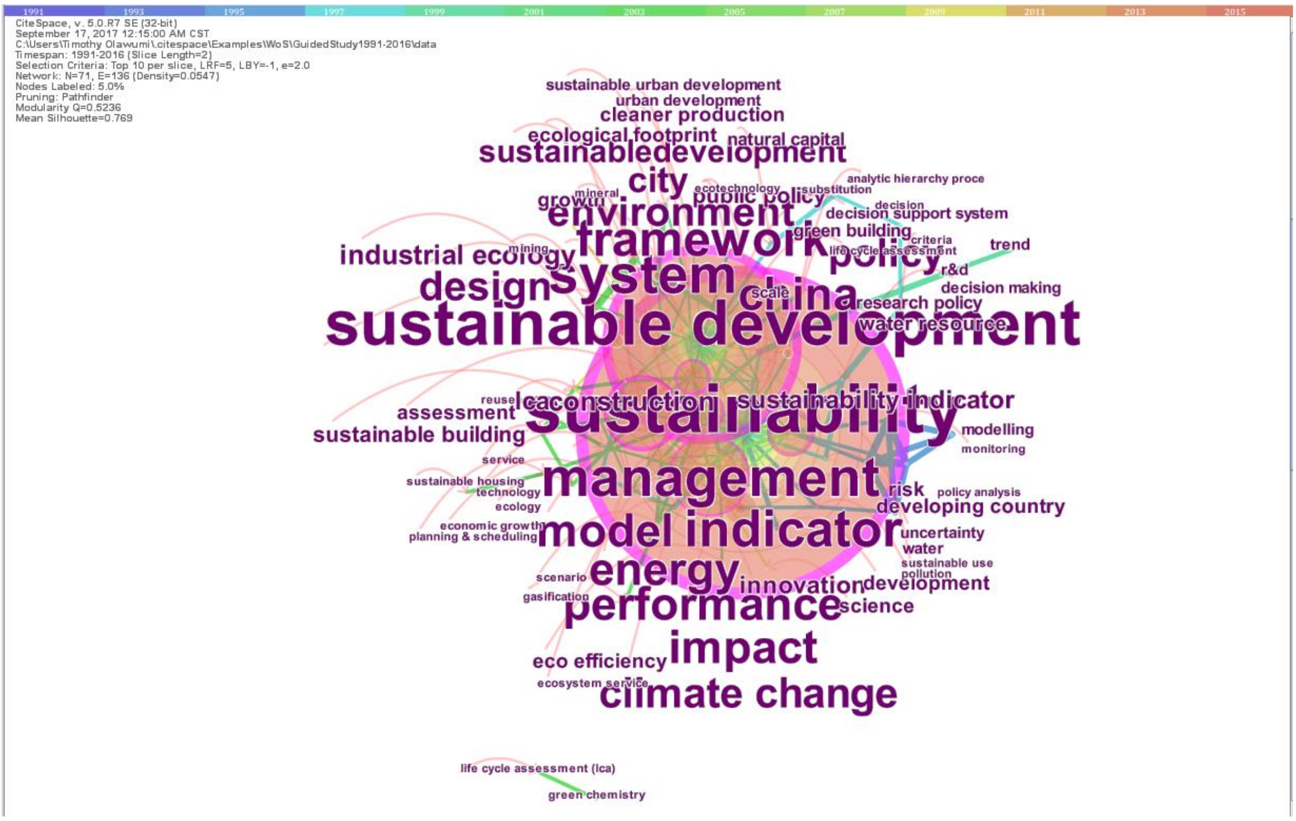

Figure 2.6: Network of co-occurring keywords

2.4.2.2 Network of co-occurring subject categories

The bibliographic records in WoS database are classified into subject categories depending on the scope of the corresponding journal, and an article could be assigned one or more subject categories. A network of co-occurring subject categories was developed as shown in Figure 2.7 with 22 nodes and 61 links. The modularity, Q = 0.467 and with a mean silhouette value, S = 0.534. The node size for each subject category is a representative of the number of articles classified within each category in the dataset. Eight (8) subject categories with 100 articles or more were identified: Environmental sciences (1327 articles); green & sustainable science technology (1294 articles), environmental engineering (925 articles); civil engineering (410 articles), environmental studies (376 articles); construction & building technology (254 articles), ecology (203 articles), and water resources (161 articles). A significant sustainability research articles have been published under these subject categories.

Meanwhile, a look at the generated network and the color of the links reveals increasing publications in the area such as urban studies, computer science and interdisciplinary applications, architecture, ergonomics, and transportation. A study by Kerebih and Keshari (2017) which employed GIS to develop a numerical model for groundwater flow is a good example of the application of computer-based technology in technology research. Other studies (Khan et al., 2017; Stuermer et al., 2017; Wang et al., 2017; Xia et al., 2017) integrated technology-based application for sustainability research. For urban studies, Kamal and Proma (2017) modeled a quantitative ranking system for sub-urban Texas using GIS while Boren et al. (2017) proposed a sustainable transport system and roadmap for southeast Sweden. Meanwhile, Zamani et al. (2012) advocated for green architecture to reduce environmental pollutions and Ruiz-Larrea et al. (2008) recommended that sustainable concepts (e.g., energy efficiency) be integrated into the design of structures as it would key to sustainable industrialization.

3.2.2.1 Citation bursts and centrality scores

Moreover, some subject categories received citation bursts: environmental studies (burst strength= 23.98, 2014–2016), water resources (burst strength= 20.80, 1993–2009), construction & building technology (burst strength= 11.93, 1998–2002), chemical engineering (burst strength= 9.61, 2000–2007) and civil engineering (burst strength= 5.16, 2000–2002). Other subject categories with citation bursts are transportation (burst strength= 4.80, 2001–2010), ecology (burst strength= 4.44, 2009–2010) and industrial engineering (burst strength= 3.41, 2005–2010). These categories represent the most active areas in the evolution of sustainability research.

Areas such environmental sustainability have received significant citations in recent years (2014-2016), and this aligns with the findings of Olawumi et al. (2017).

Also, some subject categories nodes received high betweenness centrality score as indicated by purple trims in the network (Figure 2.7) and these include engineering (centrality = 0.77), civil engineering (0.63), environmental science & ecology (0.46), environmental sciences (0.26), environmental engineering (0.23), computer science (0.22), and construction & building technology (0.18). They connect the distinct aspects and concepts in the research field and are pivotal in the development of the field.

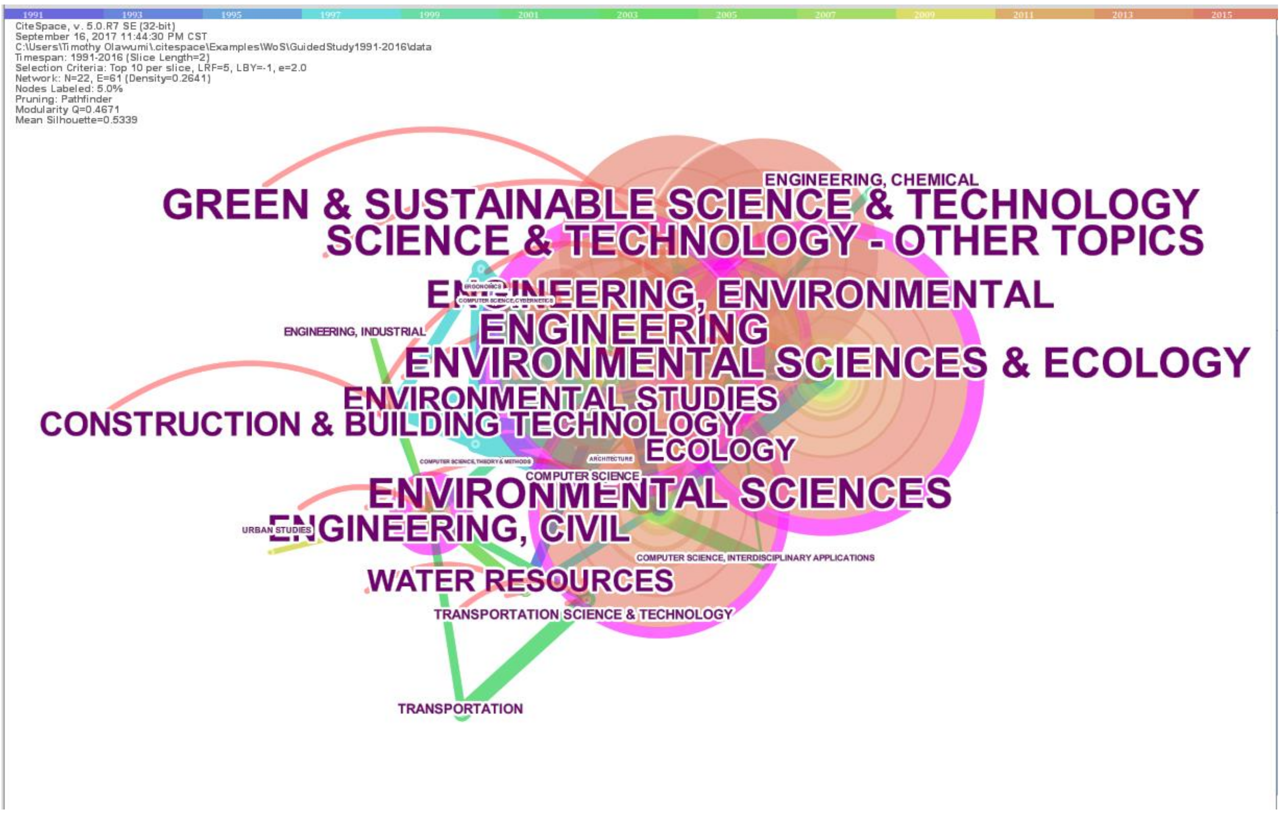

Figure 2.7: Network of co-occurring subject categories

2.4.3 Co-citation analysis

Co-citation is the number of instances in which two items, say in this case, authors, documents, or journals are cited by a journal article (Chen, 2005a; Small, 1973) and described by Zhao (2017) as a “proximity measure” for the items. Indexed bibliographic records from WoS database are analyzed to produce the journal co-citation network, author co-citation network, and the document co-citation network.

2.4.3.1 Journal co-citation network

The 2094 WoS bibliographic records used for this study are sourced from a hundred and thirty-eight (138) journals; with thirty-seven (37) journals having at least ten (10) records in the research corpus. The structure of the published research corpus on sustainability studies is consistent with the Pareto principle in that 1764 articles (84 percent) are published in 28 journals (20 percent) which relate to an 84/20 rule for this study's research corpus. Table 2.4 shows the top 20 source journals for sustainability research along with their impact factors (IF). Meanwhile, the publishers in the USA and Netherlands account for six (6) and (5) journals of the top 20 source journals.

The references cited by each of the 2094 indexed research corpora were analyzed and was used to generate a network of co-cited journals with 69 nodes and 133 links to identify the most significant cited journal as shown in Figure 2.8. The network has a modularity (Q = 0.53) and mean silhouette, S= 0.80. The node size is a representative of the co-citation frequency of each journal within the dataset. Moreover, the co-citation frequency of the top five most co-cited journals as revealed within the network are Journal of Cleaner Production (frequency = 722); Ecological Economics (frequency = 482), Journal of Environmental Management (frequency = 312); Science (frequency = 300), and Energy Policy (frequency = 278). These journals have made significant contributions to sustainability studies, and hence they are more cited by researchers in the field.

Table 2.4: Top 20 source journals in the research corpus

Source Journal	Host Country	Impact Factor (IF)	Publisher	Count	Percentage
Journal of Cleaner Production	USA	5.715	Elsevier Sci Ltd	496	23.69
Sustainability	Switzerland	1.789	MDPI AG	371	17.72
International Journal of Sustainable Development and World Ecology	USA	1.864	Taylor & Francis Inc	176	8.40
Sustainability Science	Japan	3.429	Springer Japan KK	56	2.67
Ambio	Sweden	3.687	Springer	52	2.48
Water Science and Technology	United Kingdom	1.197	IWA Publishing	46	2.20
International Journal of Life Cycle Assessment	Germany	3.173	Springer Heidelberg	46	2.20
Resources Conservation and Recycling	Netherlands	3.313	Elsevier Science BV	41	1.96
Proceedings of The Institution of Civil Engineers Engineering Sustainability	United Kingdom	0.341	ICE Publishing	40	1.91
Clean Technologies and Environmental Policy	USA	3.331	Springer	32	1.53
Building and Environment	United Kingdom	4.053	Pergamon-Elsevier Science Ltd	29	1.38
Water Resources Management	Netherlands	2.848	Springer	27	1.29
Ecological Engineering	Netherlands	2.914	Elsevier Science BV	27	1.29
Journal of Industrial Ecology	USA	4.123	Wiley-Blackwell	25	1.19
Sustainable Cities and Society	Netherlands	1.777	Elsevier Science BV	24	1.15
Environment Development and Sustainability	Netherlands	1.080	Springer	24	1.15
Energy and Buildings	Switzerland	4.067	Elsevier Science SA	24	1.15
Transportation Research Record	USA	0.598	Natl Acad Sciences	21	1.00
Current Opinion in Environmental Sustainability	United Kingdom	3.954	Elsevier Sci LTD	21	1.00
Water International	USA	1.538	Routledge Journals, Taylor & Francis LTD	20	0.96

Note: Impact Factor (IF) as at the year 2016.

2.4.3.1.1 *Citation bursts and centrality scores*

Twenty-four (24) cited journals received citation bursts, out of which 11 journals received citation bursts of 10.0 and above as shown in Table 2.5.

Table 2.5: Journals' citation bursts

Journals	Burst strength	Span
World Commission on Environment and Development [WCED]	47.71	1996 – 2009
International Journal of Sustainable Development & World Ecology	37.63	1997 – 2010
Building and Environment	24.59	2007 – 2012
Environmental Science & Technology	23.50	2011 – 2014
Proceedings of the National Academy of Sciences	23.19	2013 – 2014
Environmental Impact Assessment Review	21.34	2009 – 2012
Journal of Industrial Ecology	19.08	2013 – 2014
Nature	18.23	2011 – 2014
Journal of Environmental Management	17.55	1993 – 2008
Landscape and Urban Planning	14.34	2011 – 2012
Sustainable Development	11.11	2013 – 2016

The highlighted journals with citation bursts imply articles in these journals have received strong citations within the specified ‘short’ time span. Hence they are recommended together with the top 20 source journals for researchers in the field to follow.

Some nodes received high betweenness centrality scores as identified by purple trims in the network (Figure 2.8). The network revealed source journals such as Ecological Economics (centrality = 0.80), Our Common Future (0.49), International Journal of Sustainable Development and World Ecology (0.32), Environmental Management (0.30), Water Science & Technology (0.26), Nature (0.24), Science(0.23), Energy Policy (0.20), Journal of Cleaner Production (0.13), Ambio (0.13) and Environmental Impact Assessment Review (0.12). These journals serve as links between distinct journals and acts as key intellectual hubs for academics, practitioners and government bodies.

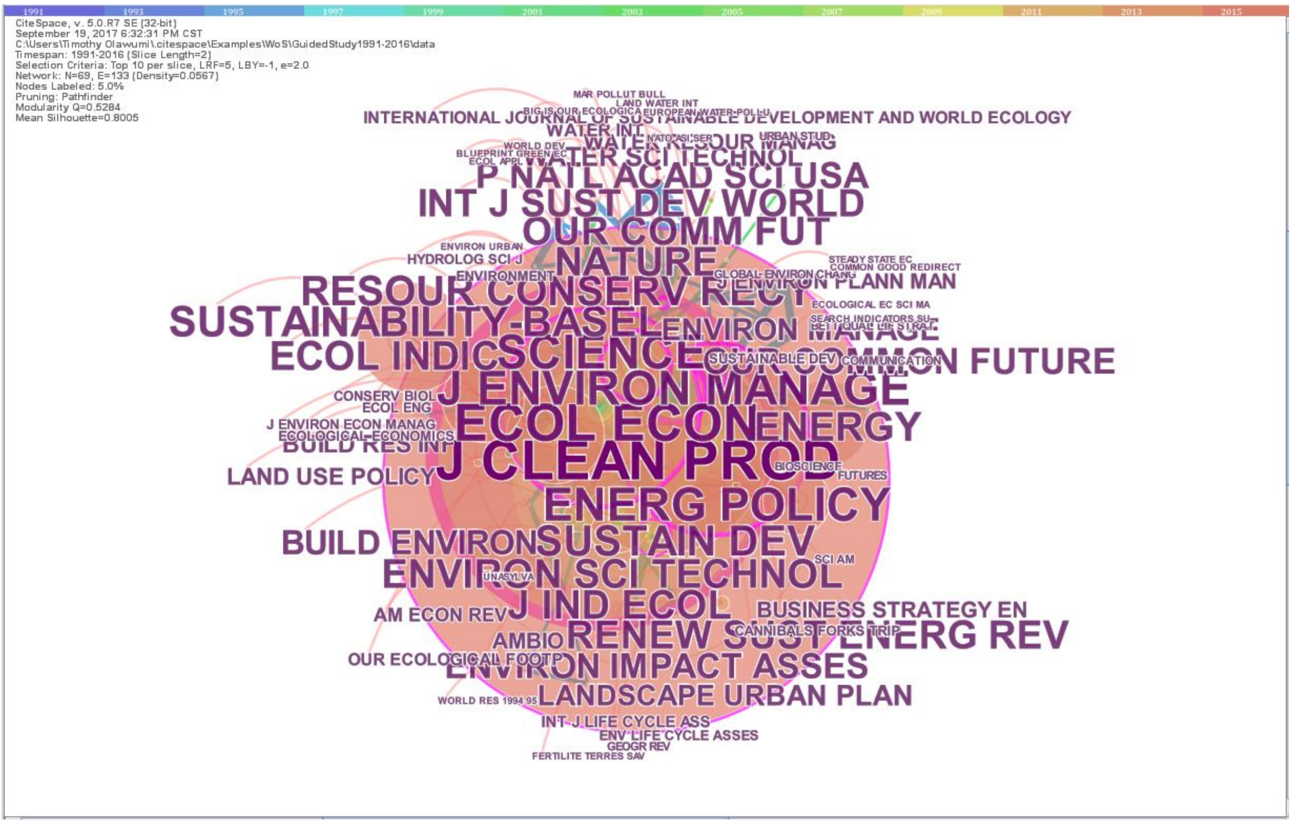

Figure 2.8: Journal co-citation network

2.4.3.2 Author co-citation network

The author co-citation analysis draws a pattern of relationships among distinct authors whose work appeared as cited references in the same publication. The dataset from the WoS records was used in generating the author co-citation network as shown in Figure 2.9 with 98 nodes and 271 links. Also, the network has a modularity (Q = 0.529) and mean silhouette, S= 0.781. The node size is a representative of the co-citation frequency of each author within the dataset, and the links indicate an indirect cooperative alliance of the authors based on their co-citation frequency.

The ten (10) most cited authors were identified from the network, and it is noteworthy that five (5) of the ten most cited authors are international and regional governmental organizations, this finding is a great plus to the global drive for sustainable urban development. These authors include (<u>note</u>: * *headquarter of organization*): United

Nations (frequency = 230, USA*), World Commission on Environment and Development [WCED] (frequency = 209, USA*), World Bank (frequency = 129, USA*), Rodrigo Lozano (frequency = 126, Sweden), Organization for Economic Co-operation and Development [OECD] (frequency = 110, France*), European Commission (frequency = 87, Belgium*), John Elkington (frequency = 54, Australia), Thomas Saaty (frequency = 50, USA), Donella Meadows (frequency = 44, USA) and Robert Yin (frequency = 41, USA). Also, there is affiliation-based diversity among the authors, which lends further credence to the evolution of sustainability research field. One of the authors in the person of Rodrigo Lozano also appeared among the top productive author in the field (Table 2.1) and based on WoS records his article on "*Envisioning sustainability three-dimensionally*" (Lozano, 2008) has received 117 citations as at the end of 2016.

2.4.3.2.1 Citation bursts and centrality scores

Authors with citation bursts with an increase in their articles' citations within a brief period were identified from the networks. These authors include: WCED (burst strength= 29.67, 1996–2012), European Commission (burst strength= 13.24, 2004–2018), IPCC (burst strength= 12.85, 2011–2014), UNESCO (burst strength= 12.26, 2013–2014), and Mathis Wackernagel (burst strength= 11.49, 1996–2010), Johan Rockstrom (burst strength= 11.30, 2013–2014). Other authors with citation bursts are Karl-Henrik Robert (burst strength= 11.24, 1998–2008), World Bank (burst strength= 9.77, 2004–2012), David Pearce (burst strength= 9.53, 1993–2000) and Donella Meadows (burst strength= 8.85, 2013–2014). Articles, documents, and communique issued by these authors are worth following, and their works have influenced the development of sustainability research and the idea of the sustainable urban city.

Moreover, some nodes with high betweenness centrality were identified from the network (Figure 2.9) as indicated by purple trims. Authors with high betweenness centrality scores are Mathis Wackernagel (centrality = 0.46), WCED (0.22), OECD (0.19), Rodrigo Lozano (0.17), Donella Meadows (0.15), and World Bank (0.15). Other authors with high centrality scores are Gordon Mitchell (centrality = 0.13), Robert Costanza (0.12), Joel Heinen (0.12), European Commission (0.12) and Karl-Henrik Robert (0.11). These authors are the influential and pivotal contributions to sustainability research and help connect the different research communities. Zhao (2017) noted that it is an unlikely occurrence for an author to receive a high betweenness centrality score and have high citation count and that in cases of such rare instances then such author(s) have made significant impacts in such field.

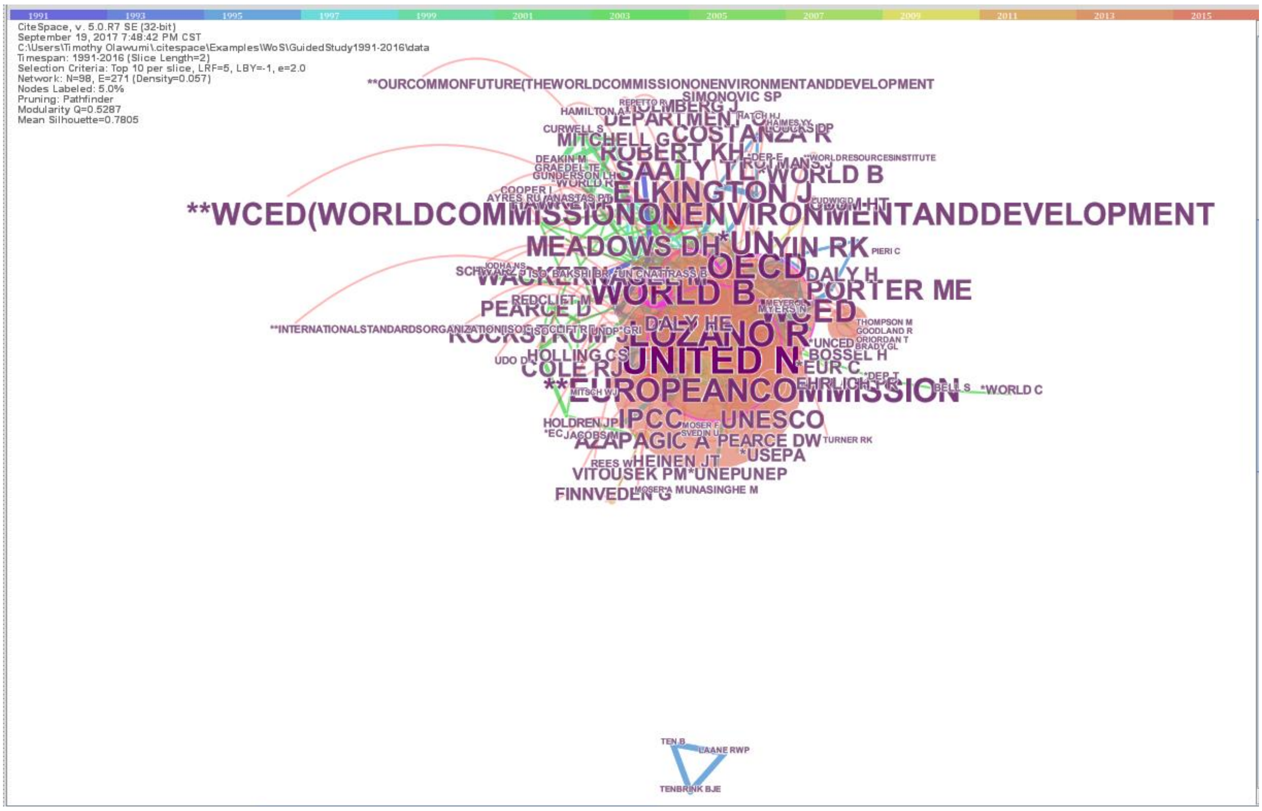

Figure 2.9: Author co-citation network

2.4.3.3 Document co-citation network

Document co-citation analysis evaluates the references cited by the 2094 bibliographic records towards understanding the intellectual structures of sustainability knowledge domain. Citation records from the WoS records reveal that 35 cited documents received a hundred or more citations as at the end of 2016 as shown in Table 2.6. Also, 13 articles (37 percent) of the top 35 top cited articles were published in the *Journal of Cleaner Production* which was also the source journal with most publication on sustainability topics. Mohanty et al. (2002) who received the highest citations count of 770 citations examined the challenges and opportunities in using natural fibers or its polymers which are based on renewable materials to resolve environmental issues in the industry. The article also advocated production of materials and products from a mix of both renewable and nonrenewable sources and continuous research in that direction.

Moreover, Nicol and Humphreys (2002) investigated the theoretical concept of thermal comfort in buildings and recommended several parameters such as the best comfort temperature, indoor temperature and the advocated the need for the development of sustainability criteria for adaptive thermal comfort in facilities. Meanwhile, Kennedy et al. (2007) carried out a comparative analysis of the urban metabolism of eight cities across five continents and discovered an increased metabolism with respect to water, solid waste, energy and air pollutants flow which threatens the sustainability of these cities. They advocated for the development of strategies to reduce its impact on the ecosystem.

Table 2.6: Top 35 cited articles based on WoS citation metric

S/N	Article	Total citations	S/N	Article	Total citations	S/N	Article	Total citations
1	Mohanty et al. (2002)	770	13	Luttropp and Lagerstedt (2006)	168	25	Liu et al. (2008)	116
2	Nicol and Humphreys (2002)	358	14	Sophocleous (2000)	167	26	Troschinetz and Mihelcic (2009)	110
3	Kennedy et al. (2007)	311	15	Glavic and Lukman (2007)	163	27	Baddoo (2008)	109
4	Ortiz et al. (2009)	271	16	Fiksel (2003)	162	28	Krotscheck and Narodoslawsky (1996)	107
5	Azapagic (2004)	233	17	Lozano (2006)	140	29	Jeon and Amekudzi (2005)	106
6	Robert et al. (2002)	226	18	Schneider et al. (2010)	135	30	Cole (1999)	106
7	Folke et al. (1997)	215	19	Krajnc and Glavic (2005)	131	31	Kloepffer (2008)	104
8	Tukker and Tischner (2006)	212	20	Mitchell et al. (1995)	125	32	Corinaldesi and Moriconi (2009)	103
9	Damtoft et al. (2008)	208	21	Brown et al. (2009)	122	33	Makropoulos et al. (2008)	102
10	Labuschagne et al. (2005)	196	22	Adger et al. (2002)	120	34	Lozano and Huisingh (2011)	100
11	Cucek et al. (2012)	174	23	Dovi et al. (2009)	118	35	Shrestha et al. (1996)	100
12	Maxwell and van der Vorst (2003)	173	24	Lozano (2008)	117			

A document co-citation network (see Figure 2.10) was generated from the WoS dataset which resulted in 176 nodes, and 549 links and each node represented a cited document and labeled with the name of the first author and the year of publication, while the link signifies the co-citation relationship between two articles.

Also, the network has a modularity (Q = 0.741) and mean silhouette, S= 0.538. The node size for each document is a representative of the co-citation frequency of the node article. The node documents in this network (Figure 2.10) are in the distinct set of 74,998 articles cited by the 2094 bibliographic records in this study and may not constitute part of the indexed corpus. The top six (6) co-cited documents with more 30 or more co-citation counts are: WCED (1987) (frequency = 178), Rockström et al. (2009) (frequency = 45), Lozano (2006) (frequency = 39), Gardiner (1995) (frequency = 38), Lozano (2010) (frequency = 30), and Seuring and Müller (2008) (frequency = 30).

2.4.3.3.1 Citation bursts and centrality scores

Several documents (19 articles) received citation bursts, of which the top 10 articles with citation bursts were identified and include: Gardiner (1995) (burst strength= 11.12, 2013–2016), Rockström et al. (2009) (burst strength= 10.65, 2011–2012), Robert et al. (2002) (burst strength= 10.07, 2005–2012), Lozano (2010) (burst strength= 9.56, 2013–2016) and Seuring and Müller (2008) (burst strength= 9.56, 2013–2016). Articles such as Lozano (2006) (burst strength= 9.34, 2013–2016), WCED (1987) (burst strength= 9.34, 2005–2012), Robèrt (2000) (burst strength= 6.22, 2005–2011), Barth et al. (2007) (burst strength= 5.70, 2013–2014), and Cortese (2003) (burst strength= 5.49, 2009–2014) received increased citations over a short period. Lozano (2010) research focused on integrating SD studies in curricula of universities and schools and used Cardiff University as a case study, and the findings revealed a more balanced and holistic course delivery. Also, Lozano (2006) presents challenges that could be faced by institutions who decide on integrating SD concepts in their curriculum and highlight ways of resolving such issues.

Meanwhile, some documents also have high betweenness centrality scores as denoted by purple trims in the network (Figure 2.10) and these include: WCED (1987) (centrality = 0.70), Elkington (1997) (0.45), Wackernagel et al. (1999) (0.35), Mitchell (1996) (0.28), Meadows et al. (1972) (0.19) and Mitchell et al. (1995) (0.17). These documents are the fundamental bedrock of sustainability research and form the base of most sustainability themes.

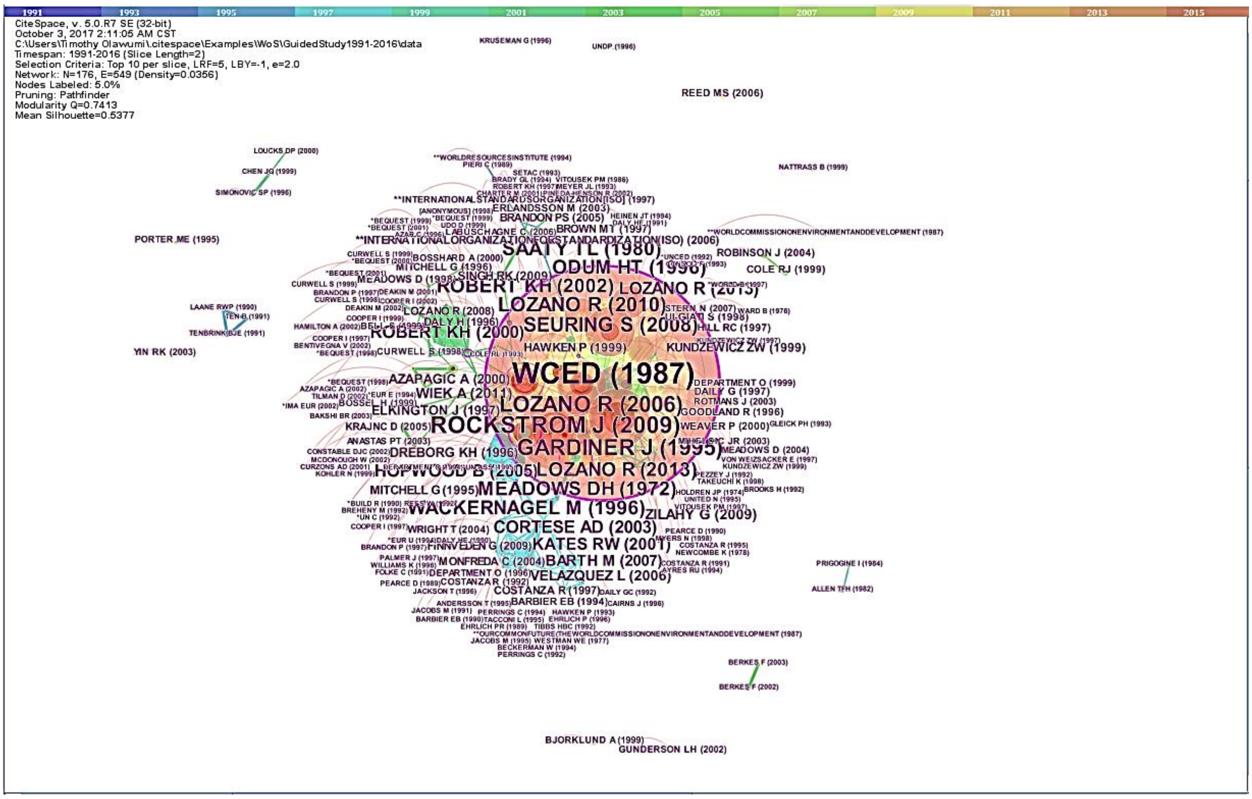

Figure 2.10: Document co-citation network

2.4.4 Clusters analysis

Cluster analysis is an exploratory data mining technique used in this study to identify and analyze the salient terms and context, its trends and their interconnection within the sustainability research field. CiteSpace was used as the tool to get insight into the distribution and structures of the research themes over the years. These terms, themes or context are of distinct classification, and the Log-Likelihood ratio (LLR) was used as the clustering technique due to its ability to generate high-quality clusters with high intra-class similarity and low inter-class similarity. Hence, keywords or terms grouped within a group must be related to one another and different from keywords in other categories. Therefore, cluster analysis facilitates the classification of a large corpus of research data into manageable units and helps to deduce information about each group or cluster objectively.

Clusters defined in this study are in two parts: (i) keyword clusters- which are based on the classification of the author keywords and the keywords plus (journal's indexed terms); and (ii) document co-citation clusters – which are based on keywords in cited references or documents.

2.4.4.1 Keywords clusters

Nine salient keyword clusters were identified in the clustering of the indexed corpus keywords as defined by the LLR algorithm. The keyword clusters as shown in Table 2.7 are labeled and sorted by size; the cluster size is the number of members in each cluster. Hence, cluster #0 "sustainable development" and #1 "sustainable indicator" with 12 members each are the cluster IDs with the largest group size and cluster #8 "green chemistry" been the smallest sized cluster with two (2) members. Majority of the relationships (as depicted by green links) in clusters #0, #1, #2 and #4 are formed between 2003 – 2006 while some links in clusters #1 and #2 are formed between 2015-2016. The relationships between clusters #3 and #5 (depicted by blue links) are mostly developed in the early days of sustainability research (1993 – 1996). It is evident from the keyword cluster network (Figure 2.11) that recent development in sustainability research has centered around clusters #1 and #2, as shown by the orange and red links.

Table 2.7: Keyword clustering of Sustainability research (1991 - 2016)

Cluster ID	Size	Silhouette	Cluster label (LLR)	Alternative label	Mean year
#0	12	0.588	Sustainable development	LCA; economic growth	2000
#1	12	0.749	Sustainability indicator	Framework; analytic hierarchy process	2003
#2	11	0.569	Public policy	Research policy; R & D	2002
#3	10	0.617	Impact	Performance; pollution	1998
#4	9	0.860	China	Water resource; ecological footprint	2002
#5	6	0.933	Indicator	Monitoring; sustainable use	1995
#6	5	0.832	Management	Perspective; strategy	2005
#7	4	0.774	Natural capital	Decision; cost benefit	1995
#8	2	1.000	Green chemistry	Metrics; hydrocarbon	2003

The silhouette scores for the clusters ranges from 0.558 to 1.000 which shows the members of the cluster falls well within their group. The silhouette metric according to Rousseeuw (1987) measures and compares the average homogeneity (tightness and separation) of a cluster and could be used to validate a cluster. Meanwhile, the mean year depicts whether the cluster is formed by recent articles or old ones. Clusters #3, #5 and #7 are formed by relatively old articles than other clusters.

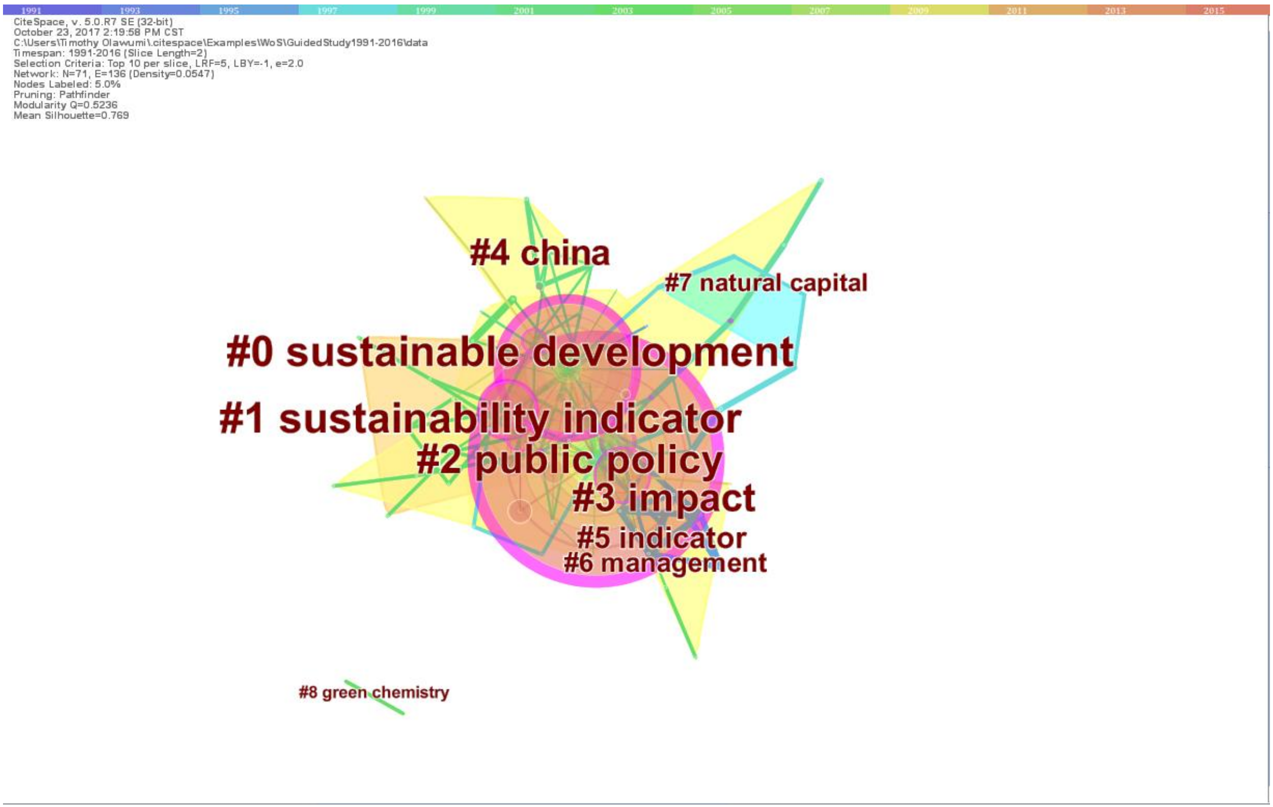

Figure 2.11: Keyword clusters network

2.4.4.2 Documents co-citation clusters

Twenty-one (21) document co-citation clusters were generated from the research power network using the LLR algorithm as shown in Figure 2.12. Meanwhile, only 12 clusters (see Table 2.8) are significant while the other nine (9) clusters have zero silhouette scores and just one (1) cluster member, hence are not counted as salient clusters in sustainability research. The 12 salient and significant clusters are sorted by size as shown in Table 2.8. Cluster #0 “water management” with 38 members is the largest cluster of proportion and while clusters #12 to #20 with just one member are the smallest clusters by size. Most of the relationships in the clusters as depicted by light blue and green links revealed that most of the relationships within the clusters are formed between 1994 and 2001; and this timespan forms the period in which the bedrock of the sustainability research field was laid.

Table 2.8: Documents co-citation clusters of Sustainability research (1991 - 2016)

Cluster ID	Size	Silhouette	Cluster label (LLR)	Alternative label	Mean year	Representative documents
#0	39	0.827	Water management	Flood protection; hydrological data	1994	WCED (1987)
#1	24	0.852	Higher education	University; campus sustainability	1999	Lozano (2006)
#2	21	0.758	Perspective	Sustainable consumption and production; systemic perspective	2001	Rockström et al. (2009)
#3	21	0.951	Cost-benefit	Substitution; conservation	1992	Costanza et al. (1998)
#4	20	0.992	Sustainable urban development	Evaluation; classification of assessment method	1999	Mitchell (1996)
#5	19	0.945	Development model	Environmental protection; public participation	1995	Wackernagel and Rees (1998)
#6	11	0.967	Sustainability indicator	Guideline; service	1999	Azapagic and Perdan (2000)
#7	3	1.000	Monitoring	Modelling; policy analysis	1990	Ten Brink et al. (1991)
#8	3	1.000	China	Water resources management; urban water supply	1998	Loucks (2000); Simonovic (1996)
#9	2	1.000	Environmental assessment	Building assessment; stakeholder participation	2001	Robinson (2004)
#10	2	1.000	Management	Himalaya; India	2002	Berkes et al. (2003)
#11	2	1.000	Human ecology	Hierarchy theory; diversity	1983	Prigogine and Stengers (1984)

The silhouette metric scores for the 12 salient document co-citation clusters ranges from 0.758 to 1.000 which shows relatively higher scores than the keyword clusters and shows that there is consistency within the cluster members. Meanwhile, as regards the clusters’ mean year, most of the clusters are formed by relatively old documents, and this is consistent with the fact that the foundation of sustainability research was formed from the mid-1990 to early 2000s. As shown in Table 2.5, each salient cluster has representative documents which are the journal articles or documents with the most co-citation frequency within each cluster. The representative document influences the labeling of each cluster and are also well cited in the field, hence worth following.

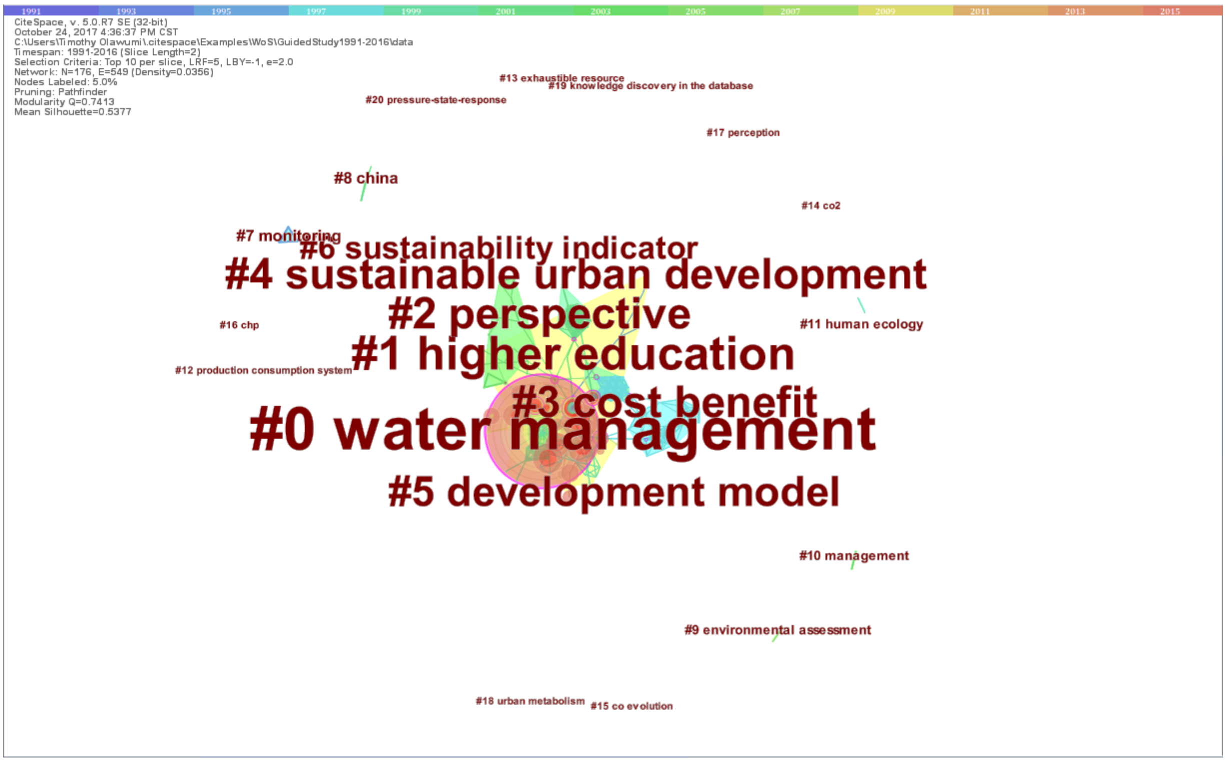

Figure 2.12: Document co-citation clusters

2.4.5 Geospatial analysis

A geospatial analysis of sustainability research corpus was carried out with the generation of Keyhole Markup Language (KML) files using CiteSpace. These KML files are then converted into animated maps using Google Earth® application which ease its visualization functionality for the location (or origins) of the authors of the study's indexed sustainability research corpus and highlighting the authors' published documents from 1991 – 2016 at a specific location.

Figure 2.13 shows the geospatial visualization of published sustainability research documents across Europe spanning the period from 1991 – 2016. The red nodes on the map (see Figure 2.13) are the origins of the published works while the lines (of differing colors such as green, yellow, orange, red, pink and purple, etc.) connects the location of documents of the same year. Some of the nodes are a combination of several linked nodes within the same location; this is revealed when such nodes are clicked on the animated map.

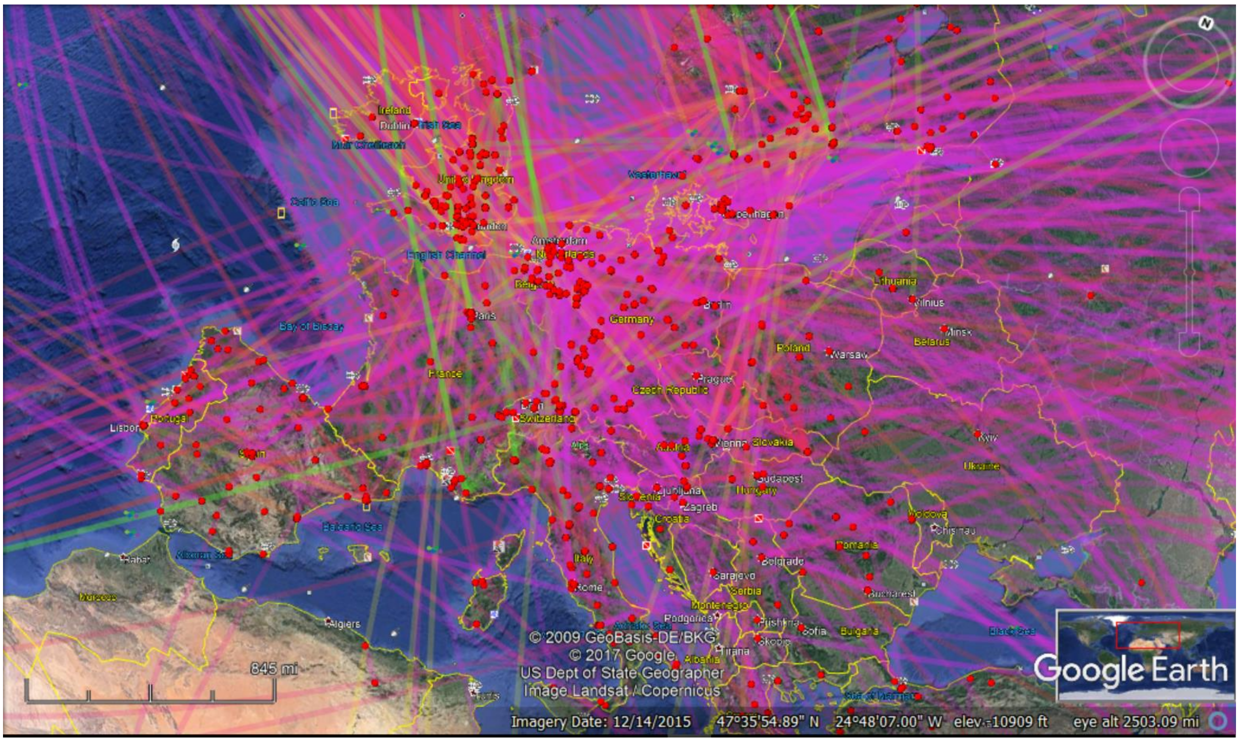

Figure 2.13: Geospatial visualization of published research documents (Europe)

Also, when any of the nodes is clicked, the pop-up dialog is revealed (see Figure 2.14) detailing the documents linked to the specified node. Such information detailed as a link, the name of the first author, year of publication and the journal of the published document. When a specific document link is clicked, the Google Earth® app will redirect the user to the source (web link) of the published document or article. The animated map is handy for academics and practitioners, as a more dynamic alternative to scientific databases such as Scopus or ISI Web of Science in the quest to ease the identification of sustainability research publications within a city or region. Hence, using this study animated map would be useful in tracking the trend of articles published over the years in the various countries. The dataset for the geospatial map (*including the dynamic geospatial map and the KML files*) is accessible as published via Mendeley data, DOI: 10.17632/sv23pvr252.1 (Olawumi & Chan, 2017).

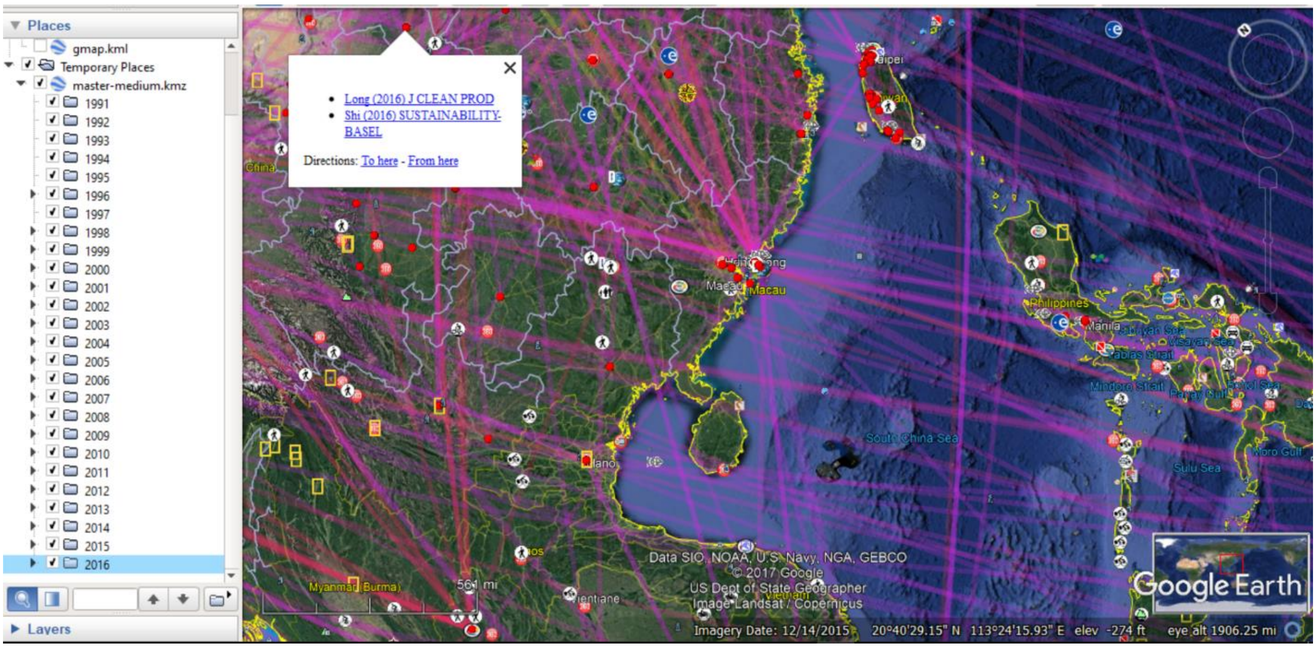

Figure 2.14: Geospatial visualization of published research documents (showing part of China)

2.5 Identification of the salient research clusters

The salient clusters in sustainability research field as shown in Table 2.8 are cluster #0 to cluster #11, however, to conserve space, the review centered on seven (7) clusters (clusters #0 to cluster #6) with a minimum of 11 cluster members. Cluster #0 "water management" has 39 members and the representative document is a communique published by the United Nations (WCED, 1987) which detail the opinions, reflections of the Brundtland conference on environment and SD. The report gave the first definition of sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). It further for an actualization of SD, there must be the identification of needs and the limitations that might hinder the capacity to meet such needs. The report by WCED (1987) also highlighted challenges faced in the realization of sustainable urban development which includes issues related to energy, industrial growth, the ecosystem, urban problem in developing countries and resource base (such as water management, land use, human resources, technological support) among others.

Meanwhile, a study by Holden et al. (2014) shows no country has achieved the four thresholds of sustainable development as identified in the Brundtland report, with many nations far off the minimum target. Accordingly, they argued for the integration of technology and behavioral changes of stakeholders for the actualization of sustainable urban development by 2030. Cluster #1 “higher education” had 24 members with Lozano (2006) has the representative document for the cluster. Lozano (2006) work focused on how the SD concepts proposed in the Brundtland report can be integrated into universities and colleges. Accordingly, Lozano (2006) highlighted the possible resistance the idea of institutionalizing SD could face from the stakeholders and presented strategies to overcome these challenges to integrate the SD ideas and concepts in universities' policies, system, and activities and ensure campus sustainability.

Cluster #2 “perspective” had 21 members with Rockström et al. (2009) has the representative document for the cluster. Rockström et al. (2009) proposed a novel approach to serve as guideline or preconditions for current and future urban development. They argued that defining boundaries for human development which help to prevent catastrophic environmental changes and ensure the stability of the built environment. Cluster #3 “cost-benefit” also had 21 members with the representative document published by Costanza et al. (1998). Costanza et al. (1998) attempted to make an analogy between the ecosystem functions and ecosystem services and argued that they contribute the social well-being of humans as well as represent a significant part of the economic value of the planet earth. The article also highlighted various valuation method to estimate the ecosystem services and recommended the need to safeguard the scarce ecosystem services to prevent its misuse.

Cluster #4 “sustainable urban development” had 20 members with the representative document published by Mitchell (1996). Mitchell (1996) outlined the challenges and limitations faced in the application of SD index and the various sustainability principles which have been hindering the implementation and promotion of SD at the local level. Also, Mitchell (1996) noted that there is no specific measurement tool for assessing SD. Although some building rating systems such as LEED, BREEAM, BEAM Plus and others have been developed since then; yet these tools focused mainly on some aspect environmental sustainability with gaps to be filled in areas such as social and economic sustainability constructs of SD.

Cluster #5 “development model” had 19 members with the representative document published by Wackernagel and Rees (1998). Wackernagel and Rees (1998) relayed the need for humans to reduce its ecological impacts on the environment and categorized the challenge being faced in achieving it, as that that has more to do with human’s social behavior than a technical or environmental crisis. A planning model was proposed by Wackernagel and Rees (1998) to serve as a tool for the measuring humans’ ecological footprints. Cluster #6 “sustainability indicator” had 11 members with the representative document published Azapagic and Perdan (2000). Azapagic and Perdan (2000) proposed a framework featuring sustainability indicators that cover the three pillars of SD- social, economic and environmental sustainability. Although the sustainability indicators (SI) were designed for its application for the whole industry, it would be more useful and functional when refined to specific sectors of the built environment. The SI can only be implementable when its users or stakeholders adopt appropriate strategies by evaluating alternative options. One of such multi-criteria decision-making technique is the Analytic Hierarchy Process (AHP) or the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS).

2.6 Conclusions and future directions

The concept of sustainability and sustainability development have received increasing global attention and consideration from government agencies, academics, practitioners and international organizations. It has evolved from its concept statements stated in the 1987 Brundtland commission report to the integration of technological tools to enhance its implementation. This study provides a scientific visualization method to analyze 2094 WoS bibliographic records using scientometric techniques such as co-author analysis, co-word analysis, co-citation analysis, clusters analysis, and geospatial analysis. These methods were used to an in-depth understanding of the status quo and trend in sustainability research field.

An analysis of the research publication trend revealed a steady increase in the number of the bibliographic records of the years which shows more efforts and resources are devoted to sustainable urban development. Also, as regards general productivity and contribution among authors, findings revealed Donald Huisingh, Rodrigo Lozano, and Yong Geng as the top three lead authors in the field. These authors along with Tsuyoshi Fujita, Robert Axelsson, and Per Angelstam are the central authors within their research circuits. However, only Donald Huisingh and John Cairns received high citation bursts over a short period, although John Cairns does not have many publications.

Meanwhile, in terms of distribution of the publications on sustainability, the majority of the journal articles originated from the United States, China, United Kingdom, and Canada. The Chinese Academy of Sciences, China PR, Delft University of Technology, Netherlands, and the University of British Columbia, Canada are the most productive institutions in sustainability research projects. Also, the diversity of the highly cited authors from various regions and organizations reveals the evolution of sustainability research and demonstrates its widely flourishing acceptance. Also, there are some active and connected exchange platforms between the countries and institutions.

Furthermore, key subject categories such as “environmental sciences,” “green & sustainable science technology,” “environmental engineering,” and “civil engineering” have had considerable influence on the structure and development of sustainability research and help to connect the distinct aspects and concepts in the research field. In terms of keywords, “sustainability”, “sustainable development”, “management”, “system”, “indicator”, and “framework” had the most frequency; while “impact”, “environment”, “climate change”, “design”, “policy”, “city” and “energy” received the citation bursts in recent years (2012 to date). It is consistent with the fact that more efforts are devoted to these critical research themes in the past years which are pivotal in achieving a sustainable urban development.

The core and high impact journals such as Journal of Cleaner Production, Sustainability, International Journal of Sustainable Development & World Ecology, Sustainability Science, Ambio, and Water Science & Technology have published significant findings in sustainability research. Some of these journals also received co-citation frequency and high citation bursts in the past years and a considerable number of the 35 highly cited articles are published in these journals. Also, the top 20 source journals have a minimum of 1.00 impact factor. The document co-citation analysis reveals Mohanty et al. (2002), and Nicol and Humphreys (2002) have the most cited documents while publications by the Brundtland Commission, WCED (1987) received the highest co-citation frequency along with documents such as

Rockström et al. (2009) and Lozano (2006). Meanwhile, documents such as Gardiner (1995), Seuring and Müller (2008), Lozano (2006), Barth et al. (2007) and Cortese (2003) received high citation bursts in recent years (2014 – 2016).

Cluster analysis was used in this study to analyze and conceptualize the salient terms and context of sustainability research using two approaches of keyword and document co-citation clusters. Nine (9) keyword clusters and twenty-one (21) document co-citation clusters were identified based on the indexed research corpus. These emerging trends and hot-topics related to sustainability research can be summarized as sustainable urban development, sustainable indicators and impact, water management, environmental assessment, strategy, public policy and monitoring, cost-benefit analysis, stakeholders' participation, campus sustainability and human ecology.

The discussion section on the salient research clusters reveals the evolution of sustainability research field from the definition of its concepts in the Brundtland Commission report to the recent development of models and sustainability indicators to enhance the actualization of sustainable urban development. Moreover, a geospatial analysis and visualizations of the research corpus produced a useful and dynamic animated map to improve the ease of identifying the sustainability researchers' origin and highlighting the authors' published documents for a specified year and region.

The study provided valuable information to researchers, practitioners and governmental bodies in the field of sustainability research. The power research networks offered valuable insight and in-depth understanding of the key scholars, institutions, state of the research field, emerging trends, salient topics and an animated map for researchers. Also, the study helped to crystallize out information and key findings to enhance the implementation of a holistic sustainability to achieve SD. It also identified the key authors and institutions who they can consult to assist in developing sustainability policies or templates for their applications.

The scientometric analysis and visualization had helped to reflect the global picture of sustainability research accurately, and these tools could be useful to visualize the emerging trends in other research fields. Meanwhile, it is recommended for researchers to focus more attention on the emerging sustainability research themes such as ecological footprint, LCA, sustainability assessment model, policy analysis and monitoring, evaluation metrics, stakeholder participation. The findings will be applicable to (1) government agencies and corporate organizations in their policy formulation and consultation as well as partnering with the key institutions identified in the study, (2) graduate students in identifying gaps and progresses made in the sustainability research area (3) academics in networking with other researchers in their areas of specializations (4) industries or sectors such as the construction industry in identifying and enhancing their level of implementation of sustainability to achieve a sustainable smart city initiative.

Future studies on sustainability research themes may focus on the application or integration of innovative technologies such as BIM, augmented reality, radio-frequency identification (RFID), geographical information system (GIS) among others to enhance the sustainability of the built environment towards the achievement of sustainable smart cities. Other aspects for future research may center on the application of sustainability knowledge in waste management, reduction of carbon footprint, campus sustainability, green neighborhoods as well as developing country-specific sustainability evaluation index.

2.7 Chapter Summary

The concept of sustainable development has gained worldwide attention in recent years which had enhanced its implementation. However, few studies have attempted to map the global research of sustainability. This chapter presented the scientometric review of global trend and structure of sustainability research in 1991 – 2016 using techniques such as co-author, co-word, co-citation, clusters, and geospatial analyses. A total of 2094 bibliographic records from the Web of Science database were analyzed to generate the study's research power networks and geospatial map. The findings reveal an evolution of the research field from the definition of its concepts in the Brundtland Commission report to the recent development of models and sustainability indicators. The most significant contributions in sustainability research have originated primarily from the United States, China, United Kingdom and Canada. Also, existing studies in sustainability research focus mainly on subject categories of environmental sciences, green & sustainable science technology, civil engineering, and construction & building technology. Emerging trends in sustainability research were sustainable urban development, sustainability indicators, water management, environmental assessment, public policy, etc., while the study generated 21 co-citation clusters. This chapter provides its readers with an extensive understanding of the salient research themes, trends and pattern of sustainability research worldwide. The following chapter reviews the extant literature and practice on the intellectual structure of BIM and the current trends and application of BIM in the built environment.

CHAPTER 3: EVOLUTION IN THE INTELLECTUAL STRUCTURE OF BIM RESEARCH: A BIBLIOMETRIC ANALYSIS[3]

3.1 Chapter Overview

The previous chapter conducted a comprehensive review and scientometric analysis of the concept of sustainability and sustainable development as it relates to the built environment. The current chapter presents the comprehensive reviews and bibliometric analysis of 445 corpus data of BIM literature towards investigating and understanding the pattern of BIM research. Network maps that display the visualization of the structure of BIM are also presented. This chapter will also provide relevant research areas that require considerations, and the discussion of selected research areas provide an extensive understanding of salient BIM fields.

3.2 Introduction

The development and integration of information technologies (IT) have helped improved construction processes and practices in the built environment (Aksamija, 2012; Chien & Mahdavi, 2009; Dawood, 2009; Thomassen, 2011; Wikforss & Löfgren, 2007). Thus, the construction industry been as a composite sector, made up of diverse stakeholders (Olatunji et al., 2016b; Olawumi et al., 2016; Olawumi & Ayegun, 2016) need to be proactive in its adoption of IT in its operation. Buswell *et al.* (2007) noted that a construction project has traditionally relied on 2D drawings to convey project information and data. However, the advent and increasing importance of Building Information Modelling (BIM) have changed the working system in the industry with the development of 3D models of building structures, and its capacity to integrate other concepts such as sustainability, project scheduling, costing and facility management.

[3] This chapter is fully published in:
Olawumi, T.O., Chan, D.W.M., & Wong, J.K.W. (2017). Evolution in the Intellectual Structure of BIM Research: A Bibliometric Analysis. *Journal of Civil Engineering and Management*, 23(8), 1060–1081. https://doi.org/10.3846/13923730.2017.1374301
And partially in:
Olawumi, T.O., & Chan, D.W.M. (2019b). Building Information Modelling and Project Information Management Framework for Construction Projects. *Journal of Civil Engineering and Management*, 25(1), 53–75. https://doi.org/10.3846/jcem.2019.7841
Olawumi, T.O., & Chan, D.W.M. (2019e). Development of a Benchmarking Model for BIM Implementation in Developing Countries. *Benchmarking: An International Journal*, 26(4), 1210–1232. https://doi.org/10.1108/BIJ-05-2018-0138

BIM is currently receiving worldwide recognition in the AEC industry due to its ability to store and also ease the use and reuse of project data across the project development phases; while also preventing unnecessary replication of project or design tasks (Kovacic et al. 2015; Kim et al. (2013b); Lee & Yu 2016; Sun & Wang 2015). However, BIM is a revolving and innovative digital technology (Mahalingam et al. 2015; Malekitabar et al. 2016; Succar & Kassem 2015); with recent applications in areas such as sustainability (Ajayi et al., 2015; Liu et al., 2015b) and facility management (Motamedi et al. 2013); despite the fragmented nature of the construction industry.

Meanwhile, BIM has started to receive more attention in the academic community with several research papers on BIM. It include articles on the development of BIM curriculum for university undergraduate students. Related works on BIM curriculum development including literature such as "*course development and collaborative teaching*" (see Ahn et al., 2013; Becerik-Gerber et al., 2012b; Becerik-gerber & Kensek, 2010; Kim, 2012; Sacks & Barak, 2010; Wang & Leite, 2014; Wu & Issa, 2014a). It also includes "*evaluating BIM curriculum vis-à-vis industrial needs*" (Aibinu & Venkatesh 2014; Solnosky et al. 2014) and "*in-class experimentation with BIM tools*" (Lewis et al. 2015; Nassar 2012) among many other related topics.

BIM per Eastman et al. (2008) is "a new approach to design, construction, and facilities management, in which a digital representation of the building process [is used] to facilitate the exchange and interoperability of information in digital format." Gilkinson et al. (2015) regarded it as both constituting a process and technology. It is an innovative solution with much to be explored; they further stressed that since it ensured a "coordinated integrated process"; it is a useful tool for all project stakeholders as they could found it fit and suitable for their jobs due to its diverse nature (Olawumi 2016a), and the collaborative outlook of the construction industry (Olatunji et al., 2016a, 2016b). Olatunji et al. (2017b) listed one of the benefits of BIM as an increase in return on investment (ROI) for clients; and to "*facilitate the ease of dissemination of information*" and this, in turn, helps to secure project success (Olawumi 2016b; Olawumi et al. 2016). Also, related technological tools such as augmented reality (AR) system and Geographic Information System (GIS) have also been integrated into the BIM process to facilitate the visualization of the construction process.

More so, BIM is a repository of digital information which eases the management of information in a project. Abanda et al. (2015) depicts BIM as a "global digital technology" with the capacity to ease the construction process, facilitate coordination and enhance the efficient delivery of project information. Also, Sampaio (2015) described BIM as an "innovative technology" which can support project activities throughout the project lifecycle. Moreover, Eastman et al. (2008) defined it as a "modeling technology and associated set of processes to produce, communicate, and analyze building models." More so, Zhao (2017) noted that BIM had transformed the construction industry in such a way that construction stakeholders have developed an interest in its implementation for their diverse job nature (Olatunji et al., 2016b; Olawumi et al., 2016; Olawumi & Ayegun, 2016). Mccuen (2008) advocated that BIM provide "single, non-redundant, interoperable information repository" capable of supporting every stage, process and functional units in a construction project.

Tulubas Gokuc and Arditi (2017) described BIM as a "trend of the future" with significant impacts on professional performances. One of the benefits of BIM implementation in projects is to facilitate effective communication among project stakeholders (Olatunji et al., 2017b) and could enhance business operations (Ahankoob et al., 2018). Consequently, BIM has seen a dramatic increase in its application across the project phases in recent years (Dim et al., 2015; Patrick & Ii, 2010). According to Eastman et al. (2008), BIM is one of the several other technologies in the architecture, engineering, and construction (AEC) industries and per Autodesk (2010b), BIM is a more sophisticated tool with better feedback mechanisms for its users. Also, according to Olawumi and Chan (2018d), BIM as a versatile technology can help advance the implementation of green buildings and innovations in the built environment. In contrast, some of the existing IT applications in the construction industry are constrained by their reliance on static methods of information delivery (Aziz et al., 2009; Buswell et al., 2007).

Olawumi and Chan (2018b) identified BIM as one of the recent innovative concepts in the country industry which per Olawumi and Chan (2018d) has improved the design and construction of building projects. Inyim et al. (2015) described BIM as "an advanced example of an ICT approach" and outlined ways in which the construction industry uses ICT: (1) information management and service; (2) communications;

and (3) processing and computing. Pero et al. (2015) pointed out the usefulness of BIM as a veritable IT tool for data sharing and exchange. BIM is a process of generating and managing information of a building or infrastructure during its life cycle (Kuiper & Holzer, 2013). Eastman et al. (2011) also defined it to be "*a modeling technology and associated set of processes to produce, communicate, and analyze building models*." Nevertheless, per Van Lith et al. (2015), the definition of BIM is still under debate with several interpretation depending on how it is deployed in a project. Meanwhile, Olawumi et al. (2018) categorize BIM implementation in two aspects such as (1) the BIM product or technology uses in creating building models and simulating the design parameters, and (2) the BIM process which affords the synthesis of relevant of information relating to a project within a central hub. However, according to Matthews et al. (2018), the inadequate knowledge and experience on how to adopt BIM in a project as resulted in stakeholders undertaking its implementation in a cluttering manner.

In recent years, several research studies have been conducted on the impact of BIM implementation in the Architectural, Engineering, and Construction (AEC) industry. extant literature such as Bradley et al. (2016) outlined the benefits of BIM in infrastructural projects while Fan et al. (2014) using a case study project examined the influence of BIM during the construction phase. The case study's findings reveal a significant reduction in change orders, requests for information (RFI) and a better compliance to project schedule. Also, a study by Johansson et al. (2015) pointed out the capacity of BIM to facilitate large projects by providing visualization and real-time rendering of the projects while Karan and Irizarry (2015) argued that extending BIM capacity using tools such as Geographical Information System (GIS) can enhance its efficiency at the preconstruction stage.

Moreover, Inyim et al. (2015) highlighted areas in which BIM has been of benefit to the construction industry to include information management and service, communications. Studies (*see* Kim et al., 2015c, 2016c; Matthews et al., 2015; Morlhon et al., 2014; Neto et al., 2016; Oti et al., 2016; Olatunji et al. 2017b) also revealed the significant advantages gained in project information management through the implementation of BIM to include (1) compliance to project's delivery schedule; (2) resource planning and management; (3) faciltate collaboration among key stakeholders; and (4) real-time simulation and analysis of building performance among others. Extant literature (see Kang & Hong, 2015; Pärn & Edwards, 2017; Park & Cai, 2017) also examined the influence of BIM at the facility management stage of the building lifecycle. Also, some empirical studies (*see* Ham & Golparvar-Fard, 2015; Ilhan & Yaman, 2016; Kim et al., 2015a, 2015b, 2015c) argued for the enrichment of BIM to aid sustainable development.

Demian and Walters (2014) highlighted the use of BIM to manage project information management in construction projects and stressed that the adoption of BIM in the construction industry has helped bring solutions to the sector's problems. Fisher and Yin (1992) dated the utilization of Information Technology (IT) in the United Kingdom to early 1970s and further opined that the globalization of construction works such as the pre-fabrication and assembly of building components will greatly increase the usefulness of IT in construction projects. The prediction of Fisher and Yin (1992) is a current reality in the construction industry as evidenced in some construction projects (Bansal, 2011a; Davies & Harty, 2013). Moreover, Olawumi et al. (2017) and Olawumi and Chan (2018b) argued that for the construction industry to strive and be competitive, it needs to be innovative and improve the ways, methods, and techniques of delivering its products.

3.2.1 Knowledge Gap and Research Objectives and Value

Previous studies on reviews of BIM literature have focused on specific research areas or themes such as facility management (Becerik-Gerber et al., 2012a; Kang & Hong, 2015; Wetzel & Thabet, 2015), environmental sustainability (Wong & Zhou 2015). Studies have outlined the current practices and future directions via various research approaches such as surveys, critical literature reviews, and interviews (Azhar 2011; Gu & London 2010; Volk et al. 2014). More so, researchers have carried out reviews and analyses on BIM which include contractors' blueprint to adopt BIM (Ahn et al., 2016); e-tendering process model (Ajam et al. 2010); waste management (Ajayi et al. 2015; Akinade et al. 2015); education and knowledge (Ahn et al. 2013; Alci & Sampaio 2015). Others include: social network simulation, cloud-BIM and technology adoptions (Al Hattab & Hamzeh, 2015; Alreshidi et al., 2016; Arayici et al., 2011; Becerik-Gerber et al., 2012b; Becerik-gerber & Kensek, 2010; Chen & Hou, 2014; Choi & Kim, 2015; Davies & Harty, 2013; Du et al., 2014).

Extant studies also exist on BIM-GIS integration (Bansal, 2011b; Borrmann et al., 2015; Deng et al., 2016) and sustainability (Bynum et al. 2013; Henry et al. 2015; Inyim et al. 2015). However, in recent years (2015 – 2017) there have been literature reviews (see Table 3.1 & Table 3.2) on BIM research field such as Yalcinkaya and Singh (2015), who reviewed BIM literature to deduce twelve (12) BIM core research areas and ninety (90) factor labels using Latent Semantic Analysis (LSA) described as a "natural language processing technique"; which was used to analyze the abstracts of the journal articles. Meanwhile, Zhao (2017) used a computer software "Citespace" to examine citation records downloaded from the Web of Science database to identify authors with the most citations and co-citations and the "hot topics" in BIM research areas with the most citations. More so, Santos et al. (2017) review of the extant literature focused on identifying research areas with the most citations and the most cited authors. Accordingly, he also proposed nine (9) research areas in BIM field. Table 3.1 and Table 3.2 identifies and summarize what is new in this current study and compares it with previous published reviews of BIM literature.

Moreover, previous BIM reviews focused mostly on authors and journals' citations analyses, this study attempts to bridge the gap in the reviews of extant literature and add value to BIM knowledge area. This study proposes the following objectives: (1) to carry out an holistic review of BIM journal articles (as against abstracts' review by Yalcinkaya and Singh (2015) and citations records by Zhao (2017)); (2) to define the subfields that constitute the intellectual structure of BIM research fields (core research categories and areas); (3) to identify funding (grants) structure for BIM research based on country (research origin) analysis and research category analysis; (4) to identify and establish the network of BIM publication by research origin and geographical scope; (5) to identify the salient research methodology employed in past BIM studies; (6) to identify relevant BIM software, data schema, and project areas for BIM application; and (7) to classify BIM publications based on project sectors they are applied to (such as energy, transportation, etc.).

Meanwhile, throughout the bibliometric analysis and the literature reviews, the study would adopt a more systematical and analytical approach in achieving the seven (7) objectives of this study. A wide range of publication will be analyzed across several journal publication houses. The next section focuses on a discussion of the research methodology applied (bibliometric analysis) and the literature search strategy. Other sections focus on (i) the findings and discussion of the results of the bibliometric analysis, (ii) discussion on the proposed core BIM research categories and areas, (iii) the research implications (iv) and research limitations and (v) the conclusion and future directions.

3.3 Research Methodology

The study adopted a bibliometric analysis technique to achieve the predefined research objectives of which is to articulate the distinct set of the main research categories in BIM's research to gain a better perspective and identify critical areas in which more research efforts is still been required. Per Marsilio et al. (2016) bibliometric research approach is an "*attempt(s) to quantify and address the intellectual structure of a research field starting from the mathematical and statistical analysis of patterns that appear in the publication and use of documents*." Meanwhile, this analysis technique has been utilized in some research publications both in the science and management research fields (see Neto et al. 2016; Marsilio et al. 2016; Ramos-Rodriguez & Ruiz-Navarro 2004).

This research aims to bridge the gap in the BIM literature by applying the bibliometric technique to a corpus of published articles relevant to this disciplinary field towards achieving the predefined objectives as stated in the previous section. The research design for this study is as outlined in Figure 3.1.

3.3.1 Literature Search Strategy

In commencing the bibliometric analysis, a decision as to which scientific repository to use was made; there are several academic digital databases, but the three most commonly utilized for scientific inquiries include Google Scholar, ISI Web of Science and Scopus. Although there is no clear difference in Scopus and Web of Science databases as it pertains to science-based publications, however, there is a considerable overlap in their records. Moreover, Google Scholar seems to have a more extensive collection of publications than both Scopus and Web of Science. However, Google Scholar is noted to contain many incorrect publication attributions- as an author with the same first initial and last name may be attributed more citations. Also, Google Scholar also has another minor problem with indexing of articles, as it counts all conference abstracts which has nothing to do with citations, thereby increasing the numbers of papers very dramatically.

However, for this study, a comprehensive search as detailed in Figure 3.2 was carried using the ISI Web of Science database because of its "*comprehensiveness, organized structure and scientific robustness*" (Neto et al. 2016). Marsilio et al. (2011) also argued that it is the "*most commonly used and generally accepted source for bibliometric studies*." The search keywords are: "*Building Information Modelling*," "*BIM*" and "*Building Information Modeling*."

The selected time span is between 1990 and 2016 equivalent to 26 years. The research corpus only comprises of articles published in a journal instead of a doctoral thesis (*since most of them are afterward published in journals)*, books or conference papers. Moreover, authors do publish their work in scholarly journals because they are classified as "certified knowledge" (Ramos-Rodríguez & Ruíz-Navarro 2004) and have gone through a peer-review process. The search results gave 567 journal articles. However, 122 papers were excluded from further analysis as they fail to meet the inclusion criteria (see Table 3.3) due to several reasons such as abstracts written in a language other than English (*12 articles*). We also have three articles with no abstracts and 107 articles found to be unrelated to research (such as papers that only refer to BIM but cannot be related to any of the categorized research areas). A total 445 articles which were downloaded in Mendeley Desktop (*reference manager*) and indexed in the Microsoft Excel program. The indexed articles consisted of 316 case studies papers, 47 surveys/interviews articles, and 82 articles which utilized mixed method research approach.

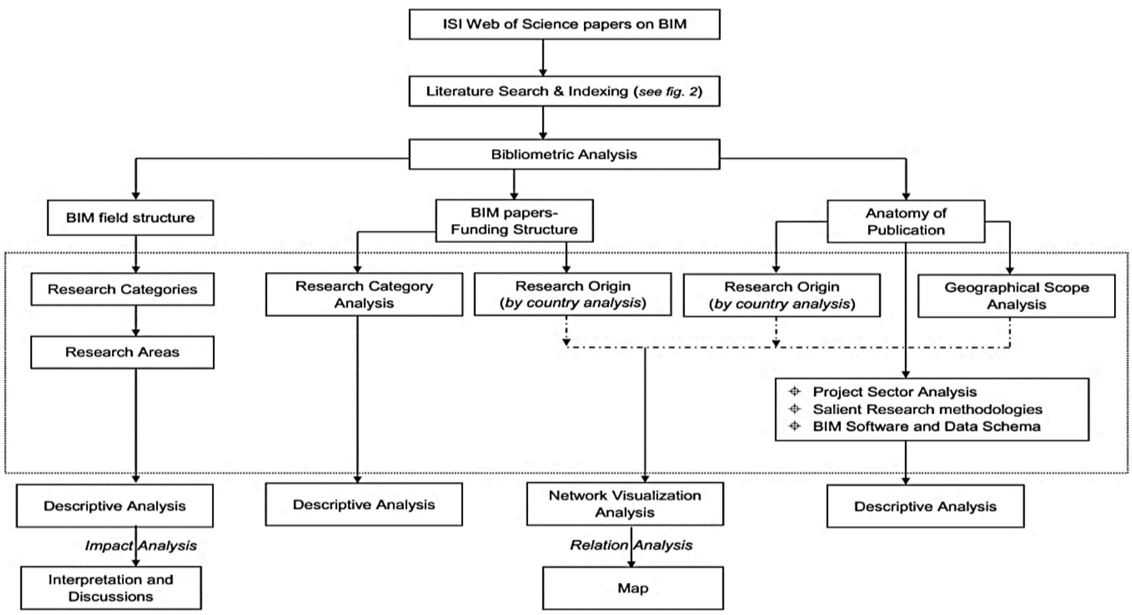

Figure 3.1: Outline of Research Design

Table 3.1: Summary of Recent BIM Literature Reviews

Paper	Number of journals analyzed	Number of papers analyzed	Period of analysis	Proposed research categories (*research areas*)	Research areas	Type of literature review	Scope/Focus of analysis
Wong and Zhou (2015)	9	84	2004 – 2014	4 (none)	• Green-BIM • Sustainability	No bibliometric	Each journal paper' sections
Yalcinkaya and Singh (2015)	Only Top 20 journal listed	• 525 (journal articles) • 450 (conference papers)	2004 - 2014	12 (90)	BIM	Latent Semantic Analysis (LSA)	Abstracts
Zhao (2017)	-	614	2005 - 2016	-	BIM	Scientometric review	Citation records only • Co-author analysis • Co-word analysis • Co-citation analysis • Co-occurring keywords
Santos et al. (2017)	49	381	2005 -2015	9	BIM	Content analysis	Each journal paper' sections
Current study	62	445	2006 - 2016	10 (107)	• BIM • Review of sustainability studies	Bibliometric analysis	Each journal paper' sections

Table 3.2: Comparison between previous BIM Literature Reviews' Findings and the Current study

Paper	Database used	Contribution to Existing Knowledge
Wong and Zhou (2015)	Scopus	• Provided a summary of research focus of green-BIM publications • Identified the low utilization of BIM in facility management phase • Proposed a 'one-stop-shop' BIM for environmental sustainability monitoring
Yalcinkaya and Singh (2015)	Several databases like Elsevier, ProQuest, Emerald, EBSCO, etc.	• Identified 12 core BIM research areas • Identified 90 BIM factor labels or keywords.
Zhao (2017)	Web of Science	• Identified ten (10) co-citations clusters • Identified 7 hot topics in BIM research • Identified 5 research areas with most citations
Santos et al. (2017)	Web of Science and other unlisted databases	• Proposed 9 research categories • Identified research areas and journals with most citations • Identified current trends in BIM
Current study	Web of Science	• Identify funding (grants) structure for BIM research (*country analysis and research category analysis*) • Identify the salient research methodology employed in past BIM researches • Identify the network of BIM publication by research origin and geographical scope • Propose a much concise and precise core research category (10) and areas (107) • Identify relevant BIM software, data schema, and project areas for BIM application • Classify BIM publications based on project sectors they focused on (such as energy, transportation, etc.)

Table 3.3: Indexed Corpus Profile

Profile	Number of Papers	Percentage (%)
Total publications in web of science	**567**	**100**
Abstracts which are written in languages other than English	12	2.12
Papers excluded for not having abstracts	3	0.53
Papers excluded for being registered twice	0	0
Papers excluded for not being related to the research area/topic	107	18.87
Total papers excluded before analysis	122	21.52
Total papers to be analyzed for this guided study research	**445**	**78.48**

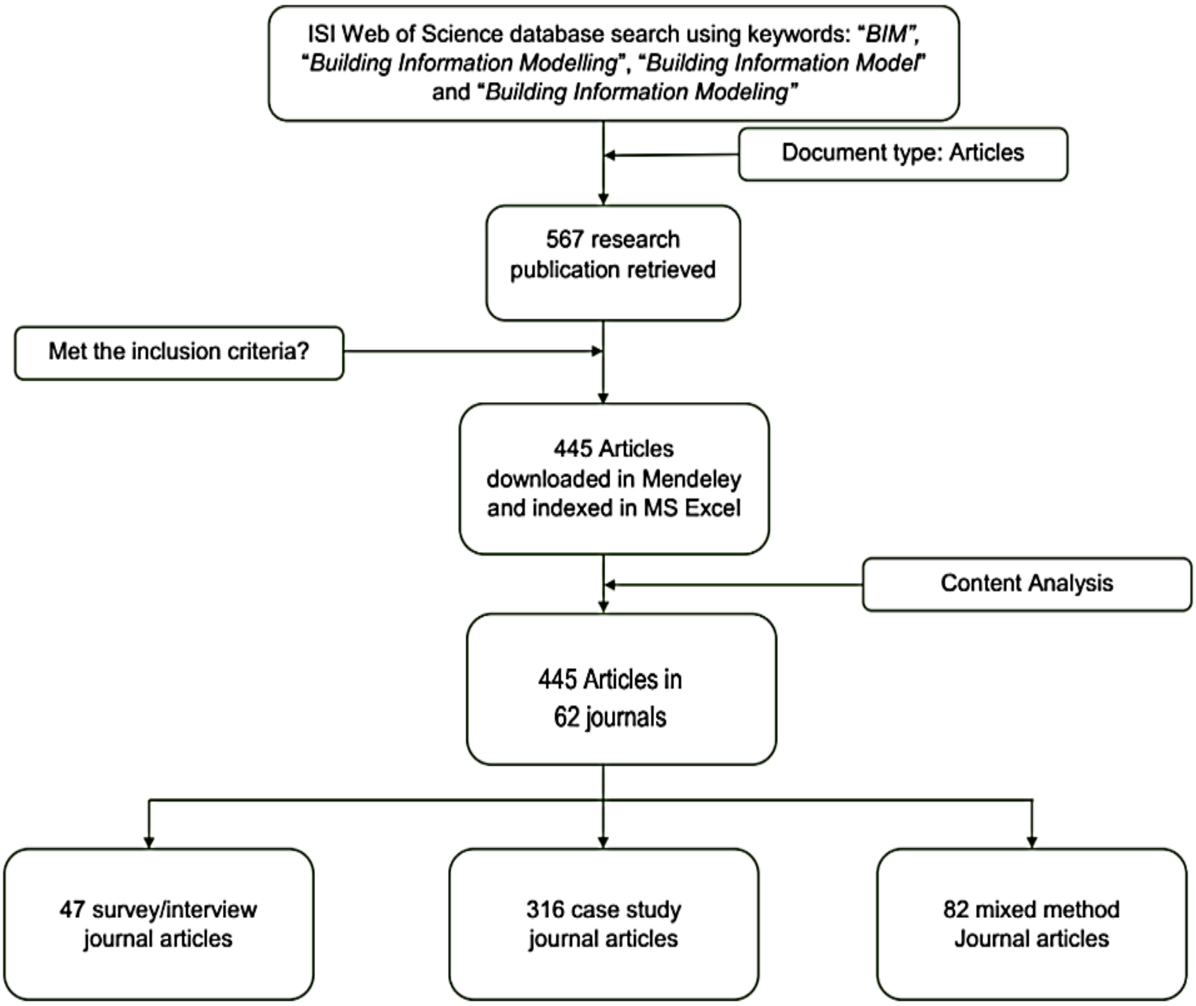

Figure 3.2: Literature search & indexing approach

3.4 Bibliometric Analysis

This section discusses the facets and results of this study of bibliometric analysis. These include (i) descriptive analysis of published research in BIM (ii) defining the BIM subfields and research areas (iii) BIM funding structure, and (iv) the anatomy of the BIM publications as outlined in this study research design.

3.4.1 Published Research in BIM

The volume of published research in BIM has notably increased in recent years (Santos et al. 2017); since it has emerged as a key, and innovative approach to construction and civil engineering (Yalcinkaya & Singh 2015) and these studies covers diverse areas including several technical and non-technical issues (Zhao 2017). More so, in the last four years, more than 75 percent of BIM articles were published.

The literature used in this bibliometric analysis are journal articles, and all but one of the journals has no impact factor (IF). The analysis of the journals reveals that 36 out of the 62 journals (58 per cent) has an impact factor (IF) greater than 1.000 while 16 journals have IF value between 0.500 and 0.999 representing 26 per cent and the rest of 9 journals are below 0.500 IF value. Meanwhile, an analysis of BIM publishing journals reveals several concepts and issues revolving around the BIM research field; also 32 out of the 62 journals (52 per cent) published just one article. More so, another cluster of 20 journals published between 2 and 6 papers; meanwhile, there is another group of ten (10) journals whose number of published articles on BIM is 10 articles or more (see Table 3.4).

The structure of the published research on BIM closely followed the “Pareto-principle” also known as the 80/20 rule (Brynjolfsson et al. 2011; Pareto 1964). In this study, it follows that 349 articles (78.4 percent) are published in just 10 journals (16 per cent) which can be termed a 78/16 rule which aligns with the Pareto postulation; the average impact factor for the 10 journals whose publications followed the Pareto principles is 1.568. More so, from year 2012 to date the number of published articles on BIM have significantly increased with more volumes of articles coming from journals such as “Automation in Construction”, “Advanced Engineering Informatics”, and “Journal of Computing in Civil Engineering”.

3.4.2 BIM Sub-fields and Research Areas

The next stage in the bibliometric analysis is to define the BIM sub-fields (research categories and research areas). We identify ten (10) research categories namely “IT-enabled simulations and visualization”; “building design and energy conformance”; “BIM software & data schema”; “BIM model development”; “BIM learning, adoption & practice”; “construction and project management”; “safety and risk management”; “facility management”; “sustainability-related studies”; and “literature review” (see Table 3.5).

The establishment of the semantic link and classification of the published works to the ten (10) research categories was based on a directed content analysis approach using articles keywords, titles, scope covered and the research findings. Meanwhile, further clustering of the articles enables us to define one hundred and ten (107) research areas/themes based on the ten research categories. The analysis of the research categories reveals a prevalent of publication in aspects such as “construction and project management” with 78 articles; “BIM learning, adoption & practice” with 70 articles; and “building design and energy conformance” with 65 articles which sums up close to fifty (50) percent of all published works in BIM. The defined category in this study is more concise and specific than previous studies, although there is a partial overlap when compared with those provided by previous authors (Yalcinkaya & Singh 2015; Zhao 2017).

Furthermore, for the research areas, one hundred and ten (107) themes were identified (see Table 3.6) through an iterative process whereby identified themes are grouped in a cluster under each research category. After the loading of the research themes into the research categories, three research areas- “construction and project management” with 18 themes, “facility management” with 17 themes and “BIM model development” with 16 themes are the most represented research areas. It can be deduced from the analysis that BIM has found more application in research in construction and project management with more published articles and themes, this is because of diverse use in the construction industry (Zhao 2017); and the fact that more contractor has started making use of BIM (Fan et al., 2014). Further discussion on the research categories and areas are outlined in section 5 of this chapter.

3.4.3 BIM Publications' Funding Structure

BIM disciplinary field is a technologically backed research area which requires researchers to experiment with, develop and interoperate various BIM software and tools of which many of them are only commercially available and expensive, hence this section attempts to investigate the funding arrangement used in the various journal articles.

The bibliometric analysis in this section focuses on reviewing the funding structure (i) based on research category analysis, and (ii) research origin analysis (author & co-authors' affiliations). An analysis of the funding structure reveals a steady increase in the number of BIM research receiving some form of funding or grants to carry out the relevant studies (from 20 articles in 2011 to 67 articles in 2015); also, more than half (51 percent, #231 articles) received funding. Meanwhile, based on an analysis of the research categories which received more funding, we identified four (4) research categories which have more than thirty (30) funded articles, and these include: RC2- "Building design and Energy conformance" which 40 funded articles, RC6- "Construction and Project Management." Others are RC3- "BIM Software & Data schema," and RC4- "BIM model development" with 39, 35 and 32 funded articles respectively which represent more than 60 percent of the funded articles of all BIM research categories (see Table 3.7).

More so, the analysis of the funding structure of BIM publication (based on research origin analysis) was analyzed using a mapped network visualization technique as shown in Figure 3.3. The funding arrangement for any given article was based on the information provided by the author(s) in the acknowledgment section of the published paper. The format for the map network visualization analysis in Figure 3.3 is based on "Country ('articles per research origin,' 'funded articles,' 'articles per geographical scope')." Therefore, by "articles per research origin" we imply the number of articles published by the author(s) or co-author(s) affiliated with an institution based in that country. More so, the term "articles per geographical scope" implies the number of articles with originating data or case studies based in that country. A bibliometric analysis of public-private partnership (PPP) by Neto et al. (2016) also used the terms "research origin" and "geographical scope" to portray similar expressions.

For example, we have USA (147,45,118) - this imply that they are 147 BIM authors/co-author(s) from the United States based on the bibliometric analysis and 45 of their BIM articles were funded, while there are 118 articles with the research data (that is, case studies, questionnaire surveys or interviews, etc.) based solely in the United States. BIM articles from countries namely the Republic of Korea, the US and China, have more funded articles with 68, 45 and 17 articles than any other countries which represent a combined 56 percent of all funded articles. The funding of BIM projects in South Korea, and China has aided the adoption and implementation of BIM in the AEC industries of these two countries; also, BIM standards, guidelines and component families which are essential for successful BIM implementation have been developed in Korea (G-SEED) and Hong Kong (BEAM-Plus).

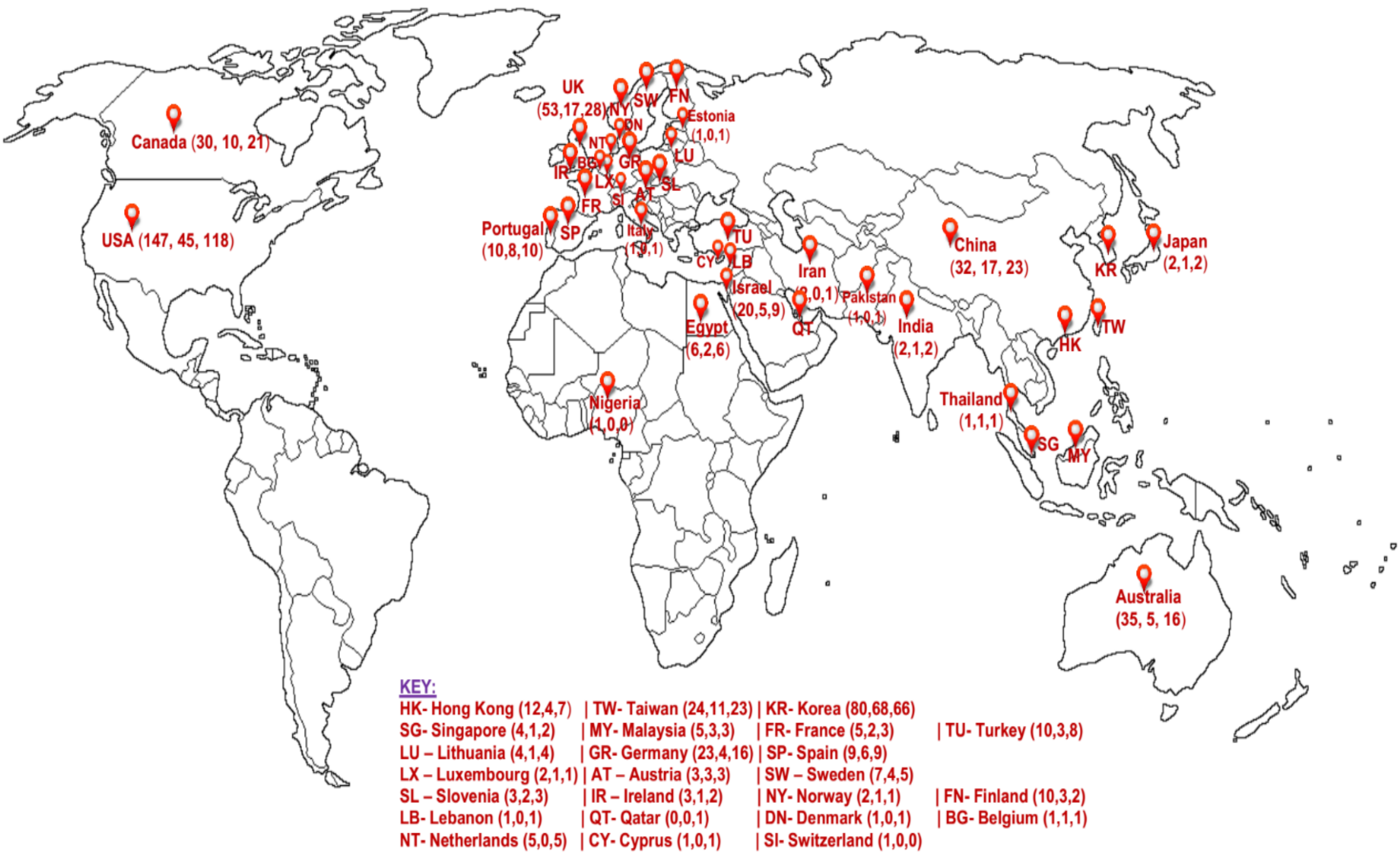

Figure 3.3: Map network visualization analysis (funding structure)

The relative high funding rate from the Republic of Korea is not far-fetched because as noted by Lee and Yu (2016), the Korean central government have strongly encouraged BIM usage and adoption via the promulgation of policies and funding through the National Research Foundation of Korea (NRF). Also, a recent study by Won et al. (2013) revealed a significant increase in the adoption rate in both USA and Korea.

3.4.4 Anatomy of BIM Publications

This section focuses on other aspects of the anatomy of the published BIM articles as depicted in the research design. The bibliometric analysis in this section focuses on (i) project sector analysis (ii) the salient research methodologies (iii) related BIM software and data schema.

3.4.4.1 Project Sector Analysis

A bibliometric analysis of the corpus of BIM publications reveal a greater focus on the 'building and housing sector' of the built environment with a total of 347 BIM articles out of the overall 445 articles. BIM articles in the "*building and housing*" sector focuses on aspects such as "*single family houses*", "*residential floors*", "*parking garage*", "*storey buildings*", "*high-rise structures*", "*building component and elements*", "*sports center*s", and "*educational buildings*" (see Table 3.8). A study by Chang and Lin (2016) reveals that BIM "*is currently being applied mostly to buildings*" with few applications elsewhere. Table 3.8 outlines the project sectors covered by the BIM publication corpus as deduced through this study's bibliometric analysis; meanwhile, aspects covered by the articles under each project sectors were defined.

3.4.4.2 Salient Research Methodologies

The bibliometric analysis of the articles' corpus in this section focus on defining the primary research design and approaches utilized by previous BIM authors. An analysis of the articles reveals that 316 articles out of 445 BIM articles (i.e. 71 percent) utilize the case study as the research method, this implies that BIM articles' authors prefer case study approaches in their studies. Basbagill et al. (2013) argued that case study research design is the best approach to introduce new concepts to industry practice and since BIM is still relatively new to the construction industry; and this can be adduced as the reasons behind the use of case studies for BIM researches.

More so, Davies and Harty (2013) believed case study research method does help to challenge fundamental misconceptions when applying innovative technologies to practice; although, case study approach has no need for internal validation (Hartmann et al., 2012). Furthermore, the analysis of the articles' corpus shows that "questionnaire surveys and interviews" research approaches with 47 articles (11 percent) and "general discourse and literature reviews" approaches with 38 articles (8 percent) are also quite common among BIM authors.

3.4.4.3 BIM Software and Data Schema

The bibliometric analysis of the BIM articles in this section assesses the frequency of usage and mentions of different BIM software and data standard as analyzed from the BIM publications' corpus. An analysis of the articles reveals that there are eleven (11) BIM data schemas in use in the construction industry; and in fact, the industry foundation class (IFC) and the green building eXtensible markup language (gbXML) are very popular among BIM authors with 187 and 30 mentions in the articles' corpus (see Table 3.9). However, of the two interoperability standards, IFC is mainly employed in the AEC industry (Belsky et al., 2014; Karan & Irizarry, 2015; Tashakkori et al., 2015).

More so, the high usage of the IFC schema is because of its continuous improvement so as to advance interoperability among BIM software (Kota et al., 2014), although it is not yet at a satisfactory level (Aram et al., 2013). Meanwhile, the MVD schema is only a subset of the IFC schema (Lee et al., 2013a). Also, the IFCXML schema is another subset of the IFC schema that allows the IFC to be transmutable over the web (Redmond et al., 2012). Furthermore, unlike IFC, the gbXML data schema is specifically developed for energy analysis while the IFC data format is a schema developed by buildingSMART and can be used for data exchange across the building life cycle (Kim et al., 2012).

Furthermore, the analysis of BIM software for architectural and structural designs reveals 10 software in use in the AEC sector, of which Autodesk Revit with 132 articles' mentions is the most used software; previous studies unveiled similar findings (Kim et al., 2015b; Wang et al., 2015b). Survey results by Bynum et al. (2013) revealed that Revit is the dominant BIM authoring tool in the AEC industry with 78 percent of respondents utilizing it. However, there was low usage of BIM energy analysis software such as Ecotect, IES Virtual Environment. Nevertheless, no single BIM application can support all the process functionalities required in the AEC industry.

Table 3.4: BIM journal publication lists and Impact factors

S/N	Journals	Total	Impact factor	S/N	Journals	Total	Impact factor
1	Applied Energy	2	5.746	32	IEEE Transactions on Engineering Management	1	1.103
2	Environmental Science and Technology	1	5.393	33	International Journal of Precision Engineering and Manufacturing	1	1.075
3	Computer-Aided Civil& Infrastructure Engineering	5	5.288	34	Journal of Bridge Engineering	1	1.069
4	Journal of Cleaner Production	1	4.959	35	Sustainable Cities and Society	3	1.044
5	Waste Management	1	3.829	36	Scientia Iranica	1	1.025
6	Building and Environment	6	3.394	37	Structural Design of Tall and Special Buildings	1	0.898
7	Resource Conservation and Recycling	2	3.28	38	Journal of Performance of Constructed Facilities	2	0.893
8	Energy Policy	1	3.045	39	HVAC&R Research	2	0.871
9	Expert Systems with Applications	1	2.981	40	Journal of Transportation Engineering	1	0.801
10	Energy and Buildings	10	2.973	41	Journal of Industrial and Management Optimization	1	0.776
11	IEEE Transactions on Intelligent Transportations System	1	2.534	42	Transportation Research Record	1	0.770
12	Automation in Construction	177	2.442	43	Journal of Asian Architecture and Building Engineering	11	0.750
13	Construction and Building Materials	2	2.421	44	Journal of Environmental Protection and Ecology	1	0.734
14	Applied Mathematical Modelling	1	2.291	45	Studies in Informatics and Control	1	0.723
15	Building Research and Information	2	2.196	46	Mathematical Problems in Engineering	1	0.689
16	Safety Science	4	2.157	47	KSCE Journal of Civil Engineering	10	0.600
17	Carbon Management	1	2.092	48	Canadian Journal of Civil Engineering	6	0.586
18	Advanced Engineering Informatics	40	2.000	49	Advances in Structural Engineering	1	0.577
19	Journal of Computing in Civil Engineering	36	1.855	50	International Journal of Engineering Education	2	0.559
20	Journal of Management in Engineering	14	1.840	51	Journal of Professional Issues in Engineering Education and Practice	11	0.538
21	Journal of Building Performance Simulation	1	1.807	52	PCI Journal	1	0.526
22	Research in Engineering Design	1	1.786	53	Proceedings of the Institution of Civil Engineers-Structures and Buildings	1	0.429
23	Measurement	1	1.742	54	International Journal of Civil Engineering	1	0.372

S/N	Journals	Total	Impact factor	S/N	Journals	Total	Impact factor
24	Advances in Engineering Software	3	1.673	55	Proceedings of the Institution of Civil Engineers-Civil Engineering	2	0.348
25	Journal of Civil Engineering and Management	14	1.530	56	Journal of the Chinese Institute of Engineers	4	0.246
26	Engineering with Computers	1	1.460	57	Research Journal of Chemistry and Environment	1	0.240
27	Building Simulation	3	1.409	58	Informes de la Construccion	3	0.227
28	Sustainability	3	1.343	59	Ashrae Journal	5	0.223
29	International Journal of Computer Integrated Manufacturing	1	1.319	60	Gradevinar	3	0.158
30	Structure and Infrastructure Engineering	1	1.202	61	Civil Engineering	1	0.153
31	Journal of Construction Engineering and Management	26	1.152	62	Intelligent Computing in Engineering and Architecture	1	N/A
		363				82	
	Total	**445**					

Note: Year (*Number of Publications*) **-** 2006 (2), 2007 (3), 2008 (7), 2009 (6), 2010 (17), 2011 (32), 2012 (28), 2013 (63), 2014 (96), 2015 (114), 2016 (77).
N/A – Not available Impact Factor as at year 2016.

Table 3.5: BIM Research Categories

Code	BIM- Research Categories	Number of articles
RC1	IT-enabled simulations and Visualisation	40
RC2	Building design and Energy conformance	65
RC3	BIM Software & Data schema	54
RC4	BIM model development	52
RC5	BIM learning, adoption & practice	70
RC6	Construction and Project Management	78
RC7	Safety/ Risk Management	31
RC8	Facility management	37
RC9	Sustainability	17
RC10	Literature review	1

Table 3.6: Theme loading for the BIM research areas

Code (research category)	Research areas/themes	Number of themes
RC1	RC1.1- Emergencies sensing localization; RC1.2- Real-time and 3D visualizations RC1.3- Fire safety simulations RC1.4- Point-cloud data extraction RC1.4- Automated or semi-automated generation of data RC1.5- Virtual support systems RC1.6- Synchronous online collaboration	6
RC2	RC2.1- Building energy regulations RC2.2- Code checking & compliance RC2.3- Building envelope cost and energy performance RC2.4- Energy management and analysis RC2.5- Structural analysis and design RC2.6 Building rating systems and assessments RC2.7- Tracking of design changes and errors RC2.8- Daylighting profiling RC2.9- Design validation and coordination	9
RC3	RC3.1- Interoperability RC3.2- Usefulness, benefits, and limitations of BIM applications RC3.3- Augmented reality system RC3.4- Industry Foundation Class (IFC); RC3.5- BIM & Semantic web interoperability RC3.6- Semiotic User interface analysis RC3.7- Cost Estimating BIM tools RC3.8- Software coupling RC3.9- BIM data exchanges RC3.10- Mobile BIM RC3.11- Data schemas (GbXML, City GML, MVD, etc.)	11
RC4	RC4.1- Quantity take-off RC4.2- As-built BIM creation RC4.3- Domain vocabulary & Ontology development RC4.4- Model validation process RC4.5- Cloud-BIM RC4.6- BIM collaborative system RC4.7- Semantic web technology RC4.8- Physical BIM library RC4.9- Scan-to-BIM techniques RC4.10- Open query language for BIM RC4.11- nD developments RC4.12- Mapping of BIM & domain knowledge RC4.13- Discrete Event Simulation (DES) model RC4.14- Information extraction RC4.15- Topological information extraction model RC4.16- Java-based BIM	16
RC5	RC5.1- BIM usage and adoption RC5.2- BIM curriculum development RC5.3- Construction stakeholders' BIM adoption strategies RC5.4- BIM teaching and support; RC5.5- Drivers of BIM adoption RC5.6- Cost-benefit analysis of BIM implementations RC5.7- BIM adoption barriers RC5.8- BIM standardization & Intellectual property rights RC5.9- BIM competency assessment RC5.10- BIM ethics & professionalism RC5.11- BIM practice paradigms & governance approach.	11

Code (research category)	Research areas/themes	Number of themes
RC6	RC6.1- Construction planning and monitoring RC6.2- Schedule optimization RC6.3- BIM governance platform RC6.4- Material management & quality assessment RC6.5- Waste management RC6.6- Supply chain management RC6.7- Lean construction management & BIM RC6.8- Construction sequencing & logistics optimization RC6.9- Real-time progress management RC6.10- Labour productivity assessment RC6.11- Automated, rule-based constructability checking RC6.12- 3D compliance checking RC6.13- Project cost control RC6.14-Project delivery and asset management RC6.15- Construction knowledge management RC6.16- BIM-based procurement framework RC6.17- RCE-procurement RC6.18- Construction collaborative networks.	18
RC7	RC7.1- Automated safety planning and management RC7.2- Risk knowledge management RC7.3- Walkability & hazardous area identification RC7.4- Site risk identification RC7.5- Search & Rescue algorithm RC7.6- Fire safety management RC7.7- Workspace safety and requirements RC7.8 Automatic safety checking of construction models.	8
RC8	RC8.1- Automated access control RC8.2- Defect management system RC8.3- Earthquake damage assessment RC8.4- Performance-based maintenance RC8.5- FM data extraction & conversion RC8.6- Indoor emergency response facilitation RC8.7- Virtual retrofit RC8.8- Tracking the built status of MEP works R8.9-Failure root-cause detection RC8.10- Security analysis RC8.11- Localization of RFID-equipped assets RC8.12- Handover model RC8.13- Building maintenance RC8.14- Energy retrofitting RC8.15- Facilities lifecycle information on RFID tags RC8.16- Heat flow modeling RC8.17- Image-based verification of as-built documentation.	17
RC9	RC9.1- Sustainability performance of building RC9.2- Environmental impact evaluation RC9.3- Integrating BIM & LEED RC9.4- Sustainable energy usage RC9.5- BIM-based decision support for master planning RC9.6- Sustainability Appraisal (steel design) RC9.7- Indoor environmental quality (IEQ) RC9.8- Sustainable design and construction RC9.9- 3D analysis of lifecycle assessment RC9.10- Sustainable Material selection.	10
RC10	RC10.1- Pattern and trend in BIM research.	1

Table 3.7: Funding structure

Year	Funded articles	Percent (%)	Research categories	Funded articles	Percent (%)
2016	40	17.3	RC1	21	9.1
2015	67	29	RC2	40	17.3
2014	46	19.9	RC3	35	15.2
2013	32	13.9	RC4	32	13.9
2012	10	4.3	RC5	26	11.3
2011	20	8.7	RC6	39	16.9
2010	8	3.5	RC7	15	6.5
2009	5	2.2	RC8	16	6.9
2008	1	0.4	RC9	7	3
2007	2	0.9	RC10	0	0
2006	0	0			
Total	**231**	**100**		**231**	**100**

Table 3.8: Articles' project sector analysis

Project Sector	Aspects covered	Number of articles
Building and Housing	Single family houses; Residential floors; Parking garage; Storeys buildings; High-rise structures; Building component and elements, Sports center, Educational buildings	347
Transportation	Bridges; Highways; Tunnel construction; Subways; Airports; Subway stations; Railways; Railway tracks	17
Environment	Safe walking environment; Safety; Traffic noise control; Earthquake damage assessment; Waste effectiveness; Hazard identification & prevention; Safety planning; Work-Space Planning	24
Education	BIM curriculum development; BIM implementation; BIM in Quantity Surveying practice; BIM teaching; Developing Students’ Collaborative Skills; Course developments	22
Energy infrastructure	Natural gas plant construction; Gas pipeline; Renewable energy system	5
General	Applies to all project sectors (Procurement, Estimating, Construction projects & Built environment)	28
Urban regeneration	Post-earthquake operations (such as search and rescue, and damage assessment)	2

Table 3.9: BIM Software and data schema

BIM Software category	Software (frequency of mentions or usage)	Number
Data Schema	Industry Foundation Classes [IFC]- 187; GbXML [green building XML]- 30 MVD [model view definitions]- 22; IFCXML- 22; AecXML- 5; City GML- 4; Omni class- 2; NBDM [TrySys]- 1; bcXML- 1; LandXML- 1; EcoXML- 1	11
Architectural and Structural tools	Autodesk Revit- 132; Graphic Soft ArchiCAD- 67; AutoCAD- 28; Bentley Architecture systems- 26; Vico Constructor- 13; Digital Projects- 8; Nemetschek AllPlan- 8; Nemetschek Vectorworks- 4 Google SketchUp- 3; Autodesk Inventor- 1	10
Building Energy Analysis & Simulation Tools	Energy Plus- 24; Ecotect- 17; IES VE- 10; eQuest- 10; DOE-2.2- 7; Radiance- 6	6
Estimating Tools	Quantity take-off- 3; On-screen take-off- 2; Innovaya- 2; BuildSoft Estimating software- 1; CATO CAD- 1; Estimator- 1	6
Structural Tools*	Tekla structures- 30; SAP- 2; MIDAS- 2; STAAD Pro V8i- 1; ADAPT (Structural Concrete Software)- 1	5
Construction Management Tools	Navisworks- 27; MS Excel- 13; MS Project- 11; DProfiler- 3	4
Sustainability Analysis	Green Building Studio- 13; IES Virtual Environment- 10; Project Vasari- 1	3
Model Viewer	Solibri Model Viewer- 32; Bentley Micro Station- 13	2
Geographic Information System	ESRI's ArcGIS- 4	1
Ontology Development Tools	Protégé- 2	1

3.5 Discussions on the BIM Research Categories

This section provides a semantic link between the defined BIM research categories and research areas/themes that were established in section 3.4.2 with a view to providing a more qualitative analysis of the articles in alignment with the categories descriptions. Therefore, we conducted a critical appraisal of selected articles based on their relevance to the established BIM research categories.

To conserve space, we reviewed four research categories out of the ten defined BIM research categories, which are presented in the following sub-sections. Moreover, a total of 175 articles were examined in the section.

3.5.1 Construction and Project Management (RC6)

The research category "construction and project management (RC6") is the most trending BIM sub-field (with 78 articles) among the ten identified research categories, and it also has the highest number of research areas with 18 themes as seen in Tables 3.5 and 3.6. Trending topics in this field include *RC6.1-* "*construction planning and monitoring"* (Faghihi et al., 2016; Kim et al., 2016a, 2014); *RC6.2- "schedule optimization"* (Altaf et al., 2014; Chen et al., 2013; Faghihi et al., 2014; Gelisen & Griffis, 2014; Kang et al., 2016; Kim et al., 2013b; Liu et al., 2015a; Moon et al., 2014; Tserng et al., 2014; Wang et al., 2014a); *RC6.3- "BIM governance platform"* (Dossick & Neff, 2010; Farr et al., 2014; Knight, 2008); *RC6.4- "Material management & quality* assessment" (Chen & Luo, 2014; Francom & El Asmar, 2015; Kim et al., 2015d), and *RC6.5- "Waste management"* (Akinade et al., 2015; Liu et al., 2015c; Porwal & Hewage, 2012; Won et al., 2016).

sMore so, other research areas focus on *RC6.6- "supply chain management"* (Babic et al. 2010; Irizarry et al. 2013; Lu et al. 2016); *RC6.7- "lean construction management & BIM"* (Dave et al., 2016; Sacks et al., 2010a, 2010b); *RC6.8- "construction sequencing & logistics optimization"* (Han et al. 2015; Kumar & Cheng 2015; Marzouk & Abubakr 2016); *RC6.9- "real-time progress management"* (Kim et al., 2013a; Matthews et al., 2015); *RC6.10- "labour productivity assessment"* (Lee et al. 2014; Poirier et al. 2015); and *RC6.11- "automated rule-based constructability checking"* (Hu et al., 2016b; Nahangi & Haas, 2016).

Furthermore, other research themes under RC6 are *RC6.12- "3D compliance checking"* (Jiang & Leicht 2015; Nahangi & Haas 2014); *RC6.13- "project cost control"* (Turkan et al., 2013; Wang et al., 2014b); *RC6.14-"project delivery and asset management"* (Choi et al., 2014; Tsai et al., 2014c); *RC6.15- "construction knowledge management"* (Lin 2014; Peterson et al. 2011; Wang & Leite 2016); *RC6.16- "BIM-based procurement framework"* (Goedert & Meadati 2008); *RC6.17- "RCE-procurement"* (Grilo & Jardim-goncalves 2011; Grilo & Jardim-Goncalves 2013), and *RC6.18- "construction collaborative networks"* (Abedi et al. 2016; Grilo et al. 2013; Neath et al. 2014).

Furthermore, Fan et al. (2014) carried out eight (8) case studies research to assess the effect of BIM on construction projects on aspects such as request for information

(RFI), reworks, schedule compliance and change orders. The findings of the case studies reveal a marked reduction in the RFI between 50 and 90 percent, fewer or no modification(s), and compromises in the project with improved quality. More so, there was more accurate schedule compliance with shorter duration and altogether less reworks and significantly fewer change orders. Meanwhile, to facilitate real-time visualization of BIM models; Johansson et al. (2015) developed a prototype BIM viewer. Tan (2017) use the genetic algorithm (GA) technique to optimize for the visualization of lift planning in offshore rigs. Other studies include BIM for infrastructural projects (Bradley et al. 2016), the development of a prototype BIM-GIS architecture to facility management practices (Kang & Hong, 2015); the use of geospatial and semantic technologies for pre-construction operations (Karan & Irizarry 2015), BIM for quality assurance (Kim et al., 2016c); BIM for work sequencing (Kim et al., 2016b); project progress and productivity improvement (Matthews et al. 2015; Nath et al. 2015), and BIM for as-built documentation (Park & Cai 2017).

In summary, there has been a significant increase in the number of publications classified under the labeled theme "*construction and project management"* between 2013 and 2016, in fact, 65 out of the 78 BIM articles under this research area were published during this period. More so, of the 18 BIM research areas under RC6, we have four themes with more than 6 articles, these include *RC6.2- "schedule optimization"* with 11 articles, *RC6.9- "real-time progress management", RC6.18- "construction collaborative networks"* and *RC6.15- "construction knowledge management"* with 9, 6 and 6 BIM articles respectively.

The review and analysis of the BIM articles reveals the benefits of BIM in construction and project management as (1) to facilitate collaboration and coordination among construction stakeholders; (2) to optimize the construction schedule, (3) to track the progress of work on site, and (4) to serve as hub or central house for the management of construction information and processes.

3.5.2 BIM learning, adoption & practice (RC5)

The next identified BIM research category is "*BIM learning, adoption & practice"* with 70 BIM articles and under this category are 11 research area/themes as shown in Tables 3.5 and 3.6. Without the framework to aid and strengthen the implementation of innovative technology, approaches or techniques in a diverse and competitive industry like the construction industry such technology or approach may not seek the light of the day. The previous statement enforces the importance of BIM paper in this research category.

More so some of these studies and research themes covered include: *RC5.1- "BIM usage and adoption"* (Eadie et al., 2013; Fortner, 2008; Gilkinson et al., 2015; Kim et al., 2016d); *RC5.2- "BIM curriculum development"* (Pikas et al., 2013; Sacks & Pikas, 2013; Sampaio, 2015; Solnosky et al., 2014; Wu & Issa, 2014a); *RC5.3- "construction stakeholders' BIM adoption strategies"* (Ahn et al., 2016; Jung & Lee, 2016; Salleh & Fung, 2014; Xu et al., 2014); *RC5.4- "BIM teaching and support"* (Gnaur et al. 2015; Kim 2012; Kovacic et al. 2015; Sacks & Barak 2010); *RC5.5- "drivers of BIM adoption"* (Mom et al., 2014a); *RC5.6- "cost-benefit analysis of BIM implementations"* (Giel & Issa 2013; Lu et al. 2014).

Other research themes in this research category are *RC5.7- "BIM adoption barriers"* (Chien et al. 2014; Watson 2011); *RC5.8- "BIM standardization & intellectual property rights"* (Fan 2014; Howard & Björk 2008; Kraatz & Hampson 2013); *RC5.9- "BIM competency assessment"* (Giel & Issa 2016; Succar et al. 2013; Wong et al. 2015); *RC5.10- "BIM ethics & professionalism"* (Jaradat et al. 2013; Love et al. 2015; Succar 2009); and *RC5.11- "BIM practice paradigms & governance approach"* (Alreshidi et al. 2016; Becerik-Gerber & Kensek 2010; Hanna et al. 2013; Hanna et al. 2014; Rezgui et al. 2013; Samuelson & Björk 2016; Taylor & Bernstein 2009; Won & Lee 2016).

A study by Lee and Yu (2016) compared the acceptance level of BIM in South Korea and the United States of which the data were collected using interviews and questionnaire surveys. Their findings revealed a higher adoption and user satisfaction rate in the US than those in South Korea. More so, an ethnography research conducted by Mahalingam et al. (2015) on two metro railway stations projects in India, exemplified the effect of BIM in the decision-making process leading to precise planning and reduced contract duration. The rapid growth in BIM adoption in the Swedish construction industry was elucidated in a study by Samuelson and Björk (2014) while Zhang et al. (2016) developed a framework to facilitate the integration of BIM and sustainability studies into the curriculum development for civil engineering students. Also, some set of principal areas or factors to consider in the adoption and implementation of BIM in an organization has been developed (Won et al. 2013).

Conclusively, there have been a steady increase in the number of BIM articles published under the category- "*BIM learning, adoption & practice"* between 2013 and 2016; however, prior to this period, less than four BIM articles in this research area were disseminated. Meanwhile, BIM research in this category had focused mostly on *RC5.1- "BIM usage and adoption"* and *RC5.11- "BIM practice paradigms & governance approach"* (with 13 articles each); we can then surmise that BIM being a novel approach in the built environment has led BIM authors to direct their attention to the core of its adoption and practice and to set up a governance mechanism to facilitate its implementation. Next, are research themes such as *RC5.2- "BIM curriculum development"* and *RC5.4- "BIM teaching and support"* with 7 articles each; this analysis reveals the increasing spotlight on the development of BIM module and training for undergraduate university students and professionals who would be the fulcrum in the adoption and implementation of BIM.

Therefore, based on the analysis of this category, we deduce the critical drivers of BIM adoption to include: (1) The development of undergraduate BIM curriculum and modules which should incorporate the practical aspects of BIM to train students who are potential 'recruits' to the industry. (2) The institution of a training and support programs such as workshops, seminars, and conferences on BIM to aid the skill sets and development of in-house personnel on the use of BIM. (3) Establishment of a working BIM governance mechanism or framework to support its overall implementation and increase the success rate of BIM-enable projects.

3.5.3 Building design and Energy conformance (RC2)

The research category of "*Building design and Energy conformance (RC2)"* is another major area of immense publication and interest among BIM authors and in the construction industry with 65 BIM articles as at the year 2016. The bibliometric analysis of its research areas and themes crystallize out nine (9) main BIM research themes which are: *RC2.1- "building energy regulations"* (McGuire et al. 2016; Thompson & Bank 2010); *RC2.2- "code checking & compliance"* (Dimitrov & Golparvar-Fard 2015; Jung et al. 2015; Li et al. 2014); *RC2.3- "building envelope, cost and energy performance"* (Ahn et al., 2014; Asl et al., 2015; Chardon et al., 2016; Gökçe & Gökçe, 2013; Migilinskas et al., 2016); and *RC2.4- “energy management and analysis”* (Gökce & Gökce 2014; Kim & Anderson 2013; Kim & Yu 2016a; Lee et al. 2016).

Meanwhile, other preeminent research themes in this category include: *RC2.5- “structural analysis and design”* (Bosché & Guenet, 2014; Ham & Golparvar-Fard, 2015; Lee et al., 2012b; Marzouk & Abdelaty, 2014b); *RC2.6- “building rating systems and assessments”* (Basbagill et al. 2013; Oti et al. 2016; Ryu & Park 2016); *RC2.7- ”tracking of design changes and errors”* (Dong et al., 2014; Lee et al., 2015a; Pilehchian et al., 2015); *RC2.8- “daylighting profiling”* (Welle et al. 2012), and *RC2.9- “design validation and coordination”* (Gimenez et al., 2016; Kim & Jeon, 2012; Kim & Yu, 2016b; Lee et al., 2012a; Shin & Cho, 2015). Meanwhile, a bibliometric analysis of this category reveals more BIM publications in areas such as *RC2.5- “structural analysis and design”* with 13 articles and *RC2.3- “building envelope, cost, and energy performance”* with 12 BIM articles.

Other aspects such as *RC2.9- “design validation and coordination”* and *RC2.4- “energy management and analysis”* with 12 and 10 BIM articles respectively are current research directions in this category. Authors with research interest in “*building design and energy conformance (RC2)”* tends to center the studies mostly in these four main themes; and it signifies the increasing importance of developing BIM models for projects which are of (1) high structural design and integrity; (2) validated and vetted designs, and (3) a profiled and efficient energy usage and management.

Studies such as Ham and Golparvar-Fard (2015) developed a system using the gbXML schema to improve the energy performance of buildings while query systems based on IFC schema have also been advanced (Gao et al. 2015; Kang 2017; Solihin et al. 2017). More so, Kim et al. (2015b) developed a physical BIM library to aid the simulation of building component thermal conditions; while Kim et al. (2015a) observed that most energy analysis for buildings are done when the design has been completed. Hence, they developed an IFC framework to map building materials with energy properties of which the results shows “significant gain in accuracy.” Meanwhile, Gökçe and Gökçe (2014) introduced an efficient integrated energy platform for the residential buildings, while Shiau et al. (2012) utilized Ecotect software to improve the energy usage of old structures; and studies such as Cho et al. (2014) and Knight et al. (2010) discusses the benefits of BIM in HVAC design and placement of reinforcement bars in concrete slabs respectively. Other researches focus include case studies reviews on structural BIM (Robinson 2007); quantitative assessment of carbon-dioxide emission (Jun et al. 2015); strategies for design error management (Al Hattab et al. 2015); creation of BIM models from laser scanner data (Xiong et al. 2013), and the design of track alignment using BIM (Huang et al. 2011).

3.5.4 Sustainability (RC9)

Sustainability is one of the increasing and preeminent issues in the construction industry and in other sectors of the global economy, while the concept of sustainable development represents a pyramid shift in the three-wheel drive of construction projects otherwise known as the "project management triangle" which are the time, cost and quality. The adoption and implementation of sustainable practices in construction ensure such projects meets its environmental, social and economic needs, considerations and implementation. BIM publications in this category are on the increase since the year 2011 till date with ten (10) main research themes has identified by the bibliometric analysis of this category articles' corpus.

The predominant research areas in this category include: *RC9.1- "sustainability performance of building"* (Jrade & Jalaei 2013; Kreiner et al. 2015); *RC9.2- "environmental impact evaluation"* (Lee et al., 2015b); *RC9.3- "integrating BIM and LEED"* (Azhar et al., 2011; Jalaei & Jrade, 2015; Wu & Issa, 2014b); *RC9.4- "sustainable energy usage"* (Azzi et al., 2015; Liu et al., 2015b); *RC9.5- "BIM-based decision support for master planning"* (Kim et al., 2015c); *RC9.6- "sustainability appraisal"* (Oti & Tizani, 2015; Wong & Kuan, 2014); *RC9.7- "indoor environmental quality (IEQ)"* (Marzouk & Abdelaty 2014a); *RC9.8- "sustainable design and construction"* (Bynum et al. 2013; Geyer 2012); *RC9.9- "3D analysis of lifecycle assessment"* (Inyim et al. 2015; Kulahcioglu et al. 2012); and *RC9.10- "sustainable material selection"* (Bank et al. 2011).

Prominent studies on sustainability issues in construction projects include Oti et al. (2016) who utilized the BIM API extension to embed sustainability issues to simulate the assessment of structural steel design; while Oh et al. (2015) in a case study approach, reviewed the enhancement of the design quality of a hospital design using an integrated system. Ilhan and Yaman (2016) advanced an IFC-based sustainability decision support system (“Green building assessment tool (GBAT)”) of which green building data can be certified for BREEAM (Building Research Establishment Environmental Assessment Method).

3.6 Research Limitations

The main limitation of this study’s bibliometric analysis is the literature search strategy.That is, the choice of the scientific database (ISI Web of Science) which despite being “*the world’s leading citation database, offering a high level of accuracy and detail on a multidisciplinary scale*” (Neto et al. 2016), it may only represent a fraction of the whole population. Another drawback might evolve from the exclusion of articles not written in English and some other false positives in the removal of some unrelated papers or the categorization of items within research areas.

3.7 Conclusions

The advent of BIM in the construction industry has brought about tremendous improvement in the process and system of coordinating construction projects and enabling collaboration among professionals both in the academia and the industry. The research’s objectives were to investigate and evaluate the extant literature on BIM; and identify the trends, research impacts, research categories, BIM funding structure and other parameters of the research publications’ corpus through a bibliometric analysis of 445 BIM articles; which are of high impact factors from the Web of Science which Neto et al. (2016) regarded as the “largest and most reliable source for academic publications”.

The level and depth of the bibliometric analysis is considered as the prime distinction between this study and previous literature reviews on BIM literature; which allows academics, industry practitioners and readers to track the funding structure of BIM research, the research categories and the project sectors for which BIM has had the most impact; and have an overview of how BIM literature has evolved over the years. Moreover, based on the bibliometric analysis of the BIM articles, there was a marked increase in the number of BIM articles from 17 papers in 2010 to almost double value of 32 BIM articles in 2011 and the volume of BIM publications crossed the threshold of a hundred (100) BIM papers in the year 2015 with a total of 114 published BIM articles.

Also, an analysis of the articles' corpus journal list reveals *Automation in Construction* as the journal with most published work on BIM themes. More so, the tremendous impacts of BIM implementation in the construction industry were felt most in the building and housing project sector with more than 340 BIM articles addressing issues such as building elements and components, etc.. Other project areas such as transportation, environment, and even the educational sector had been positively influenced by the adoption of BIM with several articles developing frameworks, models, systems and providing innovation solutions to improve the identified sectors using BIM.

More so, after the bibliometric analysis of the BIM articles, we further endeavor to classify them into 10 research categories, and the core research categories based on published BIM works are (1) Construction and Project Management. (2) BIM learning, adoption, and practice. (3) BIM design and energy conformance. (4) BIM software and data schema; and (5) BIM model development. The five research categories had more than 50 BIM articles each and are considered the salient BIM research areas. Nevertheless, research areas such as *facility management* and *sustainability* can be classified as the latest trends in BIM research with increased output in publications in those two categories since the year 2014.

Furthermore, an analysis of funding structure of BIM articles reveals that more than 50 percent of the 445 analyzed articles received some funding to undertake the research; while further funding inquiry-based research category analysis and research origin analysis reveals thus: (1) there has been a significant increase in funded articles since the year 2013 till date, (2) BIM articles relating to research categories such as "*building design and energy conformance", "construction and project management", "BIM software & data schema"* and "*BIM model development"* have received more funding (with at least 30 funded articles); (3) the Republic of Korea and the United States with 68 and 45 funded BIM publications are the countries whose BIM researchers have received a sizeable number of research grants to undertake BIM-related research. However, funding analysis by regions shows Asia with 112 articles, Europe with 57 articles and North America with 55 BIM articles are the regions with the most funded BIM publications.

Moreover, a further analysis of the research categories reveals 107 research themes. The analysis unfolds trending research themes and direction, both in the academia and in the industry and these include: "*BIM usage and adoption (RC5.1),*" *"BIM practice paradigms & governance approach (RC5.11)"; "structural analysis and design (RC6.9)," "building envelope, cost and energy performance (RC2.3)," "design validation and coordination (RC2.9)"; and "energy management and analysis (RC2.1)"* with more than 10 BIM articles each. The result is a pointer to the fact that more studies are being conducted to investigate BIM adoption and implementation in several countries and domains, and in countries where BIM has reached an acceptance level of adoption and compliance, such as the US, research tends to focus on developing and introducing BIM governance mechanisms. Other findings evaluate the salient research methodology used in previous studies and the available BIM software and data schema while the discussion centered on the established BIM research categories and themes.

However, for potential future research, researchers can select one or more research category or theme and undertake a review using the same or different research approach. The study's bibliometric analysis identified some essential gaps and opportunities for future research in BIM field. Research areas such as (1) BIM-Sustainability issues integration, (2) Using BIM for environmental and socio-economic evaluations, (3) integrating BIM and Augmented reality during the construction phase, (4) Ontology and semantic web, (5) Mapping of BIM & domain knowledge and (5) information extraction are currently not receiving adequate considerations from researchers in the academia and those in the industry. It is noteworthy that these research areas when given due attention have the benefits of enhancing the growth of the construction sector and boost its productivity level. Conclusively, the study would assist BIM researchers and other academics to recognize the pattern and structure of BIM research and field and help them to pinpoint areas of research interest for their future research works.

3.8 Chapter Summary

Building Information Modelling (BIM) processes have continued to gain relevance in the Architectural, Engineering, and Construction (AEC) industry with more resources directed toward it. This study conducts a bibliometric analysis of 445 BIM articles to investigate and understand the pattern of BIM research which include defining BIM research categories, evaluating the project sectors that are influenced by BIM, and tracking the funding structure of BIM research. A network map that displays a visualization of the structure of BIM literature by research origin, funding structure and geographical scope was designed. None of the previous reviews of literature analyzed the BIM articles' corpus to such level and depth. The findings revealed research categories such as construction and project management and BIM learning, adoption & practice as the core research areas in BIM and highlighted trending research themes in BIM research. Authors based in Asia and Europe received more research grants than their counterparts in other regions; likewise, two-third of the articles were authored by academics in the United States, Korea, and the United Kingdom. This chapter provides its readers with relevant research areas that require considerations, and the discussion of selected research areas provide an extensive understanding of salient BIM fields. The next three chapters (Chapters 4, 5, and 6) will discuss the findings of the identification and assessment of the inherent benefits, barriers and drivers associated with integrating BIM and sustainability principles in building projects towards fulfilling Objective #1 of this study. The following chapter examines the benefits of the implementation of BIM and sustainability practices – otherwise known as smart sustainable practices in this study – in building projects and in the built environment.

CHAPTER 4: AN EMPIRICAL SURVEY OF THE PERCEIVED BENEFITS OF EXECUTING BIM AND SUSTAINABILITY PRACTICES IN THE BUILT ENVIRONMENT[4]

4.1 Chapter Overview

The previous chapter presented a comprehensive reviews and bibliometric analysis of BIM literature and illustrated using network maps the structure of BIM trends. This chapter identifies and examines the benefits of the implementation of BIM and sustainability practices – otherwise known as smart sustainable practices in this study – in building projects as well as in the built environment. Two datasets were collected namely via Delphi surveys (14 experts participating) and international survey involving 220 respondents. However, to conserve space, only the result of the international survey findings will be presented in this chapter. A link to the published findings of the Delphi survey conducted in this research is provided in section 4.4 of this chapter.

4.2 Introduction

The input of technological innovations and salience to sustainability issues in the construction industry has been argued as the best approach for the built environment to achieve its goal of a sustainable smart city and buildings. Aasa et al. (2016) noted that sustainable development is achievable through the implementation of green innovations which involve implementing sustainable solutions using adaptable technologies. An excellent example of a versatile technology is the Building Information Modelling (BIM) system which is described by Olatunji et al. (2017b) as a set of applications and process capable of generating and managing project information throughout the project development phases with numerous benefits to the project stakeholders.

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[4] This chapter is largely based upon the following published papers:

Olawumi, T.O., & Chan, D.W.M. (2019a). An empirical survey of the perceived benefits of executing BIM and sustainability practices in the built environment. *Construction Innovation: Information, Process, Management*, 19(3), 321–342. https://doi.org/10.1108/CI-08-2018-0065

Olawumi, T.O., & Chan, D.W.M. (2018d). Identifying and prioritizing the benefits of integrating BIM and sustainability practices in construction projects: A Delphi survey of international experts. *Sustainable Cities and Society*, 40, 16–27. https://doi.org/10.1016/j.scs.2018.03.033

Malleson (2012) noted that BIM adoption had improved significantly in the United Kingdom (UK) as well in North America (Bernstein et al., 2012); and a sizeable number of contracting and client's organizations have switched to 3D CAD from 2D CAD. Leveraging on this significant improvement in BIM adoption and implementation in the industry, project stakeholders can enhance the adoption of sustainability practices by developing new tools and plugins where existing ones might be limited in its functionality. Abanda and Byers (2016), and Bynum et al. (2013) reported that building facilities account for 32 percent of global energy consumption and one-fifth of the associated greenhouse gases (GHS). Hence, Gourlis and Kovacic (2017) reported that emerging technologies such as BIM offers promises in the optimization of energy needs as well as identification of the potentials in synergizing building envelope and services to reduce the carbon footprints of buildings. A practical example is a real-life case study building project in which BIM was used to model the energy performance (one of several sustainability parameters) which yielded a significant energy cost savings across the building lifecycle.

Also, Tsai et al. (2014b) test-run a customized BIM tool for a design firm. Also, Oti et al. (2016) demonstrated the use of Application Programming Interface (API) in BIM tools to appraise the ability of BIM to embed sustainability ontologies as a new approach to assess some 'quantitative' parameters of sustainability. BIM without doubt promising and innovative tool capable of changing the landscapes of construction processes and activities even though, according to Oti et al. (2016), and NIBS (2007), BIM is still a maturing technology. Oti et al. (2016) noted that the existence of some proprietary functions in BIM and the flexibility to add plugins had extended its capacity to address issues such as sustainability as well as for end-user customization. More so, Tah and Abanda (2011) also explored the use of semantic web technology and ontologies to represent sustainability knowledge, although, semantic web technologies are still new, it offers a good prospect to assess sustainability parameters and ease the decision-making process.

Moreover, current application of BIM to sustainability practices include (i) lifecycle cost assessment (LCA) (Lundin & Morrison, 2002; Soust-Verdaguer et al., 2017); (ii) sustainable design (Bynum et al., 2013). (iii) Sustainable material selection (Govindan et al., 2015); (iv) waste management (Akinade et al., 2015); (v) daylighting simulation and analysis (Kota et al., 2014); (vi) energy consumption and performance (Abanda & Byers, 2016; Kuo et al., 2016); and (vii) carbon footprint (Shadram et al., 2016). Habibi (2017) examined the potential of BIM to improve the energy efficiency and indoor environmental quality of building facilities. Clearly, these emphasized the need to explore the benefits of BIM and sustainability practices to provide evidential support and to aid clients along with project teams in their quest to adopt green BIM in their projects.

Bring the perspectives together; the current study intends to bridge the gap in the knowledge and practice by identifying and assessing the practical benefits to the construction industry and the built environment when BIM and sustainability practices are implemented in construction projects. The study will consider the benefits from the various viewpoints of construction professionals such as civil engineers, construction managers, architects as well as those from diverse organizational setups such as public and private clients, contractors and project consultants. The study will also attempt to classify the identified green BIM implementation benefits as well as provide strategies and recommendations for construction organizations, project teams, local authorities and other key stakeholders towards enhancing the uptake of green BIM initiative in construction projects.

Throughout the literature and in practice, we have seen construction projects which either adopt BIM or sustainability practices with varying project success and results. However, this study addresses the benefits achievable in projects in which the clients or the project team intends to use innovative technology such as BIM to amplify the sustainability practices in construction projects. The findings are expected to apply to any buildings projects whether residential, commercial or industrial buildings; and with a focus to facilitate the support and commitment of clients and key project stakeholders by presenting the key benefits achievable via the use of BIM to enhance sustainable parameters of their projects.

More so, the integration of BIM and sustainability practices implies the use of BIM technologies such as BIM software, cloud-BIM, plugins such as those developed by Oti et al. (2016) and the use of semantic web technology (Tah & Abanda, 2011) among others for sustainability assessment and simulation in projects. It is advisable according to Ghaffarianhoseini et al. (2017) to leverage on technology tools such as

BIM to reinvent the current design and delivery practices in the industry. Hence, it is conceivable that integrating the two concepts in construction projects will assist the project team to exploit the benefits of adopting innovative technologies as well as achieve objectives such as green buildings and neighborhoods, reduced carbon footprints, etc.

4.2.1 The impact of the implementation of BIM and sustainability practices

The capacity of BIM as a platform that allows for multi-disciplinary data to be embedded in a single model (Azhar et al., 2011) provides project teams the opportunities to incorporate sustainability parameters into such building models; this informs the basis for simulating and analyzing the sustainability performance of buildings and for comparison purposes (Ahn et al., 2014; Olawumi et al., 2017). The impact of the adoption of BIM and sustainability practices have been identified in the literature as shown in Table 4.1 (Olawumi & Chan, 2018d). Wu and Issa (2014b) stressed the importance of the implementation of green BIM in a project, and that it not only ensures the project team achieves the intended project goals and outcomes but also ensures the targeted sustainability goals are realized.

Kats et al. (2003) noted that although it might cost a project like two percent increase of the initial cost of the construction, such projects stand to make significant savings in the lifecycle costs of the project which can be up to 20 percent of the initial construction cost. Hence, per Azhar et al. (2011), green buildings are economically viable with little or no environmental impact on the locality. McGraw-Hill Construction (2010) stressed that the proper integration of green BIM in construction would enable project teams to successfully steer a construction project which is usually complex and sophisticated in a collaborative manner (Ayegun et al., 2018; Olatunji et al., 2017a; Olawumi & Ayegun, 2016). Also, Azhar et al. (2011) and Bynum et al. (2013) noted that the adoption of green BIM helps to facilitate a better decision-making process among the project stakeholders and aid the sustainability analysis of design models at the early stages of a project; and these combine to promote the project’s sustainability goals.

Meanwhile, to assess the level of the implementation of green BIM, countries such as the United States, the United Kingdom, South Korea, Japan, Hong Kong has develop BIM standards and sustainability rating system to rate the performance of buildings (Azhar et al., 2011; Olawumi et al., 2017; Wong & Zhou, 2015). The standards provide the prerequisites to be met by a building or facility before it can be classified as a green building and contains practical and measurable criteria for implementing BIM and sustainability in those regions. Kriegel and Nies (2008) highlighted areas in which BIM can aid the sustainable design and these include daylighting analysis, selection of sustainable materials, selecting a good building orientation in order to reduce energy consumption, water harvesting and energy modeling among others. Saka et al. (2017) highlighted the significance of energy and its consumption to the economic development and growth of a nation. A survey study of 145 design and construction firms by Azhar (2010) revealed that a good number of the firms achieved time and cost savings when they implemented green BIM in their projects.

Meanwhile, Azhar et al. (2011) conducted a case study analysis on a project and discovered that there is no relationship between some sustainability parameters (like those of LEED) and some BIM-sustainability based analyses. However, it demonstrated the potential benefits of the synergy of BIM and sustainability towards the implementation of smart, sustainable cities. Also, Antón and Díaz (2014) while highlighting the necessity for the construction industry to adopt green BIM observed that 40% of total waste and resources are consumed in construction projects globally and that another 40% of energy consumed in the European Union is from the industry. Hence, Welter (2003) argued for construction stakeholders participation in its implementation, while Kummitha and Crutzen (2017) calls for local authorities to enact laws to promote the concept of sustainable smart city initiative which is the ultimate goal of implementing green BIM in the built environment. Olawumi and Chan (2019c) meanwhile, developed a benchmarking model to facilitate BIM implementation in developing countries and produce an assessment template for a comparative evaluation of BIM projects.

Pérez-Lombard et al. (2008) indicated that the energy consumption of buildings in recent years had exceeded those of other major sectors like transportation due to the growing demand for building services and human comforts. These various viewpoints from the literature further underlined the relevance of the integration of BIM and sustainability practices in the construction industry. A review of the literature shows increasing research on BIM and sustainability (Olawumi et al., 2017; Olawumi

& Chan, 2017; Wong & Zhou, 2015). Goldman et al. (2002), and Frankel and Turner (2008) buttressed the influence of BIM and sustainability in some reviewed LEED certified projects which shows significant energy savings in most of the building projects evaluated. The positive contribution of green BIM to the construction sector according to De Jong et al. (2015) has triggered a welcoming impression on local authorities in some major cities in the world who are now trying to upgrade the public infrastructure to create a better sustainable and attractive environment for its residents as well as enhancing the cities' overall competitiveness. Given the above reviews from existing studies, the subsequent aspects of the study will examine and assess the perception of the 220 survey participants on the benefits of the implementation of BIM and sustainability practices.

Table 4.1: Summary of identified benefits of the implementation of BIM and sustainability practices

Code	Benefits	References
BN1	Enhance overall project quality, productivity, and efficiency	Azhar (2011)
BN2	Schedule compliance in the delivery of construction projects	Azhar (2011); Philipp (2013)
BN3	Predictive analysis of performance (energy analysis, code analysis)	Lee et al. (2015b)
BN4	Improve the operations and maintenance (facility management) of project infrastructure	Azhar (2011)
BN5	Reduction in cost of construction works and improvement in project's cost performance	Bynum et al. (2013)
BN6	Improve financial and investment opportunities	Ku and Taiebat (2011); Lee et al. (2012a)
BN7	Reduction in the cost of as-built drawings	Boktor et al. (2014)
BN8	Facilitate sharing, exchange, and management of project information and data	Olatunji et al. (2017b); Wong et al. (2014)
BN9	Facilitates resource planning and allocation	Akintoye et al. (2012)
BN10	Reduction in site-based conflicts	Hanna et al. (2013)
BN11	Ease the process to obtain building plan approvals and construction permits	Antón and Díaz (2014)
BN12	Support collaboration and ease procurement relationships	Aibinu and Venkatesh (2014); Olatunji et al. (2016b)
BN13	Reduced claims or litigation risks	Bolgani (2013)
BN14	Increase firms' capability to comply with prevailing statutory regulations	Aibinu and Venkatesh (2014); Antón and Díaz (2014)
BN15	Better design products and facilitate multi-design alternatives	Lee et al. (2012a)
BN16	Facilitate building layout flexibility and retrofitting	Webster and Costello (2005)
BN17	Real-time sustainable design and analysis early in the design phase	Alsayyar and Jrade (2015)
BN18	Facilitate, support and improve project-related decision-making	Sacks et al. (2010a)
BN19	Improved organization brand image and competitive advantage	Antón and Díaz (2014)

Code	Benefits	References
BN20	Enhance business performance and technical competence of professional practice	Deutsch (2011)
BN21	Enhance innovation capabilities and encourage the use of new construction methods	Deutsch (2011)
BN22	Prevent and reduce materials wastage through reuse & recycling and ensure materials efficiency	Akinade et al. (2017)
BN23	Reduce safety risks and enhance project safety & health performance	Vacharapoom and Sdhabhon (2010)
BN24	Control of lifecycle costs and environmental data	Ku and Taiebat (2011)
BN25	Facilitate the implementation of green building principles and practices	Wu and Issa (2015)
BN26	Ease the integration of sustainability strategies with business planning	Autodesk (2010a)
BN27	Minimize carbon risk and improve energy efficiency	Wu and Issa (2015)
BN28	Improve resource management and reduce environmental impact across the value chain	Ajayi et al. (2016)
BN29	Facilitate the selection of sustainable materials, components, and systems for projects	Jalaei and Jrade (2014)
BN30	Higher capacity for accommodating the three pillars of sustainability (social, economic & environmental sustainability)	Antón and Díaz (2014)
BN31	Enhance the accuracy of as-built drawings	Akintoye et al. (2012)
BN32	Facilitate integration with domain knowledge areas such as project management, safety, and sustainability	Kam et al. (2012)
BN33	Allow the checking of architectural design of buildings from the sustainability point of view	Abolghasemzadeh (2013)
BN34	Facilitate accurate geometrical representations of a building in an integrated data environment	Azhar (2011)
BN35	Ability to simulate building performances and energy usage	Aksamija (2012)
BN36	Encourage the implementation of clean technologies that require less energy consumption	Bonini and Görner (2011)

Source: Olawumi and Chan (2018b)

4.3 Benefits of BIM and Sustainability Practices Implementation in Construction Projects

Previous studies have demonstrated the endless benefits (*see* Table 4.1) obtainable when either BIM or sustainable practices are implemented in construction projects. There has also been an increase in cross-field research in BIM and sustainability in recent years (Olawumi et al., 2017; Olawumi & Chan, 2017). Adamus (2013) reviewed some BIM-based sustainability analysis tools and highlighted the benefits that can be gained when full interoperability is achievable between BIM design and analysis tools. Accordingly, the author argued for the development of the current data formats such as gbXML and IFC towards facilitating sustainable development.

However, the previous study only highlighted few benefits which are solely related to BIM adoption.

Some benefits of adopting BIM in construction projects were also identified by Mom et al. (2014a) and Azhar (2011). One of the key benefits identified by the literature is the use of BIM to identify potential issues relating to the building design, construction, and operation. Also, Olawumi et al. (2017) reported that BIM could be used to advance sustainability practices in construction projects such as the management and profiling of energy usage in buildings. Akadiri et al. (2013) regard BIM as a veritable tool for the selection of sustainable materials for construction projects. The use of BIM software and associated simulation tools to enhance the sustainability parameters of buildings such as to reduce its carbon footprints, improve building energy performances and green neighborhoods is noteworthy. Akinade et al. (2015) developed a BIM-based algorithm to measure the practicability of measuring the deconstructability of building designs to minimize waste and facilitate efficient materials use. GhaffarianHoseini et al. (2017) revealed that BIM has helped project stakeholders to achieve the Australian Green Star rating and improve the design strategy.

Also, Khaddaj and Srour (2016) observed that BIM could be utilized to simulate building maintenance and retrofitting; hence when linked with sustainable measures using associated plugins or APIs, it could help advance the implementation of sustainability practices to the facility management stage. Moreover, the aim of implementing these sustainable measures in a construction project is to achieve sustainable development as well as the construction of green buildings which can mitigate against negative of constructed structures on the environment as well as on human lives (Maleki & Zain, 2011). Other positive effects of achieving green buildings or sustainable smart cities are the added benefits on human health, occupant productivity, organizational marketability (Ali & Al Nsairat, 2009) and green neighborhoods. These previous studies have focused mostly on the environmental aspect of sustainable development. Also, according to Ahmad and Thaheem (2017) majority of BIM software available to simulate sustainability parameters focused on the environmental aspect; hence, it is difficult to assess the benefits of using BIM technologies for the three pillars of sustainability.

Practical examples of the benefits of BIM implementation in construction projects was illustrated by Abanda et al. (2017) who identified several parameters such as cost, time, quality, productivity, and process, etc. as areas in which the adoption of BIM can profit the construction project. The study also listed some BIM software that is available in the market. Gourlis and Kovacic (2017) enumerated that utilizing BIM to simulate and model the energy needs of industrial buildings can minimize the high energy consumption of such building typologies. Also, the ability of BIM tools to embed other knowledge databases can be advantageous in evaluating some qualitative measures such as some social sustainability parameters. The development of data schemas such as the industry foundation class (IFC) and gbXML allows for data transfer from BIM design tools to simulation tools (Olawumi et al., 2017), although the challenge of interoperability is still prevalent in the industry (Jeong et al., 2016).

Huang et al. (2012) underlined the potential of BIM for the management of industrial parks in Taiwan throughout its lifecycle. In the management of these parks, BIM was augmented with other associated tools for GIS, visualization, navigation solutions; which allows real-time monitoring, feedback, and communication. Wang et al. (2013) also utilized BIM to optimize the workflow processes. There are endless possibilities in integrating to different domain areas such safety, scheduling, cost management, procurement, project management as well as sustainability. According to Gourlis and Kovacic (2017), the potential of BIM in sustainability in areas such as building performance is an increasingly exciting research area in the literature. However, the study is advocating a more adept application of BIM to more aspects of sustainability to garner maximum benefits.

Meanwhile, some difficulties are still being faced in the industry to advance BIM application in sustainability practices such as interoperability (Kovacic et al., 2013), procedural uncertainties (Gourlis & Kovacic, 2017; Morgan et al., 1992). However, the construction industry will stand to gain more possibilities by deploying BIM infrastructures to amplify sustainability practices in their projects as highlighted in the literature discussed in this section.

4.4 Research methodology

The study employed a quantitative research design to explore and assessed the benefits derivable by the construction industry when BIM initiatives and sustainability practices are implemented in construction projects. Primary data for the study were collected through empirical questionnaire surveys and secondary data via a review of relevant literature from journal papers, books, and web pages. As perceived by Olatunji et al. (2017a), the instrument and approach to data collection have a significant effect on the achievement of the study's aims and objectives.

The target respondents for the study's survey are construction professionals and stakeholders with a good knowledge of BIM and sustainability. The survey forms were prepared and sent in three formats to the survey participants, and these include: (1) fill-in PDF survey forms; (2) hand-delivered questionnaires; and (3) online survey forms. Most of the respondents were sent personalized emails with links to the online survey form and an attached fill-in PDF survey form. The questionnaire form and its items were pretested with a few related experts before distribution, and a total of 220 survey responses were received from respondents across 21 countries, and most of the responses were through the online survey form (161 responses), and the rest from hand-delivered questionnaires (45), and fourteen responses were gleaned by means of the fill-in PDF survey forms. The questionnaire form (see Appendix B) solicited necessary information on each respondent as well as their perceptions on the degree of importance of the listed factor items on the benefits on BIM and sustainability practices on a 5-point Likert scale (*1=strongly disagree, 3=neutral and 5=strongly agree*). The data collected were analyzed using statistical tools as explained in later sections of this paper.

Meanwhile, prior to the empirical international questionnaire survey, a Delphi survey was conducted involving 14 experts across eight countries towards reaching a consensus on the cross-field research topic. See Olawumi and Chan (2018d) for the published findings of the Delphi survey exercise.

4.4.1 Statistical tools and reliability test analysis

Descriptive and inferential statistical tools were employed to analyze the survey data, and these include: (1) Cronbach's alpha reliability test, α; (2) Mean ranking (M) and standard deviation (SD); (3) ANOVA, post-hoc Tukey tests & correlation analysis;

and (4) Factor analysis and groupings. More so, before subjecting the data to further statistical analysis as recommended by Field (2009), a reliability test was conducted to assess the questionnaire items and its associated scale whether it measures the right construct (Field, 2009; Olawumi et al., 2018).

The Cronbach's alpha value for the study was 0.968 which is higher than the minimum threshold of 0.70 (Olawumi & Chan, 2018c, 2019d) which implies a good internal consistency and that the questionnaire scale measures the right construct which makes the data suitable for further analysis (Olawumi & Chan, 2018b). For this study, in a case where two or more items have the same mean value, the values of their SD are used to rank them. Items with smaller SD's values are ranked higher (Olatunji et al., 2017a; Olawumi & Chan, 2018d), and in cases, the items have the same mean and SD values, the items will be allocated the same rank.

4.4.2 Demographics of the survey participants

Survey participants from 21 countries participated in the study's questionnaire survey. Figure 4.1 shows the demographics of the working experience of survey participants in the construction industry with varied lengths. The two-hundred and twenty (220) participants have practical knowledge and understanding of BIM and sustainability concepts with 43.2 percent of the respondents having at least a high level of awareness of BIM process and a higher percentage (52.8%) with at least a high degree of awareness of the sustainability process. Also, 36.8 percent and 35.9 percent of the survey participants rated their level of awareness of BIM and sustainability respectively as an average. These findings lend credibility to the data and opinions collected from the survey respondents.

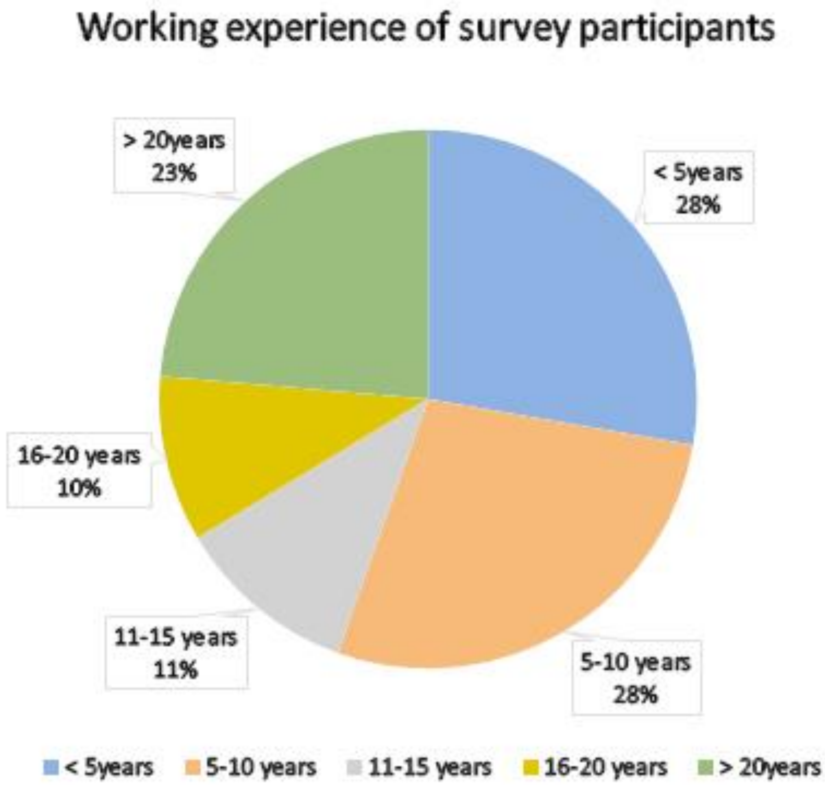


Figure 4.1: Profile of working experience of survey participants

Meanwhile, the analysis of the respondents' demographics based on their organization type reveals that majority of them are from the academics and the public-sector clients (*which included local authorities and policymakers, etc.*) with 39.5% and 25% respectively of the 220 survey respondents. Also, the analysis reveals the respondents from the main contractors (15.9%), project consultants (11.4%) and private clients (5.5%) as one of the significant groups of respondents for the study.

Moreover, an analysis of the survey participants revealed the quantity surveyors (25%), researchers (13.2%), architects (12,7%), project managers (12.3%), and civil engineers (10.9%) as the most represented professional groups among the survey participants. Furthermore, 56.8 percent of the survey participants suggested the planning stage at the best stage to implement BIM and sustainable practices in a project. Also, 37.3 percent of the respondents argued for the design stage, while 5.5 percent of the respondents considered the construction stage as the best time.

4.3 Analysis and discussion of survey results

This section presents the data collected via the empirical questionnaire surveys and discusses the findings of the statistical tools utilized in the study.

4.3.1 Descriptive statistical tests

The mean values for the 36 identified benefits range from M= 4.30 (SD= 0.784) for "*BN8 - facilitate sharing, exchange, and management of project information and data*" to M=3.51 (SD= 1.027) "*BN11 - ease the process to obtain building plan approvals and construction permits*" at a variance of 0.79 (see Table 4.2). More so, the study adopted the benchmark score of 4 out of 5 on a 5-point Likert scale (Lu et al., 2008; Olatunji et al., 2017a; Olawumi et al., 2018) to identified some factors have highly significant factors. Using this metric, the analysis revealed the top-five key benefits of implementing BIM and sustainability practices in construction projects. These include: "*BN8 - facilitate sharing, exchange, and management of project information and data*" (M= 4.30, SD= 0.784), "*BN1 - enhance overall project quality, productivity, and efficiency*" (M= 4.29, SD= 0.700), "*BN17 - real-time sustainable design and analysis early in the design phase*" (M= 4.20, SD= 0.733), *"BN15 - better design products and facilitate multi-design alternatives*", (M= 4.18, SD= 0.796) and "*BN22 - prevent and reduce materials wastage through reuse & recycling and ensure materials efficiency*" (M= 4.18, SD= 0.828". The study's findings and based on the perceptive of the survey participants, it is revealed that the implementation of these two concepts will have a vital effect on not only the final product (buildings and infrastructure) by massively improving it both in design and its efficiency; it can also enhance the process whereby construction products are delivered in the built environment. As advocated by Ayegun et al. (2018), project quality and effective communication is a vital ingredient to measure project success. More so, adopting BIM and sustainability in a project will reduce construction material wastages as well as facilitate the simulation analysis of design alternatives and building performance.

Also, there is an agreement by the respondents from various organization setups on some of the key factors such as "BN1 - enhance overall project quality, productivity, and efficiency" which is ranked among the top-five factors by most of the respondents' groups except the private clients which rated the factor as the eighth-ranked benefits. The findings is highly expressive and is consistent with the literature

(Gu & London, 2010; Olatunji et al., 2017b; Olawumi et al., 2017) which argued that the innovative concepts such as BIM and sustainability has the capacity to improve the stakeholders' productivity and enhances the chances of achieving the project's goals. Also, among the professionals such as the architects, project managers, quantity surveyors, and civil engineers; there is a consensus on the five key benefits.

Moreover, on factor "BN17 - real-time sustainable design and analysis early in the design phase", the majority of the respondents' groups agreed on the factor as a significant benefit derivable when BIM and sustainability practices are implemented in construction projects. However, the project consultants averagely ranked the factor. The differing viewpoint from the project consultants group is consistent with the fact that it might be difficult to conduct a proper sustainable design analysis in the early phase of project design due to: (i) incomplete design and specifications at the early stages of building designs; and (ii) issues with and lack of collaboration and coordination among the project consultants (i.e. architects, structural engineers, building services engineers, etc.) involved in project designs. Also, the findings revealed that implementing these concepts (BIM and sustainability) as little effects on the process of securing building plan approvals and construction permits as well as the reduction of project risks or litigations. Adopting these concepts currently has little effects as captioned above because except in cities like Hong Kong, most governments are yet to enforce and incorporate as an incentive, the implementation of BIM and sustainability practices by clients in their construction projects.

4.3.2 Inferential statistical tests

Parametric statistical tools such as ANOVA was employed to investigate the differences in the perception of the various respondents' groups such as the organization setups (project consultants, public clients, main contractors, etc.) and the professional disciplines (civil engineers, architects, quantity surveyors, etc.). ANOVA is a parametric statistical measure of variance based on the mean of scores (Olatunji et al., 2017a; Tsai et al., 2014a), and for factors that are significant ($p<0.05$) a further test, which is a post-hoc Tukey test was conducted (Mom et al., 2014a; Olatunji et al., 2017a).

4.3.2.1 Statistical tests based on organizational setups

The ANOVA carried out on the survey data revealed some significant divergencies (at significance <5%) in the perceptions of the different groups of the respondents' organization setups on twelve factors. These include "BN1- enhance overall project quality, productivity, and efficiency" [$F(5,214) = 2.538$, $p = 0.030$]; "BN3- predictive analysis of performance (energy analysis, code analysis)" [$F(5,214) = 3.945$, $p = 0.002$]; "BN4- improve the operations and maintenance (facility management) of project infrastructure" [$F(5,214) = 2.312$, $p = 0.045$]; "BN7- Reduction in the cost of as-built drawings" [$F(5,214) = 2.373$, $p = 0.040$]; "BN13- reduced claims or litigation risks" [$F(5,214) = 2.386$, $p = 0.039$] among others (see Table 4.3). Furthermore, a post-hoc Tukey test was conducted on the twelve significant benefits, of which nine factors were found to be more important ($p<0.05$). These include "BN1- enhance overall project quality, productivity, and efficiency" with a moderate significance ($p=0.014$) of which the respondents from the academics (M= 4.48, SD= 0.626) perceived the factor to be of higher importance than their public client counterparts (M= 4.09, SD= 0.752). The high rating given to the factor by the academics could be likely be based on their previous reviews or experience of the impact of these concepts in the construction industry. Also, academics' perception could be based on happenings in other regions beyond their local context as argued by Olawumi and Chan (2018a), unlike their public-sector counterparts whose perception might be based solely on the impact of these concepts in their locality.

Moreover, for "BN3- predictive analysis of performance (energy analysis, code analysis)", there is a high significance ($p= 0.003$) between the public-sector clients (M= 3.93, SD= 0.716) and the academics (M= 4.39, SD= 0.653) with the academics rating the factor to be of higher importance the respondents from the public-sector clients. Likewise, at a moderate significance of $p= 0.024$, the survey participants from the academics perceived the factor to be of higher merit than the project consultants (M= 3.88, SD= 0.881). Evidently, these viewpoints of the respondents' groups emphasize the role of BIM software to aid the implementation and provide further support to the previous submissions in the literature (Jalaei & Jrade, 2015; Kivits & Furneaux, 2013; Olawumi & Chan, 2018a) that the implementation of BIM and sustainability practices in construction projects will facilitate smart and sustainable urbanization. The interlink between the academics and the industry is getting stronger (Olawumi et al., 2017), and since most research institutes constitute mostly the testbeds for most industrial innovation; it is believed that might have affected the higher rating by the academics for this factor (BN3). See Table 4.3 for the other results of the post-hoc Tukey test analysis.

4.3.2.2 Statistical tests based on professional disciplines

The ANOVA statistical analysis conducted on the data collected from the respondents' groups based on their professional disciplines yield some significant differences (at significance < 5%) in nine-factor such as "BN6- improve financial and investment opportunities" [$F(10,209) = 2.519$, $p = 0.022$]; "BN11- ease the process to obtain building plan approvals and construction permits" [$F(10,209) = 3.131$, $p = 0.001$]; "BN12- support collaboration and ease procurement relationships" [$F(10,209) = 2.068$, $p = 0.028$]; "BN25- facilitate the implementation of green building principles and practices" [$F(10,209) = 2.011$, $p = 0.034$]; "BN27- minimize carbon risk and improve energy efficiency" [$F(10,209) = 2.150$, $p = 0.022$]. A further analysis using post-hoc Tukey test reveals very high divergencies among the professional groups in three factors only. These include "BN11- ease the process to obtain building plan approvals and construction permits" which shows a very high significant difference (p= 0.000) in the perception of the construction managers (M= 3.18, SD= 0.951) and the academics (M= 4.00, SD= 0.707). Also, between the quantity surveyors (M= 3.71, SD= 0.875) and the construction managers at a very high significance (p= 0.005) for the same factor. The construction managers in both cases ranked the factor below average with their academics' counterpart ranking it the highest. Although, some countries such as the United Kingdom and Hong Kong has put into place incentives for BIM-compliance firms, however, it is yet to be replicated in the other 21 countries represented in the survey data. When such initiative is introduced in other regions, the factor can be a significant one for the construction industry as projected by the respondents from the academics.

Meanwhile, for "BN12- support collaboration and ease procurement relationships" there is a moderate significance (p= 0.035) as the architects (M= 4.11, SD= 0.832) identified the factor to be more important than the construction managers (M= 3.21, SD= 1.182). Although both sets of respondents are significant in the procurement process, the architects utilize the BIM software for building model designs and communicate their designs to other key stakeholders who utilize the designs to simulate various building performance. Hence, architects are more involved in the collaborative activities (especially, at the planning and design stages where these concepts are usually integrated into construction projects), and their perceptions about this factor as one of the benefits of BIM and sustainability practices in the built environment is crucial. Lastly, for "BN28- improve resource management and reduce environmental impact across the value chain" there is a highly significant difference (p= 0.002) between the project managers (M= 4.19, SD= 0.622) and the building services engineers (M= 3.18, SD= 1.015) with the project managers identifying the factor has a more significant benefit of the implementation of BIM and sustainability practices. Also, there is a highly significant divergence (p= 0.005) between the quantity surveyors (M= 4.04, SD= 0.793) and the building services engineers. However, since the project managers and the quantity surveyors are more involved in the management and control of project resources than the building services engineers, their perceptions on this factor will be of more importance to the study.

Table 4.2: Benefits of implementing BIM and sustainability practices: inter-group comparisons

Benefits	**Public clients**		**Private clients**		**Project consultants**		**Main contractors**		**Academics**		**Overall**				
	Mean	**Rk**	**Mean**	**Rk**	**Mean**	**Rk**	**Mean**	**Rk**	**Mean**	**Rk**	**Mean**	**SD**	**Rk**	**F**	**Sig.**
BN1	4.09	2	4.33	8	4.20	1	4.20	3	4.48	1	4.29	.700	2	2.538	**.030**
BN2	3.98	9	4.00	28	3.84	24	3.77	31	4.03	26	3.97	.784	26	1.264	.280
BN3	3.93	13	4.08	23	3.88	22	4.03	15	4.39	4	4.13	.744	9	3.945	**.002**
BN4	3.98	8	4.25	16	4.04	8	3.91	24	4.34	7	4.14	.801	8	2.312	**.045**
BN5	3.56	31	4.17	19	3.76	30	3.86	27	3.89	32	3.80	.886	31	1.435	.213
BN6	3.45	33	4.17	19	3.92	19	3.86	28	3.72	30	3.72	.872	33	2.222	.053
BN7	3.56	32	4.33	8	3.96	16	3.97	21	3.89	31	3.83	.976	30	2.373	**.040**
BN8	4.29	1	4.25	16	4.04	7	4.09	10	4.48	2	4.30	.784	1	2.081	.069
BN9	4.00	6	4.50	3	3.92	17	3.86	29	4.20	13	4.08	.781	14	2.028	.076
BN10	4.09	3	3.92	31	4.12	3	3.74	32	4.17	19	4.06	.912	16	1.215	.303
BN11	3.27	35	3.50	36	3.28	30	3.49	36	3.76	34	3.51	1.027	36	1.938	.089
BN12	3.62	30	4.00	28	3.64	33	3.69	33	3.99	30	3.80	.915	32	1.598	.162
BN13	3.22	36	3.67	35	3.64	34	3.63	34	3.74	35	3.57	.911	35	2.386	**.039**
BN14	3.44	34	3.92	31	3.44	35	3.54	35	3.85	33	3.65	.876	34	2.243	.051
BN15	3.89	18	4.33	8	4.08	5	4.17	5	4.34	8	4.18	.796	4	2.939	**.014**
BN16	3.91	14	4.25	15	3.96	13	4.17	5	4.18	15	4.09	.765	13	1.224	.299
BN17	4.02	5	4.42	5	3.92	19	4.14	8	4.41	3	4.20	.733	3	3.400	**.006**
BN18	4.05	4	4.33	12	3.92	17	4.03	14	4.31	10	4.15	.709	6	2.086	.068
BN19	3.91	15	3.75	34	3.96	14	4.06	13	4.02	28	3.98	.849	24	.410	.842

Benefits	Public clients		Private clients		Project consultants		Main contractors		Academics		Overall				
	Mean	Rk	Mean	Rk	Mean	Rk	Mean	Rk	Mean	Rk	Mean	SD	Rk	F	Sig.
BN20	3.95	11	3.83	33	4.00	9	4.09	10	4.02	28	4.00	.825	22	.278	.925
BN21	3.85	20	4.08	24	3.96	14	4.26	1	4.20	14	4.08	.801	15	1.727	.130
BN22	4.00	6	4.08	26	4.08	6	4.23	2	4.34	9	4.18	.828	5	1.835	.107
BN23	3.85	21	4.00	30	3.84	24	3.89	26	4.08	25	3.95	.854	27	.691	.631
BN24	3.85	22	4.17	19	4.00	9	4.11	9	4.16	20	4.04	.799	18	2.116	.065
BN25	3.85	23	4.25	14	4.00	9	3.91	23	4.21	12	4.04	.793	17	2.042	.074
BN26	3.84	24	4.42	5	3.80	26	4.00	17	4.18	17	4.04	.804	19	2.350	**.042**
BN27	3.69	28	4.00	27	3.88	22	3.89	25	4.10	23	3.92	.821	28	1.925	.091
BN28	3.89	16	4.42	5	3.80	26	3.83	30	4.14	21	4.00	.822	21	1.941	.089
BN29	3.73	27	4.17	19	3.72	31	4.06	12	4.18	18	3.99	.849	23	2.715	**.021**
BN30	3.64	29	4.17	18	3.76	29	3.94	22	4.03	27	3.90	.875	29	1.927	.091
BN31	3.96	10	4.67	1	4.12	4	4.20	4	4.18	16	4.13	.863	11	2.144	.061
BN32	3.89	19	4.33	12	3.68	32	4.00	16	4.11	22	4.00	.816	20	1.738	.127
BN33	3.89	16	4.58	2	3.96	12	3.97	19	4.29	11	4.11	.775	12	3.288	**.007**
BN34	3.95	12	4.33	8	3.92	19	3.97	20	4.37	6	4.13	.834	10	3.185	**.009**
BN35	3.84	25	4.50	4	4.20	2	4.00	18	4.38	5	4.15	.835	7	3.949	**.002**
BN36	3.76	26	4.08	25	3.80	28	4.17	7	4.08	24	3.98	.860	25	1.555	.174

Note: Rk- Rank

Table 4.3: Post-hoc Tukey test results for the respondents' groups

Factors	Organizational setups (sig.)	Factors	Professional disciplines (sig.)
BN13	Public clients vs Academics* (0.012)	BN28	Architects* vs. Building Services Engineers (0.032)
BN15	Public clients vs Academics* (0.011)		Civil Engineers* vs. Building Services Engineers (0.015)
BN17	Public clients vs Academics* (0.019)		Academics* vs. Building Services Engineers (0.001)
	Project consultants vs Academics* (0.031)		Construction Managers* vs. Building Services Engineers (0.070)
BN29	Public clients vs Academics* (0.021)		
BN33	Public clients vs Academics* (0.031)		
BN34	Public clients vs Academics* (0.034)		
BN35	Public clients vs Academics* (0.002)		

*Note: *the respondent's group considers the factor of higher significance than the other respondent's group; sig. - significance*

4.3.3 Factor Analysis

Factor analysis was employed to investigate the pattern of interrelationships among a large set of variables and identifying a smaller number of factors to represent the relationships. The principal component analysis (PCA) of the factor method was used in this study; the other type is the Promax rotation method (Chan & Hung, 2015). The basic concept of factor analysis (FA) is to use the underlying factors to explain the complex and obscure phenomenon (Xu et al., 2010), interpretation of 'nonrelated clusters' (Fang et al., 2004), and define the relationship of interrelated variables (Chan & Choi, 2015). Also, according to Chan and Hung (2015), factors can be rotated in two forms- oblique and orthogonal; for this study, the varimax rotation method, a subset of the orthogonal rotation method was adopted for the PCA.

Moreover, for a set of data to be sufficient for factor analysis, it is recommended for the number of variables in relation to the sample size to be in the ratio of 1:5 (Chan & Choi, 2015; Lingard & Rowlinson, 2006). The current study fulfills this requirement, that is, with 36 variables the sample size must not be less than 180, however, this study has 220 responses which is more than the minimum sample size. The Kaiser-Meyer-Olkin (KMO) tests which evaluate the sampling adequacy shows a KMO value of 0.952 which implies an 'excellent' degree of common variance (Field, 2009), and which is above the minimum threshold of 0.50 (Norusis, 1993). A KMO value close to 1 indicates a compact structure of the correlations and indicates that the clusters generated during the factor analysis are distinct and reliable (Chan & Choi, 2015).

Meanwhile, the study utilized Bartlett's test of sphericity (BTS) to examine the suitability of the PCA for factor extraction (Field, 2009), the BTS statistic tests reveal a substantial BTS value (chi-square=5750.610) with a minimal significance value ($p=0.000$, $df=630$) which indicates the correlation matrix is not an identity matrix (Chan & Choi, 2015). Given the above, the research data has met the various pre-conditions required before PCA can be applied to the data for further analysis and discussion. Hence, factor analysis can be carried out with confidence and reliability. The PCA extraction yielded five factors which constitute 64.663% of the total variance explained (see Table 4.4) which is higher than the minimum threshold of 60% (Chan & Choi, 2015; Hair et al., 2010; Malhotra, 1996). Meanwhile, per Proverbs et al. (1997), factors within a cluster with factor loading close to 1.0 have higher significance in the underlying cluster. The 36 factors represented within one of the five cluster factors have a factor loading which is close to 0.50 or higher. Also, according to Chan and Hung (2015), the value of each variable's factor loading is a reflection of the contribution of the variable to its underlying grouped factor.

Table 4.4: Factor structure of the varimax rotation on the benefit's' factors

Code	Benefits of implementing BIM and sustainability practices	Factor loading	Eigenvalue	Percentage of variance explained	Cumulative percentage of variance explained
Factor 1 – Sustainable building and technical-related benefits			17.411	48.365	48.365
BN29	Facilitate the selection of sustainable materials, components, and systems for projects	0.758			
BN25	Facilitate the implementation of green building principles and practices	0.753			
BN35	Ability to simulate building performances and energy usage	0.744			
BN36	Encourage the implementation of clean technologies that require less energy consumption	0.736			
BN26	Ease the integration of sustainability strategies with business planning	0.723			
BN28	Improve resource management and reduce environmental impact across the value chain	0.704			
BN30	Higher capacity for accommodating the three pillars of sustainability (social, economic & environmental sustainability)	0.700			
BN27	Minimize carbon risk and improve energy efficiency	0.698			
BN33	Allow the checking of architectural design of buildings from the sustainability point of view	0.670			
BN34	Facilitate accurate geometrical representations of a building in an integrated data environment	0.637			
BN24	Control of lifecycle costs and environmental data	0.633			
BN3	Predictive analysis of performance (energy analysis, code analysis)	0.610			
BN22	Prevent and reduce materials wastage through reuse & recycling and ensure materials efficiency	0.511			
BN32	Facilitate integration with domain knowledge areas such as project management, safety, and sustainability	0.502			
BN23	Reduce safety risks and enhance project safety & health performance	0.487			
Factor 2 – Efficiency and process-related benefits			2.171	6.031	54.396
BN8	Facilitate sharing, exchange, and management of project information and data	0.711			
BN10	Reduction in site-based conflicts	0.669			
BN1	Enhance overall project quality, productivity, and efficiency	0.643			
BN18	Facilitate, support and improve project-related decision-making	0.594			
BN2	Schedule compliance in the delivery of construction projects	0.577			
BN9	Facilitates resource planning and allocation	0.559			
BN4	Improve the operations and maintenance (facility management) of project infrastructure	0.477			
BN31	Enhance the accuracy of as-built drawings	0.460			
BN17	Real-time sustainable design and analysis early in the design phase	0.455			
Factor 3 – Performance and knowledge-related benefits			1.399	3.885	58.281
BN19	Improved organization brand image and competitive advantage	0.710			
BN20	Enhance business performance and technical competence of professional practice	0.673			

Code	Benefits of implementing BIM and sustainability practices	Factor loading	Eigenvalue	Percentage of variance explained	Cumulative percentage of variance explained
BN15	Better design products and facilitate multi-design alternatives	0.637			
BN21	Enhance innovation capabilities and encourage the use of new construction methods	0.626			
BN16	Facilitate building layout flexibility and retrofitting	0.548			
Factor 4 – Financial-related benefits			1.169	3.248	61.529
BN6	Improve financial and investment opportunities	0.728			
BN7	Reduction in the cost of as-built drawings	0.725			
BN5	Reduction in cost of construction works and improvement in project's cost performance	0.719			
Factor 5 – Legal and statutory-related benefits			1.128	3.134	64.663
BN11	Ease the process to obtain building plan approvals and construction permits	0.756			
BN13	Reduced claims or litigation risks	0.718			
BN14	Increase firms' capability to comply with prevailing statutory regulations	0.678			
BN12	Support collaboration and ease procurement relationships	0.552			

4.3.3.1 Discussions of the clustered benefit factors

The underlying grouped factors are evaluated in Table 4.5 in descending order of significance based on their factor scale rating (Chong & Zin, 2012; Chan & Hung, 2015) which is based on the variables within each cluster. The factor scale rating is the ratio of the sum of the mean scores of individual variables in a cluster to the number of variables in the underlying grouped factor. More so, per Sato (2005), it is necessary to designate an attributable and collective tag to each cluster factor to ease its description, and according to Chan and Hung (2015), the tags are subjective and is based mostly on the researcher's intuitions. The study will expatiate on the top-three of the factor clusters to conserve space.

Table 4.5: Ranking results of the factor scale rating for the benefit clusters

Factor	Factor label	Factor scale rating	Ranking
2	Efficiency and process-related benefits	4.1467	1
3	Performance and knowledge-related benefits	4.066	2
1	Sustainable building and technical-related benefits	4.0373	3
4	Financial-related benefits	3.7833	4
5	Legal and statutory-related benefits	3.6325	5

4.3.3.1.1 Efficiency and process-related benefits

Factor 2 comprises nine benefit-related factors and has the highest factor scale rating (M= 4.1467) of the five clusters. The cluster details how implementing BIM and sustainability practices can reduce site conflicts, enhance the management of project information, improve efficiency and productivity in a project, support the decision-making process, and ensure timely delivery of construction projects among others. Abanda et al. (2015) and Hanna et al. (2013) acknowledged that the introduction of BIM software in the construction market had affected the efficiency and quality assurance in a construction project. Olawumi et al. (2017) noted that there are BIM software that can be used for the simulation of sustainability-related issues in a building design such as EnergyPlus, Ecotect, Green Building Studio which can be used for building energy analysis and carbon-emission analysis.

Aibinu and Venkatesh (2014) reported that the benefits of the concepts to support and improve the decision-making process would be realistic when key stakeholders collaborate effectively to define the information from BIM software needed to ease the project tasks as well as perform sustainability analysis (Adamus, 2013). Moreover, Boktor et al. (2014) opined that there must be a cost-benefit analysis of the gains of its implementation as well as an assessment of the capacity of the construction workers to grasp the BIM and sustainability processes to ensure a realistic evaluation of the impact of these concepts in a project. Also, Olawumi and Chan (2018d) and Boktor et al. (2014) recommended the development of BIM and sustainability standards in countries which are yet to set up such to be able to have a guideline to measure the impact of the concepts on the built environment.

4.3.3.1.2 Performance and knowledge-related benefits

Factor 3 with a factor rating scale of M=4.066 is another significant underlying factor cluster with five key factors with a factor loading of more than 0.5. The cluster is concerned with the impact of BIM and sustainability practices in construction projects and its capacity to improve the competitiveness of a construction firm and its brand image. Also, it is related to its effect on business performance, facilitating better design products, boosting innovation capacities, and aid building layout flexibility and retrofitting. Antón and Díaz (2014) reiterated the benefit of these concepts to include the delivery of better design products which not only improves the well-being and life quality of the users but also improve the energy performance of such facilities. Aibinu and Venkatesh (2014) recognized its impact to enhance the skill sets and technical expertise of key stakeholders in a world in which technological advancement is the order of the day.

Moreover, the ability of BIM software to facilitate design and the visualization of what is to be built in a simulated environment allows the detection of any design flaws or operational issues as well as ease the production of multi-design alternatives (Azhar, 2011). Azhar (2011) also reported the economic benefits of implementing BIM in projects with an average performance of 634% on return on investment (ROI) which reveals a high potential for its implementation. Although, there are risks and challenges to the adoption of BIM and sustainability practices in the construction industry (Olawumi et al., 2018), however, its future looks exciting (Azhar, 2011). More so, to achieve the preceding, Antón and Díaz (2014) advocated for the adoption of the concepts at the early stage of a project, improved interoperability among BIM software, and increased research and development in the construction industry.

4.3.3.1.3 Sustainable building and technical-related benefits

Factor 1 with a factor rating scale of M= 4.0373, comprises fifteen key factors and eight of these factors has a factor loading of at least 0.70 and are considered significant within the cluster. The cluster is related to the ability of BIM to simulate building performances and energy usage, the ease of selecting sustainable materials and component for a construction project, simplify the implementation of green building principles and the implementation of clean technologies with the minimal use of energy. Also, it includes its capacity to aid the smooth integration of sustainability strategies with business planning, reduce the environmental impact of the project and improving resource management among others. Jalaei and Jrade (2014) attested to the growing concern about the energy performance of buildings and how designers and other consultants have been utilizing BIM tools to make energy-related decisions as well as the selection of the right type of materials and components. Accordingly, they noted that these decisions have a significant impact on the life cycle of a building (Antón & Díaz, 2014). Wu and Issa (2014b) and Olawumi et al. (2017) stressed that despite the emerging success of green BIM in the construction, its full potential is yet to be tapped. Hence, they advocated for the formulation of an effectively BIM execution plan for use in green building projects.

Moreover, Akinade et al. (2015) affirmed that one of the essential functions of BIM that has added its acceptability in the built environment is the ability to simulate building energy performance, perform lighting analysis, and the evaluation of design models before actual construction on project site. Also, this allows the project team to identify any potential flaws in design and to select the most cost-effective and sustainable solution among a variety of design alternatives. Antón and Díaz (2014) pointed out that the integration of BIM and sustainability practices to generate synergies would enhance its robustness to tackle the environmental impact of buildings and the simplify the deployment of clean technologies in buildings. Also, Jalaei and Jrade (2014) found that green or sustainable buildings cost far less to operate and are attractive from a commercial perspective. Hence, Wu and Issa (2014b) encouraged key stakeholders to show strong interests in green BIM implementation to facilitate more sustainable projects. Also, it is necessary to enhance the capacities and functionality of existing green BIM software to comply with existing standards and rating systems (Olawumi & Chan, 2018c; Wu & Issa, 2014b).

4.4 Conclusions

The primary aim of this study was to review the impact of the implementation of BIM and sustainability practices in the built environment and to assess the potential benefits of its adoption in construction projects, and to construction firms. A review of reported literature formed the bedrock for gathering the thirty-six benefits which formed the questionnaire items sent to the survey participants. A total of 220 respondents from 21 countries participated in the empirical questionnaire survey which constitutes professionals of varied backgrounds and from different organization setups. The diversity of the survey participants was utilized as a basis to compare the ranking patterns and to detect any significant differences in their perceptions of the key factors.

Generally, most of the respondents' groups agreed on "BN1- enhance overall project quality, productivity, and efficiency" as a key benefit of BIM and sustainability practices implementation in construction projects, as the factor most as one of the top-five significant benefit in the groups' rankings. Also, the factor is consistent with similar assertions in the literature which expressed the capacity of the concepts to enhance the project's objectives, one of which includes meeting quality and productivity targets. More so, there is also a significant consensus among the groups on factor "BN17- real-time sustainable design and analysis early in the design phase" as one of the crucial impacts of the implementation of BIM and sustainability in projects. Meanwhile, adopting these concepts have little impacts on the ability of a construction firm or project team to secure building plans approval or construction permits. Moreover, the capacity of the concepts to support and enhance the collaborative working environment in the construction industry was highlighted as well as its ability to ease procurement relationship.

A factor analysis of the thirty-six benefit factors using PCA method resulted in five underlying clusters with a minimum of three factors and a maximum of fifteen factors; with each underlying grouped factor given an attributable and collective tag which is a representation of its sub-set factors. Moreover, the study conducted further analysis of the ranking patterns of the various respondents' groups which yielded impressive results of which effective blueprints and recommendation were suggested to increase the uptake of BIM and sustainability practices towards ensuring the construction industry maximizes these benefits. Some of the recommendations highlighted in the study include: (1) Local authorities and government departments should liaise with relevant professional bodies in the built environment towards setting up 'green-BIM compliance' incentives to motivate construction firms and clients to implement the concepts in their projects; and (2) Key stakeholders in the construction industry must streamline and improve the structure of their collaboration as well as the need to incorporate (as much as possible) every stakeholder in decision-making at the early stages of project development.

More so, for countries, who are yet to develop BIM and sustainability assessment standards; (3) The establishment of such standards is advocated, as this will provide both qualitative and quantitative guidelines to assess the impact of green BIM on the built environment. Also, (4) Enhancing the interoperability and functionality of green BIM software is imperative to the successful implementation of the concepts; (5) Early adoption of green BIM initiative at the planning stage of project development. (6) Increased and targeted research on green BIM; (7) Development of a green BIM execution plan for use in construction projects and to aid project teams. (8) The need for key stakeholders and construction firms to express a keen interest in green BIM adoption in their projects and training of their staff is essential to reap full benefits of the implementation of BIM and sustainability practices in the built environment.

It is evident from these significant research findings and collective perspectives that the implementation of BIM and sustainability practices have played an important role and has exerted profound impacts on construction projects and the built environment. It is recommended that future research studies can explore and conduct a quantitative cost-benefit analysis of the gains of green BIM implementation in the construction industry which is expected to provide a sound basis for project comparison and benchmarking. A concerted effort by the various construction stakeholders, local authorities, and policymakers will ensure that these concomitant benefits highlighted in the study are harvested and realized in the built environment.

4.5 Chapter Summary

The increasing urbanization of the built environment has bolstered the need to promote green Building Information Modelling (BIM) initiative in new construction projects and the rehabilitation of old premises. The study aims to explore and examine the key benefits of the implementation of BIM and sustainability practices in the built environment. The study gathered the worldwide perceptions of 220 survey participants from 21 countries which were analyzed using descriptive and inferential analytical methods in this chapter. The identified individual benefits of green BIM were further categorized into their underlying clusters using factor analysis. The key benefits are related to enhancing project efficiency and productivity, ensuring real-time sustainable design and multi-design alternatives, facilitating the selection of sustainable materials and components, together with reducing material wastage and project's environmental impact, among others. The chapter also analyzed and compared the perceptions of the diverse groups of the respondents as well. Effective blueprints and insightful recommendations for enhancing the various stakeholders' capacities to implement green BIM in their construction projects were put forward to achieve the aim of sustainable smart urbanization. The study identified salient benefits of the adoption of BIM and sustainability practices. The proper integration of these concepts and the execution of the recommended useful strategies by construction stakeholders, policymakers, and local authorities will enable the built environment to reap the gains of its implementation. The following chapter identifies and examines the barriers (impediments) to the implementation of BIM and sustainability practices – otherwise known as smart sustainable practices in this study – in building projects and in the built environment.

CHAPTER 5: BARRIERS TO THE INTEGRATION OF BIM AND SUSTAINABILITY PRACTICES IN THE BUILT ENVIRONMENT[5]

5.1 Chapter Overview

The previous chapter identified and analyzed the benefits of BIM and sustainability in building projects and the built environment. This chapter identifies and examines the barriers (impediments) to the implementation of BIM and sustainability practices – otherwise known as smart sustainable practices in this study – in building projects as well as in the built environment. Two datasets were collected namely via Delphi surveys (14 experts participating) and international survey involving 220 respondents. However, to conserve space, only the result of the international survey findings will be presented in this chapter. A link to the published findings of the Delphi survey conducted in this research is provided in section 5.4 of this chapter.

5.2 Introduction

The construction industry has been a slow adopter of innovative and smart technology (such as BIM) and implementation of sustainability practices unlike other sectors such as the automobiles. Kim and Yu (2016b) aligned with this viewpoint by revealing that 78% of current users of BIM are yet to utilize this innovative tool for green projects. Apart from the United Kingdom and the United States which have witnessed an improved adoption and implementation of BIM and sustainability, most other countries are still lagging in its execution (Jung & Lee, 2015; Olawumi & Chan, 2018a). Gu and London (2010), while expounding on the readiness and implementation level among countries as regards BIM and sustainability, reported that it varies significantly. Even countries considered to be the early adopters and initiators of these concepts experienced a disproportionate level of knowledge.

Meanwhile, according to Kummitha and Crutzen (2017) and Kim and Yu (2016b), sustainable smart approaches have recently been gaining drastic momentum in the

[5] This chapter is largely based upon the following published papers:

Olawumi, T.O., & Chan, D.W.M. (2020b). Concomitant Impediments to the implementation of Smart Sustainable Practices in the Built Environment. *Sustainable Production and Consumption, 21(January), 239-251*. https://doi.org/10.1016/j.spc.2019.09.001

Olawumi, T.O., Chan, D.W.M., Wong, J. K. W., & Chan, A. P. C. (2018). Barriers to the Integration of BIM and Sustainability Practices in Construction Projects: A Delphi Survey of International Experts. *Journal of Building Engineering*, 20, 60–71. https://doi.org/doi.org/10.1016/j.jobe.2018.06.017

industry. However, due to several inherent challenges in the industry, there are several setbacks which need to be addressed (Olawumi et al., 2018). Sustainable smart practice or approach is a system whereby technological tools and software are employed and integrated to facilitate the implementation of sustainability objectives (environmental, social and economic) in building projects, infrastructures, and urban cities. These practices have improved the efficiency of operations and projects, improved quality of life, among others; and are measured using some established performance indicators.

Meanwhile, a desktop review of the extant literature (Ayegun et al., 2018; Kummitha & Crutzen, 2017; Olawumi & Ayegun, 2016) revealed a variety of forces and conflicting expectations due to the multi-stakeholders and layered structure of projects and organizations in the construction industry. Hence, this has made the execution of sustainable smart practices in projects more complex and tasking. More so, the initial cost of acquiring necessary Information and Communication Technology (ICTs) infrastructure which is regarded as the core of smart city initiative (Graham & Marvin, 2001); and central to its successful implementation, of which BIM is a key variety (Olawumi & Chan, 2018d, 2018c) is very high.

Although, Neirotti et al. (2014) reported that ICTs alone cannot help achieve the desired improvements in the built environment as regards improving the standard and quality of human lives, and fulfilling the required sustainability potential of buildings. Hence, the need for an evaluation of other concepts that can enhance the sustainability of buildings and cities. This study intends to assess the barriers affecting the adoption and implementation of sustainable smart practices in construction projects. Conversely, the existing literature has discussed some benefits obtainable by the adoption of sustainable smart practices in the built environment. For instance, Bakici et al. (2013) and Olawumi and Chan (2019a) highlighted some benefits of implementing smart, sustainable practices in the construction project which include improving the quality of life of urban dwellers of such cities, enhancing the ability of stakeholders to simulate building energy performance (Olawumi & Chan, 2018d). Moreover, Bradley et al. (2016) stressed the functional capacity of BIM technologies to address issues in other domain areas such as sustainability, project management of which it was not initially designed for its use.

5.2.1 BIM and sustainability practices: A review

The use of technological tools like BIM for construction processes and sustainability evaluation of projects have gained the immense attention of policymakers, researchers, government agencies and key stakeholders in the construction industry in recent years (Olawumi et al., 2017; Olawumi & Chan, 2017, 2018a). Some current application of 6D BIM (BIM and sustainability) in the construction industry include the application of BIM for sustainable material selection for construction project (Govindan et al., 2015). Also, Akanmu et al. (2015) developed a decision support system (DSS) to enhance the selection and procurement of low-cost and environmental-friendly building materials for different building designs. Also, Aksamija (2012) exemplified the use of BIM analysis tools to simulate building energy performance for a case study project. Other applications of BIM and sustainability include: (1) lifecycle cost assessment (Soust-Verdaguer et al., 2017); (2) simulation of building design performance (Aksamija, 2012); (3) sustainable design (Alsayyar & Jrade, 2015; Autodesk, 2010b); (4) building energy analysis (Ham & Golparvar-Fard, 2015; Kim et al., 2015a); (5) Indoor environmental quality [IEQ] (Habibi, 2017).

Also, Olawumi and Chan (2017) developed a geospatial map depicting the distribution of the global sustainability research. Despite these attempts to utilize BIM for sustainability implementation in construction projects as exemplified by the literature, the construction industry is deficient of the necessary collaboration and coordination (Olatunji et al., 2016b, 2017b; Olawumi & Ayegun, 2016) to drive salient issues like sustainability and BIM. Hence, Aksamija (2012) and Olatunji et al. (2016b) argued for a collaborative working environment and an iterative decision-making process in the construction industry towards enhancing the capacity of BIM to strengthen the sustainability of the built environment.

However, the construction industry is faced with challenges related to the joint implementation of the two concepts in construction projects (Gu & London, 2010). Adamus (2013) pointed out the challenge of developing smart building which is consistent with sustainable development (SD) principles and the need to ensure the achievement of the three pillars of SD. Accordingly, BIM was identified by Adamus (2013) as capable of enabling the construction industry to meet the emerging sustainability requirement and facilitate the sustainability analysis and simulation of building models before construction onsite. Also, Gu and London (2010) pointed out that the readiness of the AEC industry for innovative technology and processes such as BIM varies among countries. Also, even among the early adopters of BIM and initiators of sustainability assessment metric, there is a disproportionate level of knowledge and experience (Olawumi & Chan, 2018d).

More so, the level of readiness and implementation is disproportionate among construction organizations and regions (Gu & London, 2010; Redmond et al., 2012) as well as the prevailing resistance to change from traditional working practices (Abubakar et al., 2014) by construction stakeholders have hindered a holistic implementation of BIM and sustainability in construction projects. Given the above, project clients have developed apathy for its adoption in their project (Chan, 2014). Meanwhile, Olawumi et al. (2017) observed that despite growing research and studies in BIM-sustainability issues in construction projects, most projects have focused on one aspect of the three fundamental pillars of sustainable development which is environmental sustainability. Meanwhile, these cross-study BIM-sustainability literature have dealt on energy performance issues in projects instead of a holistic view of what is possible in achieving a sustainable smart city. The current approach to sustainability assessment is still a challenge to the construction sector; this is because the design stage offers the best opportunity to influence sustainability decisions (Ding, 2008; Olawumi & Chan, 2018c, 2018d).

There have been some success stories of the use of BIM to enhance sustainability implementation of construction projects in the literature. For instance, the development of a BIM-based Deconstructability Assessment Score (BIM-DAS) by Akinade et al. (2015) who develop a set of metrics that can be utilized in making choices on building designs suitable for deconstruction. However, the model is yet to be integrated as a plugin in BIM software limiting its practical implementation in construction projects. Adamus (2013) reiterated the issue of interoperability as a significant setback affecting the use of BIM to evaluate sustainability parameters of the building model. Cidik et al. (2014) developed an information categorization framework to evaluate design alternatives in BIM environment which not only optimize such designs but also allows for a holistic design sustainability analysis to be undertaken. Jalaei and Jrade (2015) advanced a methodology that integrates BIM with LEED (Leadership in Energy and Environmental Design) building certification system which can assist project teams to make sustainability-related decisions while at the same time ensure such buildings accumulate good points on LEED rating.

Key barriers reiterated in the literature hindering the adoption of both concepts (BIM and sustainability) in the construction industry are highlighted in Table 5.1. Previous studies have highlighted the inadequacy of requisite experience, knowledge, and skills from the workforce (Nanajkar & Gao, 2014; Wu & Handziuk, 2013). For these reasons, it is recommended for stakeholders to shore up their knowledge base and learn new skills and as advised by Olawumi et al. (2017), professional bodies and organizations should organized training seminars and workshops for their members and staff and development of university curriculum in BIM and sustainability issues. Without doubts, the backbone of the BIM initiatives and sustainability simulations and practices are technologically enabled software, tools, plugins, and databases.

5.3 Impediments of implementing smart sustainable practices: A desktop review

There has been a surge in recent years in the use of variants of BIM in construction process and previous studies such as Wang and Adeli (2014) and Olawumi et al. (2017) stressed the need to integrate smart techniques such as BIM with sustainability to achieve more energy savings, reduce carbon emissions, and promote green neighborhoods. However, as it is always the case when new techniques and concepts are introduced in the construction industry, the implementation of sustainable smart practices are facing some setbacks (Jalaei & Jrade, 2015; Nanajkar & Gao, 2014; Olawumi et al., 2018). One key aspect common to the implementation of smart, sustainable practices is the use of software to model and analysis the building model and associated performance parameters. According to Adamus (2013), there have been issues relating to data exchange between building design software and sustainability analysis software, mostly known as interoperability issues in the construction industry (Olawumi et al., 2017).

Technical impediments: Angelidou (2015) observed that technology-based product in the construction industry advanced faster and received more acceptance; although its implementation, according to Olawumi et al. (2018) can be much slower. However, the issues relating to sustainability and providing solutions to the construction industry's efficiency problems has lagged (Angelidou, 2015); hence, producing an imbalance and hindering the achievement of sustainable development in the built environment (Cugurullo, 2017). As noted by Kummitha and Crutzen (2017), there has been skepticism as smart cities and buildings such as how can is such planned, whose ideas make up the plan and what are the cost and benefits.

These issues according to Moser (2015) and Datta (2015a) has heightened apprehensions among communities, its citizens and even among some stakeholders who may be the 'actual losers' due to the top-down approach of most innovative smart city initiative which has some negative implications for sustainable urban development (Calzada & Cobo, 2015). Also, according to Alsayyar and Jrade (2015), there is limited sustainability analysis software to support this initiative, and per Akinade et al. (2017), the sustainability parameters of building properties are difficult to access for performance analysis purposes.

Legal-related barriers: Kummitha and Crutzen (2017) reported how the government of India enacted some laws to fast-track the use of some specific cities as a platform to support the smart city initiative, however, per Bunnell (2015), the steps suffered some significant setbacks due to protest by marginalized communities who wanted the government to roll-back the scheme. BIM according to Aibinu and Venkatesh (2014) is not made mandatory by most clients for their projects, hence, if any contractor intends to adopt it in such projects, the contractor might likely bear the cost of the implementation. The above brings to the fore, the lack of awareness of this benefits to key stakeholders both in the construction industry and in the local communities (Gu & London, 2010; Hope & Alwan, 2012). Also, in the United Kingdom, it is mandatory for public projects exceeding five million pounds to implement BIM in such projects. Several other factors such as shown in Table 5.1 are some barriers which are evident in the literature and practice as hindering the implementation of smart, sustainable practices in the construction industry (Olawumi et al., 2018).

Education and knowledge-related barriers: Welter (2003) argued the need for citizenry participation in the design, building, and management of their buildings and cities in a bottom-top approach to city urbanization. However, currently reverse is the case in the built environment whereby only a few stakeholders are involved in building design and collaboration (Kummitha & Crutzen, 2017); amid the native non-collaborative culture of project stakeholders in the construction industry (Olatunji et al., 2016b, 2017a). More so, Wang and Adeli (2014) argued for the necessity to promote sustainable building design among project stakeholders in order to ensure efficient material use and energy consumption (Lee et al., 2013b; Pinto et al., 2013), reduce carbon emission and lifecycle costs (Hegazy et al., 2012).

Stakeholder's attitude: Abubakar et al. (2014) highlighted the resistance to change of construction organizations and key stakeholders in the built environment as a key impediment to the implementation of innovative concepts such as BIM and sustainability in building projects. Hence, per Gu and London (2010) and Redmond et al. (2012) this has led to the disproportionate level of implementation of sustainable smart practices in construction projects. Abubakar et al. (2014) classified this resistance to change into – societal and habitual resistance. Wu and Handziuk (2013) noted that the resistance to change had impacted negatively on the skills, knowledge, and the experience of project stakeholders as regards sustainable smart practices and its adoption in building projects. Hence, for the built environment to experience a full implementation of these concepts in every construction project; a significant change in stakeholders' attitude and perception to the uptake of innovative and revolutionary concepts such as BIM and sustainability practices.

Organizational and project-related barriers: Antón and Díaz (2014) regard the construction industry as a project-based sector which requires the coordination of various stakeholders from different organizations to collaborate to accomplish the project objectives. More so, per Olawumi et al. (2018) argued that for a successful implementation of BIM and sustainability practices, a considerable measure of physical human efforts and coordination is required. However, as reported by Boktor et al. (2014), the inadequacy of project team coordination, as well as the fragmented nature of the construction industry, have hindered the successful implementation of sustainable smart practices in building projects; especially in labor-intensive projects. These issues highlighted above impedes the delivery of construction projects and the application of innovative technologies and concepts.

The study will, in the subsequent sections, attempts to analyze the perception of various stakeholders from twenty-one countries on the barriers to the implementation of sustainable smart practices.

Table 5.1: Summary of identified barriers to the implementation of smart sustainable practices

Code	Barriers	Related sources of data
BA1	Varied market readiness across organizations and geographic locations.	Antón and Díaz (2014); Gu and London (2010); Kivits and Furneaux (2013); Redmond et al. (2012)
BA2	Industry's resistance to change from traditional working practices.	Abubakar et al. (2014); Gu and London (2010); Kivits and Furneaux (2013); Chan et al. (2019a, 2019b)
BA3	Lack of client demand and top management commitment	Aibinu and Venkatesh (2014); Boktor et al. (2014); Rogers et al. (2015)
BA4	Lack of support and involvement of the government	Abubakar et al. (2014); Bin Zakaria et al. (2013)
BA5	Low level of involvement of BIM users in green projects	Antón and Díaz (2014); Ma et al. (2018)
BA6	Societal reluctance to change from traditional values or culture	Aibinu and Venkatesh (2014); Kivits and Furneaux (2013); Redmond et al. (2012)
BA7	The lack of awareness and collaboration among project stakeholders	Antón and Díaz (2014); Bin Zakaria et al. (2013); Gu and London (2010); Hope and Alwan (2012)
BA8	Inadequacy of requisite experience, knowledge, and skills from the workforce	Abubakar et al. (2014); Aibinu and Venkatesh (2014); Chan (2014); Gu and London (2010); Kivits and Furneaux (2013); Nanajkar and Gao (2014)
BA9	Longer time in adapting to new technologies (steep learning curve)	Aibinu and Venkatesh (2014); Nanajkar and Gao (2014)
BA10	Lack of understanding of the processes and workflows required for BIM and sustainability	Aibinu and Venkatesh (2014)
BA11	Low level of research in the industry and academia	Aibinu and Venkatesh (2014); Antón and Díaz (2014); Redmond et al. (2012)
BA12	Inadequate in-depth expertise and know-how to operate sustainability-related analysis software programs	(Ahn et al., 2014; Antón & Díaz, 2014; Gu & London, 2010)
BA13	Shortage of cross-field specialists in BIM and sustainability	Hope and Alwan (2012)
BA14	The high cost of BIM software, license, and associated applications	Aibinu and Venkatesh (2014); Kivits and Furneaux (2013); Nanajkar and Gao (2014)
BA15	The high initial investment in staff training costs	Aibinu and Venkatesh (2014); Kivits and Furneaux (2013)
BA16	Recurring need for additional and associated resources and high economic expenses	Aranda-Mena et al. (2009); Young et al. (2008)
BA17	Lack of initiative and hesitance on future investments	Gu and London (2010); Hanna et al. (2013)
BA18	Fragmented nature of the construction industry	Antón and Díaz (2014); Gu and London (2010); Kivits and Furneaux (2013); Redmond et al. (2012)
BA19	Organizational challenges, policy, and project strategy	Boktor et al. (2014); Dossick and Neff (2010)
BA20	Difficulty in assessing environmental parameters of building properties	Abolghasemzadeh (2013); Akinade et al. (2017)
BA21	Difficulty in accessing sustainability-related data (such as safety, health, and pollution index, etc.)	Adamus (2013); Antón and Díaz (2014); Olawumi and Chan (2019b, 2019c)
BA22	The risk of losing intellectual property and rights	Kivits and Furneaux (2013); Redmond et al. (2012)
BA23	Difficulty in allocating and sharing BIM-related risks	Kivits and Furneaux (2013)
BA24	Lack of legal framework and contract uncertainties	Aibinu and Venkatesh (2014); Redmond et al. (2012)
BA25	Increased risk and liability	Kivits and Furneaux (2013); Olawumi et al. (2018)
BA26	Lack of suitable procurement policy and contractual	Aibinu and Venkatesh (2014); Sackey et al.

Code	Barriers	Related sources of data
	agreements	(2015)
BA27	Non-uniformity of sustainability evaluation criteria and measures	Abolghasemzadeh (2013); Antón and Díaz (2014)
BA28	Lack of a comprehensive framework and implementation plan for sustainability	Azhar (2011); Redmond et al. (2012); Saxon (2013)
BA29	Absence or non-uniformity of industry standards for sustainability	Alsayyar and Jrade (2015); Boktor et al. (2014); Saxon (2013)
BA30	Inaccuracy and uncertainty in sustainability assessments for projects	Ahn et al. (2014); Alsayyar and Jrade (2015); Antón and Díaz (2014)
BA31	Incompatibility issues with different software packages	Antón and Díaz (2014); Kivits and Furneaux (2013); Nanajkar and Gao (2014); Rogers et al. (2015)
BA32	Absence of industry standards for BIM	Antón and Díaz (2014); Chan (2014); Redmond et al. (2012); Rogers et al. (2015); Saka et al. (2019a)
BA33	Insufficient level of support from the BIM software developers	Redmond et al. (2012)
BA34	Inadequacy of BIM data schemas to semantically represent sustainability-based knowledge	Adamus (2013); Chan et al. (2019b); Olawumi and Chan (2019d)
BA35	Lack of supporting sustainability analysis tools	Akinade et al. (2015); Alsayyar and Jrade (2015)
BA36	Non-implementation of open source principles for software development	Hope and Alwan (2012)
BA37	Domination of the market by commercial assessment tools	Hope and Alwan (2012)
BA38	User-unfriendliness of BIM analysis software programs	Ahn et al. (2014); Aksamija (2012)

5.4 Research methodology

This study identified and assessed the barriers to the implementation of smart, sustainable practices in construction projects. The study adopted a quantitative research methodology via empirical questionnaire surveys to elicit the necessary data for the study. Moreover, the questionnaire items were gathered via the use of secondary data through a systematic review of desktop literature from journal papers, government gazettes, libraries, and web pages. According to Olatunji et al. (2017), the method of data collection is significant in establishing the aim of the study as well as in the composition of the questionnaire survey form.

A purposive sampling technique, together with a snowball sampling, was used in targeting relevant respondents for the study. The survey respondents are construction professionals with good knowledge of the concepts of smart, sustainable practices as it relates to the built environment. The respondents were given brief information on what smart sustainability practices is. Three modes were adopted in sending the questionnaire surveys to the respondents: (1) online survey forms; (2) fill-in PDF survey form; and (3) hand-delivered questionnaire. More so, personalized emails were sent to some potential respondents using with the attached fill-in PDF survey form as well as a link to the online survey form.

A total of 220 survey responses were received across 21 countries, and the data were analyzed in greater detail in later sections. One hundred sixty-one responses were collected via the online survey form, 14 via the fill-in PDF form and 45 via the hand-delivered method. There was a 100% response rate via the hand-delivery method of the questionnaire distribution. However, for the other two forms of distributions (fill-in PDF form and online surveys), it was difficult to determine the questionnaire return ratio as a snowball sampling technique was used for it. The questionnaire was pretested before distribution. The questionnaire survey (see Appendix B) collected some background information on the respondents as well as asked the respondents to rate the factors on a 5-point Likert scale: 1 = strongly disagree, 3 = neutral / no comment and 5 = strongly agree. The respondents have the option to tick 'N/A' if the factor is not applicable as a barrier to the implementation of smart, sustainable practices in construction projects. The respondents were given options to add to the factors listed for assessment. However, none of the 220 respondents added to the 38 factors listed on the survey form.

Meanwhile, prior to the empirical international questionnaire survey, a Delphi survey was conducted involving 14 experts across eight countries towards reaching a consensus on the cross-field research topic. See Olawumi et al. (2018) for the published findings of the Delphi survey exercise.

5.4.1 Statistical tools for data analysis

Several statistical tools and methods were employed in analyzing the data collected in the course of the study. These include: (1) Cronbach's alpha (α) reliability test; (2) Mean score ranking and standard deviation (SD); (3) Inferential statistical tests such as ANOVA, post-hoc Tukey tests, correlation analysis; and (4) Factor analysis and groupings. According to Field (2009), a reliability test is required to be undertaken before further analysis on a set of data. Cronbach alpha reliability test was used in this study to assess the questionnaire and its associated scale to ensure its measure the right construct (Field, 2009; Olatunji et al., 2017a).

The Cronbach's alpha is employed to test the internal consistency and reliability of a construct, and the range of its α coefficient ranges from 0 to 1. It implies that the larger the α-value, the better the reliability of the scale or the generated result (Chan et al., 2019b). The arithmetic mean is a measure of central tendency which indicates the average values of a set of figures (equation i) while SD is a quantitative measure of the differences of each value from the mean and it is a measure of variability (see equation ii). A low SD indicates that the values are close to the mean, whereas a high SD implies the data points are spread out over a large range of values. ANOVA (analysis of variance) is an inferential statistical tool used to determine whether any statistically significant differences exist between the means of two or more independent data groups. ANOVA requires typically distributed data points(Olatunji et al., 2017a). The post-hoc Tukey test is regarded as a posteriori test because it is only needed to confirm and reveal where the differences occurred between groups after an ANOVA analysis has identified the statistically significant different groups. Factor analysis is discussed in full details in section 5.5.3.

$$\bar{X} = \frac{\sum x}{n} - - - - equation\ (i)$$

$$SD = \sqrt{\frac{\sum(x - \bar{X})^2}{n-1} - - - - equation\ (ii)}$$

Where $\bar{X}$ = mean score.

$\sum x$ = aggregate score of a set of values.

x = individual factor value.

n = number of values (that is, number of respondents in this study).

SD = Standard deviation.

The α-value for this study was 0.951, which is higher than the minimum threshold of 0.70 (Olawumi & Chan, 2018d) and implies good internal consistency and that the data are suitable for further statistical analysis. For the mean ranking, if two or more factors have the same mean value, the SD values are used to rank them; the factor with the lower SD value is ranked higher (Olatunji et al., 2017a; Olawumi & Chan, 2018b). However, if they have the same mean and SD value, they will have the same rank (Olawumi & Chan, 2018c).

5.4.2 *Respondents' demographics*

The section reveals vital information about the 220 respondents that participated in the survey (see Figure 5.1). The respondents were from 21 countries working under diverse organizational types with majority of them working in the academia (87, 39.5%), followed by public client participants (55, 25%), main contractors (35, 15.9%), project consultants (25, 11.4%), private clients (12, 5.5%), with the least number of participants coming from property management companies (6, 2.7%). Professional-wise, the findings a slight majority as quantity surveyors (25%), followed by academics (13.2%), architects (12.7%), project managers (12.3%), civil engineers (10.9%), builders and construction managers (8.6%), building services engineers (7.7%), urban planners (2.7%), BIM managers (2.3%), structural engineers (2.3%); and estate valuers and property managers (2.3%).

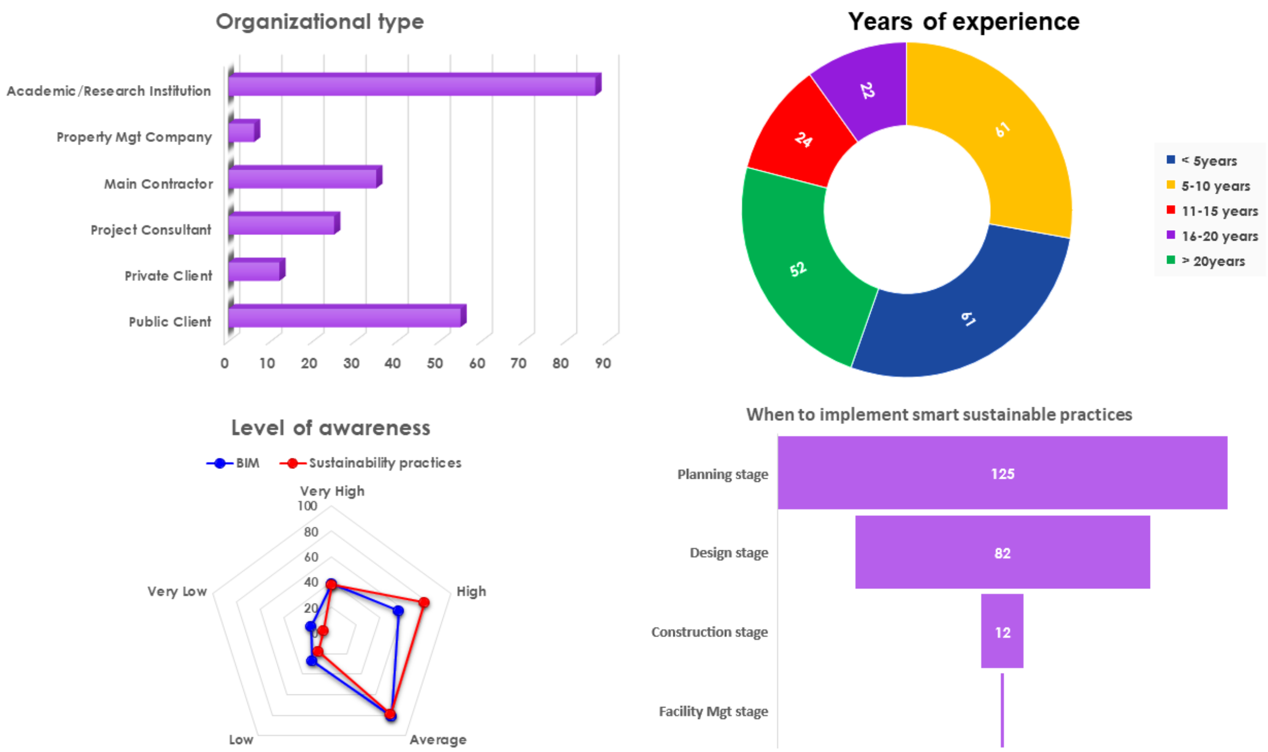


Figure 5.1: Respondents' demographics

Meanwhile, the respondents were asked about their level of awareness of the BIM concepts and processes. The findings revealed that a significant percentage of the respondents have at least a high level of awareness (95, 43.2%), while the eight-one of the respondents (36.8%) have an average level of awareness. Meanwhile, based on the respondents' level of awareness of the sustainability process, most of the respondents (116, 52.8%) have at least a high level of awareness. While about seventy-nine respondents (35.9%) have an average level of awareness of sustainability practices. The survey participants have considerable professional experience in the construction industry with 44.5% of the respondents (98) having at least 11 years working experience in the industry, and the next 27.7% of the respondents (61) have between five to ten years working experience in the construction industry. More so, majority of the respondents (125, 56.8%) argued for the implementation of smart, sustainable practices at the planning stage and another 37.3% of the respondents (82) noted that the design stage of project development is the best stage to implement the concepts while twelve respondents (5.5%) and one respondent preferred the construction and facility management stages respectively.

5.5 Results of statistical analyses

This section discusses the results of the data collected via the questionnaire surveys and the findings of the statistical tools employed in the study.

5.5.1 Descriptive statistical tests

For the 38 barriers identified, the mean values range from M= 3.32 (SD= 0.984) for "BA25 - *increased risk and liability*" to M=4.15 (SD= 0.860) for "*BA8 - the inadequacy of requisite experience, knowledge, and skills from the workforce*" at a variance of 0.83 (See Table 5.3). Moreover, based on similar benchmarks adopted by (Lu et al., 2008; Olatunji et al., 2017a) who utilized the mean value of 4 on a 5-point Likert scale to regard a factor as an important one; a total of five factors can be regarded as significant based on the mean score. These include "*BA8 - inadequacy of requisite experience, knowledge, and skills from the workforce*" (M=4.15, SD= 0.860), "*BA2- industry's resistance to change from traditional working practices*" (M=4.06, SD= 0.868), "*BA9- longer time in adapting to new technologies (steep learning curve)*" (M=4.02, SD= 0.876), "*BA10- lack of understanding of the processes and workflows required for BIM and sustainability*" (M=4.00, SD= 0.825), and "*BA15- high initial investment on staff training costs*" (M=4.00, SD= 0.934). From the research findings, it can be implied that low awareness and knowledge is still a significant hindrance to the implementation of smart, sustainable practices in the built environment along with the sustained archaic industry culture and the costs of investment.

The respondents from the public and private clients, project consultant, and the academics rated “BA8 - the inadequacy of requisite experience, knowledge, and skills from the workforce” (M=4.15, SD= 0.860) as the most significant barrier to the implementation of smart, sustainable practices in construction projects. However, the factor was rated by respondents from the main contractors as the second most significant factor who ranked “BA14- the high cost of BIM software, license, and associated applications” as the critical barrier. This findings from the various organizational set up show that the respondents from the main contractors perceived the cost of these concepts as significant because incorporating the cost of these software and its implementation in their work might increase their tender bid sum and put them in an unfavorable position against fellow competitive contractors. However, for the other set of respondents, the findings reveal there is still a lack of knowledge and expertise in both the private and public sectors of the construction industry. The civil engineers, project managers, and quantity surveyors agreed with this finding by ranking factor BA8 as the most significant barrier while the architects perceived “BA9- longer time in adapting to new technologies” (M=4.43, SD= 0.742) as the most critical barrier.

The academics regards “BA11 - low level of research in the industry and academia” as the least important barrier, this shows that there is a considerable increase in research publication in BIM (Olawumi et al., 2017) and sustainability (Olawumi & Chan, 2017, 2018a) in the literature. The private client’s respondents considered “BA25 - increased risk and liability” as the least significant factor, while to the public client’s respondents it is “BA22 - the risk of losing intellectual property and rights”. These findings are because the risks and liabilities in most construction projects are passed across to the contractors by both the private and public sectors clients. Hence, these factors have little impacts on their business interests.

5.5.2 Inferential statistical tests

In order to further investigate the differences in the perception from the diverse sets of respondents from differing organizational setups (private and public clients, project consultants, main contractors, and academics) and the professionals (architects, researchers, civil engineers, project managers, quantity surveyors, building service engineers, and construction managers). ANOVA was employed to analyze the 38 identified barriers which according to Olatunji et al. (2017a) and Tsai et al. (2014a) is a parametric statistical tool which is based on the mean of scores. More so, Olatunji et al. (2017a) recommended that a post hoc Tukey's test to be conducted on factors that are significant at $p<0.05$.

5.5.2.1 Statistical tests based on professional disciplines

The ANOVA analysis conducted on the data revealed a significant divergence in the opinions (at significance <5%) among the groups of respondents on six factors which are "BA11 - low level of research in the industry and academia" [$F(10,209) = 1.910$, $p = 0.045$]; "BA14 - high cost of BIM software, license, and associated applications" [$F(10,209) = 2.079$, $p = 0.027$]; "BA15 - high initial investment on staff training costs" [$F(10,209) = 2.532$, $p = 0.007$]; "BA16 - recurring need for additional and associated resources and high economic expenses" [$F(10,209) = 3.040$, $p = 0.001$]; "BA36 - non-implementation of open source principles for software development" [$F(10,209) = 3.002$, $p = 0.001$]; and "BA38 - user-unfriendliness of BIM analysis software programs" [$F(10,209) = 3.241$, $p = 0.001$].

A further analysis of the six significant barriers using the post hoc Tukey test revealed a very high significant difference ($p = 0.001$) on one factor "BA38 - user-unfriendliness of BIM analysis software programs"; with the architects (M=4.00, SD=1.054) perceiving it to be more significant than the construction managers (M=2.74, SD=0.991). The finding is consistent with the fact that architects use more software than an average construction manager; hence, if such software is user-unfriendly, it might hinder their use of the software.

5.5.2.2 Statistical tests based on organizational setups

The ANOVA analysis conducted on the results (at significant <5%) showed some significant differences in the opinions of respondents from diverse organizational setups on ten factors such as "BA4 - lack of support and involvement of the government" [$F(5,214) = 3.188$, $p = 0.008$]; "BA5 - low level of involvement of BIM users in green projects" [$F(5,214) = 3.599$, $p = 0.004$]; "BA7 - the lack of awareness and collaboration among project stakeholders" [$F(5,214) = 2.869$, $p = 0.016$]; "BA10 - lack of understanding of the processes and workflows required for BIM and sustainability" [$F(5,214) = 2.758$, $p = 0.019$]; "BA19 - organizational challenges, policy, and project strategy" [$F(5,214) = 2.673$, $p = 0.023$] among others (see Table 5.3). Moreover, based on the post hoc Tukey test evaluation of the ten significant barriers, eight barriers were found to be more important ($p<0.05$). These include “BA4 - lack of support and involvement of the government” with a moderate significance ($p = 0.024$) of which the respondents from the private clients (M= 4.33, SD= 0.651) perceived the barrier to be significant to their adoption of smart, sustainable practices than those from the public-sector clients. The finding is because private clients who are under less control of the governments might not receive funding or support from the government, unlike their public-sector counterparts who receive yearly or quarterly allocations for their operations.

More so, for “BA5 - low level of involvement of BIM users in green projects”, there is a high significance ($p=0.016$) between the public sector (M=3.36, SD=1.025) and private sector (M=4.33, SD=0.492) clients with the private sector identifying the factor to be of higher importance than their public counterparts. Similarly, at a significance of ($p=0.023$), the respondents from the main contractors (M=4.00, SD=0.804) perceived the factor to be of high importance than the public sector. The analysis is consistent with the findings of Olawumi et al. (2018), which revealed a higher level of involvement of BIM users in green projects in government establishments than in the private sector. See Table 5.2 for the results of the post hoc Tukey tests for the organizational setups.

Table 5.2: Post-hoc Tukey test for the organizational setups

Factors	Organizational setups	Significance	Factors	Organizational setups	Significance
BA4	Public clients vs Private clients*	0.024	BA20	Public clients vs Private clients* Public clients vs Academics* Main contractors* vs Public clients	0.006 0.003 0.017
BA5	Public clients vs Private clients* Public clients vs Main contractors*	0.016 0.023	BA21	Main contractors* vs Public clients Public clients vs Academics*	0.012 0.008
BA7	Public clients vs Private clients* Public clients vs Academics*	0.046 0.021	BA30	Main contractors* vs Public clients	0.023
BA19	Public clients vs Private clients*	0.021	BA37	Project consultants vs Main contractors*	0.019

Note: *******organizational setup considers the factor of higher significance than the other organizational setups*

Table 5.3: Barriers to smart sustainable practices in the built environment: inter-group comparisons

Barriers	Public clients		Private clients		Project consultants		Main contractors		Academics		Overall			F	Sig.
	Mean	Rk	Mean	Rk	Mean	Rk	Mean	Rk	Mean	Rk	Mean	SD	Rk		
BA1	3.98	4	4.17	17	3.88	10	3.91	11	4.01	4	3.97	0.805	7	0.452	0.811
BA2	3.95	5	4.42	2	3.96	6	3.89	18	4.18	2	4.06	0.868	2	1.326	0.254
BA3	3.62	16	4.00	28	3.92	9	3.97	8	4.01	6	3.90	0.933	9	1.347	0.246
BA4	3.24	35	4.33	10	3.96	7	3.83	23	3.55	24	3.61	1.127	25	3.188	**0.008**
BA5	3.36	30	4.33	9	3.72	18	4.00	5	3.56	22	3.64	0.963	21	3.599	**0.004**
BA6	3.56	19	4.08	24	3.76	16	3.86	22	3.49	28	3.63	1.009	23	1.313	0.260
BA7	3.49	25	4.33	13	3.88	11	3.91	12	3.99	7	3.86	0.928	10	2.869	**0.016**
BA8	4.05	1	4.50	1	4.12	1	4.09	2	4.23	1	4.15	0.860	1	1.110	0.356
BA9	3.98	3	4.42	2	3.92	8	4.00	6	4.01	5	4.02	0.876	3	0.612	0.691
BA10	3.78	9	4.33	10	4.04	2	3.94	9	4.16	3	4.00	0.825	4	2.758	**0.019**
BA11	3.25	34	3.67	34	3.64	23	3.63	35	3.22	38	3.38	1.051	35	1.554	0.174
BA12	3.85	8	4.25	16	3.80	14	3.97	7	3.71	16	3.84	0.937	12	0.965	0.440
BA13	3.93	6	4.42	2	3.96	5	4.06	3	3.93	9	3.97	0.967	8	0.900	0.482
BA14	3.87	7	4.33	12	4.00	4	4.11	1	3.93	10	3.99	0.981	6	0.768	0.573
BA15	4.00	2	4.42	7	4.00	3	4.00	4	3.91	11	4.00	0.934	5	0.795	0.555
BA16	3.71	11	4.42	7	3.60	29	3.91	10	3.79	14	3.80	0.851	13	1.824	0.109
BA17	3.60	17	3.92	29	3.60	30	3.86	21	3.67	18	3.68	0.911	17	0.595	0.704
BA18	3.62	15	4.42	2	3.68	22	3.91	15	3.84	12	3.80	0.985	14	1.551	0.175
BA19	3.64	14	4.42	2	3.72	19	3.86	20	3.93	8	3.85	0.786	11	2.673	**0.023**
BA20	3.22	36	4.17	18	3.64	24	3.80	25	3.76	15	3.64	0.862	20	4.416	**0.001**
BA21	3.29	33	4.00	25	3.60	25	3.91	13	3.80	13	3.68	0.886	16	3.494	**0.005**
BA22	3.13	38	3.67	35	3.20	36	3.57	37	3.36	33	3.34	1.058	37	1.131	0.345
BA23	3.29	32	3.67	35	3.56	32	3.71	29	3.49	27	3.49	0.986	33	1.042	0.394
BA24	3.47	27	3.75	33	3.72	19	3.80	24	3.56	21	3.60	0.953	26	0.914	0.473
BA25	3.16	37	3.50	38	3.20	35	3.63	34	3.30	35	3.32	0.984	38	1.173	0.323
BA26	3.58	18	4.17	20	3.60	25	3.66	33	3.51	26	3.58	0.992	28	1.685	0.139
BA27	3.51	21	4.25	14	3.68	21	3.74	27	3.66	19	3.67	0.867	18	1.525	0.183
BA28	3.51	22	4.17	18	3.80	12	3.77	26	3.55	23	3.63	0.915	22	1.636	0.152
BA29	3.51	23	4.08	22	3.80	13	3.86	19	3.60	20	3.67	0.908	19	1.405	0.224
BA30	3.29	31	4.08	21	3.76	15	3.89	16	3.54	25	3.59	0.895	27	3.112	**0.010**
BA31	3.78	9	3.92	30	3.76	17	3.89	17	3.69	17	3.77	0.958	15	0.283	0.922
BA32	3.69	12	4.08	22	3.60	25	3.69	32	3.47	31	3.62	1.098	24	0.862	0.507
BA33	3.51	24	4.25	14	3.48	33	3.57	36	3.29	37	3.47	1.036	34	2.079	0.069
BA34	3.65	13	4.00	25	3.56	31	3.51	38	3.45	32	3.56	0.980	29	0.839	0.523
BA35	3.47	26	4.00	25	3.60	28	3.69	31	3.31	34	3.50	0.939	32	2.125	0.064
BA36	3.53	20	3.75	31	3.32	34	3.71	28	3.48	29	3.53	0.929	30	0.707	0.618
BA37	3.44	28	3.58	37	3.12	37	3.91	13	3.48	29	3.52	0.963	31	2.542	**0.029**
BA38	3.38	29	3.75	32	3.04	38	3.71	30	3.30	36	3.36	1.039	36	2.603	**0.026**

Note: Rk- Rank

5.5.3 Classification of the key barriers based on factor analysis

The study adopted factor analysis to reduce a large number of the barrier factors to a relatively set of variables by investigating the interrelationships between the variables (Hair et al., 2010; Xu et al., 2010). There are two types of factor analysis, principal component analysis (PCA) and Promax rotation method (Chan & Hung, 2015); the PCA was used in this study. According to Chan and Choi (2015), factor analysis (PCA) is a statistical technique used to identify the underlying clustered factors that define the relationships among sets of interrelated variables; and can be used to interpret 'nonrelated clusters' of factors (Fang et al., 2004), and explain complex concepts (Xu et al., 2010). Meanwhile, before subjecting the 38 factors to factor analysis, a Pearson correlation analysis was conducted as recommended by Xu et al. (2010), who noted that the statistical method helps to eliminate the existence of any multiplier effects among the variables. Hence, the correlations of these factors were assessed, and 30 factors which are not highly correlated with each other are used in subsequent analysis.

The PCA was conducted using varimax rotation method (an orthogonal rotation method) on the thirty non-correlated barriers factors from a sample of 220 responses. The results of the factor analysis are shown in Table 5.4, while the column 'factor loading' illustrates the total variance explained by each factor. Lingard and Rowlinson (2006), Chan and Choi (2015) and Chan (2019) recommended that the sample size must be considered sufficient in the ratio of 1:5 (number of variables: sample size) which the current study fulfilled. That is, 30 barrier factors multiplied by five samples required for each factor = at least 150 samples needed to proceed with the factor analysis. Kaiser-Meyer-Olkin (KMO) tests for sampling adequacy and Bartlett's test of sphericity (BTS) was used to examine the appropriateness of PCA for factor extraction (Field, 2009).

The KMO value for the study's factor analysis is 0.904, which shows an 'excellent' degree of common variance (Field, 2009) and above the acceptable threshold of 0.50 (Norusis, 1993). More so, according to Chan and Hung (2015), a KMO value close to 1 indicates that a compact pattern of correlations and that the PCA will generate distinct and reliable clusters. The BTS analyses revealed a substantial test statistic value (chi-square=3413.643) and a small significance value (p=0.000, df=435) which per Chan and Choi (2015) implies that the correlation matrix is not an identity matrix. Therefore, as the various requirements needed to proceed with a factor analysis has been met, the PCA can be applied in this study with for further investigation and discussion; this ensures the research can be conducted with better reliability and confidence.

Seven underlying factors were extracted using PCA which represent 65% of the total variance in responses (see Table 5.4) which is above the minimum threshold of 60% (Chan, 2019; Chan & Choi, 2015; Hair et al., 2010; Malhotra, 1996).

Table 5.4: Factor structure of the varimax rotation on the key barrier factors

Code	Barriers to implementing smart sustainability practices	Factor loading	Eigenvalue	Percentage of variance explained	Cumulative percentage of variance explained
Factor 1 – Technical-related barriers			10.763	35.877	35.877
BA35	Lack of supporting sustainability analysis tools	0.788			
BA36	Non-implementation of open source principles for software development	0.713			
BA34	Inadequacy of BIM data schemas to semantically represent sustainability-based knowledge	0.710			
BA32	Absence of industry standards for BIM	0.656			
BA38	User-unfriendliness of BIM analysis software programs	0.566			
BA31	Incompatibility issues with different software packages	0.502			
Factor 2 – Attitude-related barriers			2.191	7.302	43.179
BA4	Lack of support and involvement of the government	0.759			
BA5	Low level of involvement of BIM users in green projects	0.701			
BA6	Societal reluctance to change from traditional values or culture	0.627			
BA7	The lack of awareness and collaboration among project stakeholders	0.603			
BA3	Lack of client demand and top management commitment	0.595			
BA11	Low level of research in the industry and academia	0.404			
Factor 3 – Education and knowledge-related barriers			1.642	5.473	48.652
BA8	Inadequacy of requisite experience, knowledge, and skills from the workforce	0.735			
BA9	Longer time in adapting to new technologies (steep learning curve)	0.726			
BA10	Lack of understanding of the processes and workflows required for BIM and sustainability	0.714			
BA13	Shortage of cross-field specialists in BIM and sustainability	0.668			

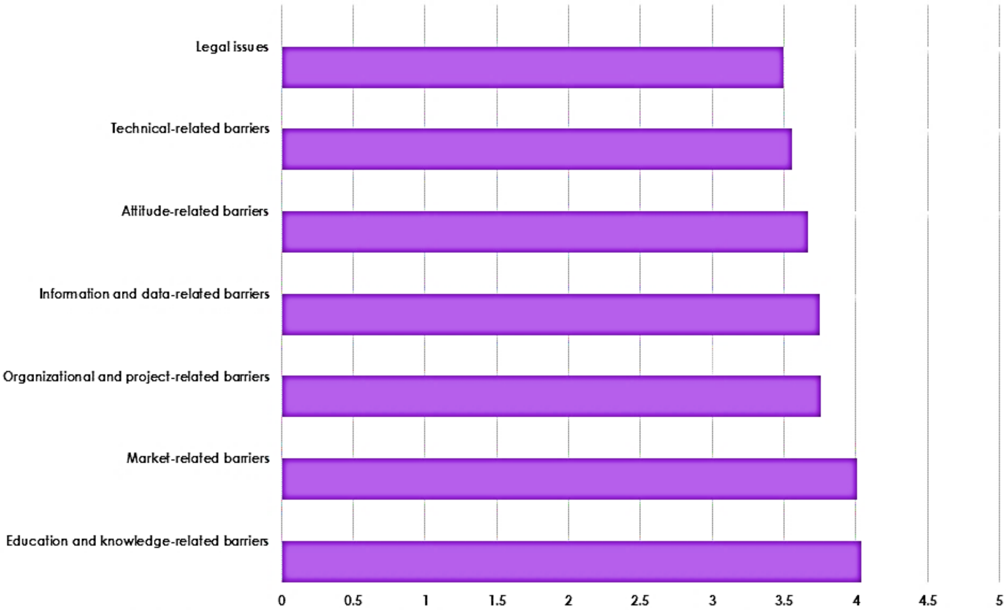
Code	Barriers to implementing smart sustainability practices	Factor loading	Eigenvalue	Percentage of variance explained	Cumulative percentage of variance explained
Factor 4 – Legal issues			1.446	4.822	53.473
BA25	Increased risk and liability	0.782			
BA24	Lack of legal framework and contract uncertainties	0.764			
BA26	Lack of suitable procurement policy and contractual agreements	0.756			
BA23	Difficulty in allocating and sharing BIM-related risks	0.633			
Factor 5 – Organizational and project-related barriers			1.251	4.170	57.643
BA17	Lack of initiative and hesitance on future investments	0.653			
BA19	Organizational challenges, policy, and project strategy	0.625			
BA18	Fragmented nature of the construction industry	0.614			
BA21	Difficulty in accessing sustainability-related data (such as safety, health, and pollution index, etc.)	0.533			
Factor 6 – Information and data-related barriers			1.207	4.024	61.667
BA30	Inaccuracy and uncertainty in sustainability assessments for projects	0.721			
BA29	Absence or non-uniformity of industry standards for sustainability	0.676			
BA14	The high cost of BIM software, license, and associated applications	0.596			
Factor 7 – Market-related barriers			1.006	3.353	65.021
BA1	Varied market readiness across organizations and geographic locations	0.648			
BA15	The high initial investment in staff training costs	0.515			
BA2	Industry's resistance to change from traditional working practices	0.504			

The 30 barrier factors are represented in one of the seven underlying grouped factors, and all the factor loadings of each barrier factors are close to 0.5 or higher as suggested by Chan and Hung (2015) and Chan and Choi (2015). According to Proverbs et al. (1997), the higher the value of the factor loading of an individual factor (which is maximum of 1.0), the higher the significance of the factor to the underlying cluster factor. The factor loading values also reflect how each factor contributes to its underlying grouped factor (Chan & Hung, 2015). The findings reveal a consistent and reliable factor loading and interpretation of the extracted individual factor.

5.6 Discussion of survey findings

5.6.1 Discussion of key cluster factors after factor analysis

The clustered factors are analyzed in Figure 5.2 in descending order of significance towards interpreting the individual factors linked to them. As suggested by Sato (2005), an identifiable and collective label is attached to each grouped factor of high correlation coefficients; which are themselves a cluster of individual factors. However, per Chan and Hung (2015), these labels are subjective, and each author may come up with different labels. The factor clusters are ranked using their factor scale rating as employed by Chong and Zin (2012) and Chan (2019). The factor scale rating is the ratio of the mean of individual factors within a cluster divided by the number of factors in the cluster (Chan and Hung, 2015; Chan, 2019). Discussion of the key factor clusters will focus on the top-four ranked factor clusters. Similarly, based on the precedent cases in the existing literature (Chan & Choi, 2015; Olawumi & Chan, 2019a; Xu et al., 2010), these studies only discussed top-three of the key cluster factors generated after factor analysis based on their factor scale ratings; and to converse space. Also, one of the purposes of employing the factor scale rating analysis is to highlight more significant cluster factors with relatively higher rating values for further discussion (Chan & Hung, 2015).



	Education and knowledge-related barriers	Market-related barriers	Organizational and project-related barriers	Information and data-related barriers	Attitude-related barriers	Technical-related barriers	Legal issues
Ranking	1	2	3	4	5	6	7
Factor scale rating	4.035	4.01	3.7525	3.75	3.67	3.5567	3.4975

Figure 5.2: Ranking results of the factor scale rating for the key cluster factors

5.6.1.1 Education and knowledge-related barriers

Factor 3, consisting of four barrier-related factors, is the highest-rated clustered factor with a factor scale rating of M=4.035. The cluster is related to experience and knowledge of construction organization staff, the steep learning curve, inadequate understanding of smart, sustainable practices processes, and the shortage of cross-field specialists in smart, sustainable practices. Gu and London (2010) observed through their study that little or no attention has been placed on the training of construction professionals to improve their understanding and skills in the adoption of new technologies. More so, Aibinu and Venkatesh (2014) noted that the rapid technological change has reduced the ability of the workforce to adapt and that despite the benefits of these concepts, the current skills shortage in the industry has reduced the potentiality of its positive impact on construction processes. Hence, as advised by Olawumi et al. (2018), professional bodies and construction firms should collaborate to improve the skillsets and capacity of their members and staff in smart, sustainable practices. Gu and London (2010) call for the training of students at an early stage on these concepts for them to appreciate it after their graduation from college. Moreover, the government can support this initiative by training its staff in construction-related departments and parastatals as well as providing financial subsidies to private firms in the training of their workforce.

5.6.1.2 Market-related barriers

The next significant clustered factor is factor 7 with three key factors and a factor scale rating of M=4.01. The cluster is concerned with the varied market readiness across construction firms and regions, the high investment cost of training, and the industry resistance to change from traditional working practices. Olawumi et al. (2018) accentuated that despite the benefits of these concepts, little progress has been achieved in implementing BIM and sustainability practices in several countries. Abubakar et al. (2014) pointed out the hesitance of construction stakeholders to new concepts and innovative technologies which has hindered developments in the industry when compared to other sectors of the economy. Kivits and Furneaux (2013) recommended firms to consider its workforce along with the adopted technology to close the gap in the interconnection of the sociotechnical system. Meanwhile, Olawumi et al. (2018) urge construction firms and project stakeholders to be proactive like their counterparts in other sectors in adopting innovative concepts and embrace dynamic and positive developments in the built environment.

5.6.1.3 Organizational and project-related barriers

Factor 5 comprises of four barriers with a factor scale rating of M= 3.7525, which are related to construction firms' hesitance to plan for future investments, challenges related to organizational policies and strategies, fragmented nature of the industry, and the difficulties in accessing sustainability-related data used for the sustainability assessments of buildings. Olawumi et al. (2018) argued that concepts such as smart, sustainable practices despite its revolutionary effects on the built environment still requires the integration of human efforts and strategies which when lacking can amplify its non-implementation in construction projects. Olawumi et al. (2018) revealed the lack of investment in most organizations, which has affected their adoption of smart, sustainable practices. Antón and Díaz (2014) described the construction industry as a project-based sector, and per Boktor et al. (2014) the uncollaborative environment nature of the industry and ineffective organization strategies has hindered the implementation of these concepts. Moreover, Adamus (2013) considered the availability of sustainability-related software and data as pivotal to the decision-making process of project stakeholders and the sustainability assessments of buildings; while, Olawumi et al. (2018) pointed out the need for the government and professional bodies to subsidize the cost of procuring related smart, sustainable practices software to aid its adoption. Overall, the need for the development of sound and effective strategies by construction firms and stakeholders towards the adoption of smart, sustainable practices cannot be overemphasized.

5.6.1.4 Information and data-related barriers

Factor 6 is composed of three key factors with a factor scale rating of M= 3.75, and it includes the uncertainty and inaccuracies in sustainability assessments of buildings, the absence or non-uniformity of industry standards for smart, sustainable practices, and the high cost of BIM software and its associated software. Adamus (2013) observed that computer-aided decision tools have the potential to improve the sustainability of the built environment. However, their effectiveness is being hindered by the interoperability between design and sustainability analysis software. Adamus

(2013) revealed that some data schemas such as the gbXML lacks contextual information that can aid sustainability assessments of building models. Alsayyar and Jrade (2015) advocated the need for uniform sets of sustainability criteria and a central database to evaluate the sustainability potentials of a building at the design stage. Aibinu and Venkatesh (2014) highlighted the cost of implementation as a significant barrier to the adoption of BIM in Australia, and this includes the high initial cost of the BIM software, yearly licenses or upgrades, and associated applications. Hence, since smart, sustainable practices feed on data as inputs for its effective impacts on the built environment, project stakeholders must collaborate to improve access to relevant data and its exchange.

5.6.2 Practical implications of research findings

The current study has revealed salient issues militating against the implementation of BIM and sustainability practices in the built environment, which have a significant impact on the proper delivery of sustainable and smart building projects. As revealed in the research findings, the private sector clients lamented the lack of support and involvement by their respective governments to enable their implementation of sustainable smart practices in building projects. Chan et al. (2019b) reported the initiative of the Hong Kong government to introduce subsidies and credit facilities to private developers and clients to facilitate adopting BIM and sustainability practices in the Hong Kong built environment too much success. Such initiatives are recommended for adoption to governments in other climes to embrace and implement in their countries and regions. When and if this recommendation is accepted, the current disproportionate level of adoption and readiness will be ameliorated and put the built environment on a fast-track for the full implementation of sustainable smart practices.

Also, the involvement of BIM users in green projects and deployment of BIM technologies to facilitate the adoption of sustainability practices is relatively low in the built environment (Kim & Yu, 2016b; Olawumi & Chan, 2019d). Also, there is a significant lack of awareness of these concepts by the critical stakeholders in the construction projects, and it has thus affected their ability to collaborate towards implementing sustainable smart practices in the built environment. Without addressing these significant barriers, the built environment might not be able to apply these innovative practices; hence, there is the need for construction organizations to empower their staff by ensuring they stay abreast of knowledge and practice regarding sustainable smart practices. More so, construction firms should strategize and restructure their company towards easing the implementation and deployment of BIM and sustainability practices in their organizations. Also, professional bodies such as the RICS, CIOB, etc. should encourage their members and prospective members to attend seminars and workshops that will aid their knowledge and technical know-how on these concepts.

Meanwhile, the research findings revealed there is currently uncertainty and inaccuracy in the assessments of projects using existing green rating systems. More so, there is a lack of uniformity in the sustainability criteria and priority given to each sustainability criteria by the existing rating tools, which are militating against the adoption of sustainable smart practices in these countries. These findings correspond with the previous studies such as Ali and Al Nsairat (2009) and Illankoon et al. (2017). These barriers are still very salient in the built environment, although some leading green rating system such as BREEAM and LEED are attempting to deploy their custom-made rating tool to other countries apart from the originating regions. However, most countries in South America, Asia-Pacific Region, Africa, and some parts of Europe are yet to have a building rating system suited to the local context of these countries. Hence, this study recommends for each country to establish their own custom-made rating systems tailored to their local context of their regions as well as establish their individual green building councils to monitor the progress of the implementation of sustainability practices in their building projects.

5.7 Conclusions and recommendations

This study identified and evaluated the key barriers to the implementation of smart, sustainable practices which was the primary research aim of this paper. A total of thirty-eight barrier factors were identified via a desktop literature review and the factors outlined in a questionnaire which was ranked by 220 respondents from 21 countries who participated in the international survey and have direct and extensive experience in smart, sustainable practices. The survey participants came from diverse professional disciplines and organizational backgrounds, which further lend credence to the data collected. The study meanwhile conducted a comparative assessment of the perceptions of the study participants based on their professional disciplines and organizational backgrounds towards establishing patterns of difference.

A significant finding of this study is that there is a relative level of agreement among most of the groups of respondents on factor BA8- "*inadequacy of requisite experience, knowledge, and skills from the workforce*" as a critical impediment to the implementation of smart, sustainable practices in the built environment. The research findings also revealed that the architects perceived the longer time required for them to learn and adapt to new technologies as the most significant barriers. Even, the academics disagreed with the perception of the practitioners that factor BA11- "*low level of research in the industry and academia*" is highly significant. On the other hand, the academics opined that there is a considerable increase in the level of research in these concepts in universities, and this perception is consistent with the recent findings in the literature. Another profound research finding, is the classification of the critical barriers or impediments via factor analysis of the thirty-eight barrier factors yielded seven clusters with a minimum of three factors in each cluster and a maximum of six factors; while each factor cluster was given an identifiable and collective label to represent its sub-set factors.

After examining the perceptions of the diverse groups of the survey respondents, some useful recommendations and effective strategies for mitigating or eliminating the barriers are suggested. These recommendations include: (1) Professional bodies and construction firms should engage more in the training of their members and staff through the mediums of training workshops and knowledge seminars; (2) Increase in funding support to aid the adoption of smart, sustainable practices; (3) Provision of government subsidy to ease the 'financial stress' of small and medium scale construction firms; (4) Incorporating smart, sustainable practices in the curriculum of construction-related colleges and departments; (5) The need for construction firms and stakeholders to be proactive in adopting new and innovative concepts; (6) The development of effective strategies and plans for fast-tracking the implementation of smart, sustainable practices by construction organizations; and (7) The need to ease the access to and exchange of relevant data among project stakeholders. An obvious limitation of this study is that only BIM out of the several smart technological tools was examined as it influenced sustainability practices. The justification for this has been provided in Chapter 1, sections 1.3.2 and 1.3.6 for perusal.

The study has qualitatively and quantitatively evaluated the impediments and barriers to smart and sustainable practices in the built environment. The ranking of the key barriers or impediments can form a sound basis for developing the practical and well-informed decision-making process by government departments and construction stakeholders. The research findings have contributed to the existing body of knowledge on sustainability and the use of smart technologies to aid the implementation of concepts in the built environment by determining the key barriers to and providing practical recommendations for the implementation of smart, sustainable practices. The findings can be adopted as a policy instrument and useful guidelines for government agencies, stakeholders, and others towards ensuring BIM can be used to deliver the full potential of sustainability practices in the construction industry.

The implementation of the findings of this study is imperative as it will enhance the capacity of the built environment to maximize the perceived benefits of smart and sustainable practices in its everyday activities. Meanwhile, if policymakers and other key stakeholders consider these significant barriers as identified and classified in this study; it is hoped that these challenges can be overcome or eliminated. Collaborative efforts from policymakers, local authorities, practitioners, academics, and other key stakeholders can help to combat these challenges. It is envisaged that the research findings have stimulated multitudinous open debate for reference to the underlying problems besetting the built environment in each local context and internationally.

5.8 Chapter Summary

This chapter examines the major barriers to the application of smart tools to enhance the implementation of sustainability practices in the built environment. The study collated 38 types of impediments from a comprehensive desktop review of the literature, and the data collected were further subjected to expert review via the use of empirical questionnaire surveys. The perceptions of 220 professional respondents from 21 countries were collated via the surveys for statistical analysis and classification purposes. The study findings revealed the significant impediments as related to inadequate knowledge and skills, the current market structure and inherent resistance to change in the built environment, and organizational challenges, among others. A comparative analysis of the perceptions of the diverse groups of survey participants was conducted and discussed. The adoption of the survey findings is envisaged to help the built environment in minimizing the impact of these barriers and can serve as a policy instrument and useful guidelines for government agencies, stakeholders, and others towards ensuring BIM can be used to deliver the full potential of sustainability practices in the construction industry. The study has provided effective practical strategies and recommendations for enhancing the implementation of smart sustainability practices in the built environment. The following chapter identifies and analyzes the key drivers or critical success factors of the implementation of BIM and sustainability practices – otherwise known as smart sustainable practices in this study – in building projects and in the built environment.

CHAPTER 6: KEY DRIVERS OF IMPLEMENTING SMART AND SUSTAINABLE PRACTICES IN THE BUILT ENVIRONMENT[6]

6.1 Chapter Overview

The previous chapter identified and analyzed the impediments to the implementation of smart and sustainable practices – BIM and sustainability – in building projects and the built environment. This chapter identifies and examines the key (critical success factors) of the implementation of BIM and sustainability practices – otherwise known as smart sustainable practices in this study – in building projects as well as in the built environment. Two datasets were collected namely via Delphi surveys (14 experts participating) and international survey involving 220 respondents. However, to conserve space, only the result of the international survey findings will be presented in this chapter. A link to the published findings of the Delphi survey conducted in this research is provided in section 6.4 of this chapter.

6.2 Introduction

Construction projects are nowadays quite complex involving several and interwoven processes and activities (Olatunji et al., 2017b; Olawumi & Ayegun, 2016) which calls for a smart and innovative system of technologies to process and manage the different project activities. Also, the Brundtland Commission report (WCED, 1987) has drawn the attention of the construction sector to implement sustainable construction practices in its activities to enhance the environmentally-friendliness of its products (infrastructures, buildings) with the ultimate aim of achieving sustainable smart cities.

Olawumi et al. (2017) regarded Building Information Modelling (BIM) as one of the smart technologies available to the construction industry along with radio-frequency identification (RFID), augmented reality which can help to facilitate collaboration among project stakeholders/ Also, it can serve as links to connect domain knowledge areas such as sustainability, facility management, safety, project management, etc.

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[6] This chapter is largely based upon the following published papers:

Olawumi, T.O., & Chan, D.W.M. (2020c). Key Drivers for Smart and Sustainable Practices in the Built Environment. *Engineering, Construction, and Architectural Management, 27(6), 1257–1281*. https://doi.org/10.1108/ECAM-06-2019-0305

Olawumi, T.O., & Chan, D.W.M. (2019d). Critical Success Factors of Implementing Building Information Modelling (BIM) and Sustainability Practices in Construction Projects: A Delphi Survey. *Sustainable Development*, 27(4), 587–602. https://doi.org/10.1002/sd.1925 to ensure a one-source management of project's information and processes throughout the construction project's lifecycle stages. Also, Olatunji et al. (2016b) highlighted further that the success of these tools hinges more on the initiatives of project stakeholders through their decision-making process and collaboration in their projects. According to Kovacic et al. (2015), Lee and Yu (2016), and Ma et al. (2018), there has been an appreciable increase in BIM adoption in some countries' construction industry. However, despite this progress in BIM adoption (although not yet worldwide), there has been little advancement in the implementation of sustainable construction practices in infrastructural projects.

Morlhon et al. (2014) argued nonetheless that the implementation of BIM is complicated due to the different standards and protocols involved which has hindered organizations to use and handle it actively. However, despite this apparent disadvantage, it permits the additional analyses of concepts such as energy performance, clash detection, and other sustainability measures (Olawumi et al., 2017). Also, BIM-enabled sustainability analysis tools can assist in the simulation of building energy performance and carbon footprints as well as reduce the cost and time involved (Ahn et al., 2014). Although, the interoperability issues between BIM design and analysis tools is still a prevalent problem in the construction industry (Abanda et al., 2015).

The integration of smart technologies such as BIM to amplify sustainability practices in construction projects can help to reduce and/or project the building energy as well as the evaluation of the lifecycle assessment in conjunction with rating systems such as LEED, BREEAM, etc. (Al-Ghamdi & Bilec, 2015). Sustainability is related to dimensions such as social, economic and environmental variables; and the use of technologies can optimize its adoption in any setting (Raut et al., 2018). More so, adopting sustainability strategies can lead to innovation which can also help to achieve competitive advantage for participating companies and reduce project overall cost (Chofreh & Goni, 2017). The deployment of cloud technologies also facilitate collaboration and improved the project governance mechanisms (Alreshidi et al., 2016). However, the lack of archival data and access to vital project information have steeped the progress and adoption of BIM in the industry (Wong et al., 2014). A case study analysis of the benefits of BIM in construction project carried out by Barlish and Sullivan (2012) showed that BIM is yet to achieve its full potential in the industry due to several factors; which include the lack of commitment from project clients. Moreover, previous authors (GhaffarianHoseini et al., 2017; Jalaei & Jrade, 2015; Reinhart & Wienold, 2011) sees smart technologies such as BIM as one of the essential vehicles to drive the implementation of sustainability practices. Meanwhile, Olawumi and Chan (2019e) developed an assessment template and scoring system to provide a quantitative metrics of measuring and comparative evaluation BIM implementation in developing countries Hence, this study intends to identify and examine the critical drivers that amplify the use of BIM to enhance the implementation of sustainable practices in construction projects.

Gardas et al. (2018a) and Raut et al. (2017) considered issues related to sustainability in any industry as a concept that is best implemented by top hierarchy of organizations, and such firms derives the benefits of its contribution to sustainable development in aspects such as economic, social, environmental. Guo et al. (2018) and Xue (2018) corroborated it by arguing for greater leadership and the institutionalization of a governance arrangement in the industry. Gardas et al. (2018b) emphasized the need for a holistic view and balancing of the three pillars of sustainability during its implementation process. More so, Jakhar (2017) and Kang (2018) regards communication and stakeholder engagement as a crucial variable in facilitating sustainable development.

Given the above, this study aims to assess the key drivers (KDs) that aid the implementation of smart and sustainable practices in the construction industry and projects. More so, the following research questions will be answered in towards achieving the aim of the study:

i. What are the significant drivers that can aid the implementation of smart and sustainable practices in construction projects?

ii. How do the perceptions of the study's respondents differ based on their professions, organizational setups, and regions?

iii. What are the practical implications of the study's findings on the implementation of smart and sustainable practices in the built environment?

Although, there are some projects which have employed either of the two concepts to varying levels of success. However, this study focuses on construction projects in which the clients or project team plans to adopt smart technologies such as BIM along with sustainable practices in their projects.

The comparative evaluation of the perceptions of the respondents based on their professions, organizational setup, and regions is expected to shed more insight and perspectives on the implementation of smart and sustainable practices in construction projects, firms, and regions. The findings are also expected to enhance the capacity of project stakeholders, professional bodies, government agencies to implement BIM and sustainability practices in their projects and locality.

Cugurullo (2017) argued that several models of urbanization of cities are flawed because little attempts are made to integrate sustainability into its planning and design. Hence such urban development becomes unsustainable in the long-run. A review of case studies by previous authors (Caprotti, 2016; Taylor Buck & While, 2017) reveals the disconnect between the development of smart cities and the ideals of sustainability. One significant disconnection between the two concepts as argued by Cugurullo (2017) is that there is little or no innovation but a rather replication of traditional strategies of urbanization. Also, as pointed out by extant literature (Chang & Sheppard, 2013; Colding & Barthel, 2017; Datta, 2015b) they hardly integrate sustainability or fulfill its promises of making it sustainable.

Conceptually and in practice, it has been seen that the use of smart technologies in construction project development to achieve smart city initiatives may not act in concert with the ideas of adopting sustainability to achieve eco-city. A good case analysis was exemplified by Cugurullo (2017) in the comparison between Hong Kong (a smart city) and Masdar City, Abu Dhabi (an eco-city initiative). Given these limitations in knowledge and practice, the current study intends to break the ‘aura of singularity’ in the application of these concepts to city urbanization by projecting the possibility of sustainable smart cities and buildings that works on the principles that a smart city and building can be sustainable and an eco-city or green building can be smart. The study argues in favor of sustainable smart buildings as against the singularity of either the advancement of smart-building or green builidng initiatives. This study reiterated the need for the application of BIM and sustainability practices in construction projects as against the singularity of the adoption of either BIM or sustainability practices initiatives. Some studies (Mom et al., 2014a; Tsai et al., 2014a) have examined the adoption of BIM in construction projects. However, they focused solely on BIM implementation. Hence, this study will bridge the gap by identifying key drivers that can aid the joint implementation of BIM and sustainability practices in construction projects.

6.3 Smart and sustainable practices: Salient issues in the built environment

The built environment has witnessed an increased knowledge and adoption of innovative concepts and processes which were intended to enhance the overall construction process, improve productivity, among others. Some of these concepts include sustainability (Lozano, 2008; Olawumi & Chan, 2018a); risk management (Xu et al., 2010), safety management (Zhang et al., 2015); BIM (Qi et al., 2014) among others. According to Albino et al. (2015) and Olawumi and Chan (2018a), the concept of smart buildings and sustainability has gained enormous recognition in the literature, government circles, and from international organizations. The nexus between BIM and sustainability issues which gave rise to the concept of smart sustainable practices as discussed in section 6.2 is found in the capacity of BIM system to embed a large amount of data for storage, document management, communication among stakeholders, visualize sustainability analyses results, etc. (Gu & London, 2010; Olawumi et al., 2017).

However, despite the increasing adoption of BIM in the construction projects, Kassem et al. (2012) and Olatunji et al. (2017b) stressed that the difficulty in evaluating the business value of smart tools like BIM in terms of return on investment (ROI) has hindered its implementation in construction projects especially in small and medium scale projects (capital-wise). Hence, per Alsayyar and Jrade (2015), to improve its implementation, it is important to provide anecdotal evidence of profitable deployment of BIM in construction projects to the prospective clients to increase their satisfaction and confidence. BIM is described as a system that consists of its product and processes (Olawumi & Chan, 2019e, 2019b). The incorporation of smart tools such as BIM in sustainability issues is aimed to serve as a decision-making tool when integrated with the existing building rating systems to evaluate the level of achievement of some sustainability criteria by buildings (Ahvenniemi et al., 2017).

Previous studies have examined the application of BIM for improving building sustainability. For instance, Lu et al. (2017) reviewed the uses of BIM in green buildings and their capacity to support the building lifecycle stages. Also, Lu et al.

(2017) and Olawumi et al. (2017) highlighted some BIM functionalities in enhancing building sustainability such as design analysis to evaluate energy performance and carbon emission analyses, daylighting analysis, sustainable material selection among others. Akinade et al. (2015) and Olawumi and Chan (2018d) also discussed some benefits of integrating smart and sustainable practices in construction projects to include – (1) enhancing the productivity and efficiency of construction projects (Gu & London, 2010); (2) real-time sustainable design analysis and simulation (Kivits & Furneaux, 2013); (3) minimize carbon emission and footprints (Hope & Alwan, 2012); and (4) improving building energy efficiency (Boktor et al., 2014; Harding et al., 2014) among others. However, despite all these benefits derivable from implementing smart sustainable practices in construction projects; Marsal-Llacuna et al. (2015) revealed that project stakeholders tend towards the sole adoption of BIM more than implementing the two innovations.

Meanwhile, to boost the adoption of smart and sustainable practices in construction projects, Aibinu and Venkatesh (2014) and Nanajkar and Gao (2014) recommended for developers of BIM tools to focus more on suitable cloud-based technology and open-source software. In a similar vein, Ahvenniemi et al. (2017) stressed the importance of smart tools to be cost and resource-efficient. Meanwhile, Becerik-gerber and Kensek (2010), Olawumi and Chan (2019d), and Sackey et al. (2015) observed that the involvement of project teams in the early stages of the construction project could enhance its adoption in such construction projects. Project complexity in terms of its shape and system can also pose challenges to the adoption of smart and sustainable practices due to instances of incomplete and unreliable information in building models (Aksamija, 2012; Olawumi et al., 2017; Peansupap & Walker, 2005). Also, Rogers et al. (2015) argued that the lack of industry standard for BIM and sustainability assessment is one of the banes for the slow progress in the adoption of smart sustainable practices in some countries.

Also, the existing green building rating tools, according to Berardi (2013) and Robinson and Cole (2015), places greater consideration on the environmental aspect of sustainable development instead of a holistic consideration of the three sustainability pillars. Towards ameliorating this significant gap in the literature, Olawumi et al. (2018) recommended for these green rating tools to embed other aspects of sustainability- economic and social pillars in their evaluation of building sustainability. Also, Huang et al. (2009) reported that some of the sustainability criteria used in evaluating building sustainability do not reflect its actual interaction with the urban system nor provide indications on the strategies to deploy to achieve these criteria. Another salient issue regarding the implementation of smart and sustainable practices in the built environment is the legal issues regarding their use and ownership. Aranda-Mena et al. (2009) and Azhar (2011) advocated for the development of a uniform legal framework and practice to resolve the problem of proprietary ownership of BIM models, simulation results and, contractual issues, and project uncertainties among others. Therefore, to ensure an industry-wide implementation of smart and sustainable practices in the built environment, Aibinu and Venkatesh (2014) and Redmond et al. (2012) recommended for local authorities and government agencies to set out policies and legislation for its deployment and enforcement of relevant guiding laws and statues.

The establishment of good working practice and strategy to aid the implementation of smart sustainable practices cannot be over-emphasized (Azhar, 2010). Jung and Joo (2011) recommended the development of standards that can enhance the effectiveness of the adoption of BIM (Jung & Joo, 2011; Olawumi & Chan, 2019b, 2019e) and sustainability practices (Olawumi & Chan, 2018a) in the built environment. Meanwhile, vital support of construction firms' top management is critical to the continuous and successful implementation of these innovative concepts in the construction industry (Boktor et al., 2014; Saxon, 2013). Also, the firm's leadership support can be in diverse forms- such as financial supports, redesign of the firm's structure and policy to suit the new concept, and training supports among others (Chan et al., 2019a). Cugurullo (2017) acknowledged the quest by some cities such as Masdar City in Abu Dhabi to be an eco-city project and Hong Kong as a smart city among others. However, it resulted in an uneven pattern of urban development because of the singularity of the adoption of either smart tools or sustainable practices. Hence, it is important to consider both concepts – BIM and sustainable practices; and one of the ways to achieve this is to investigate the key drivers that can enhance the adoption of smart and sustainable practices in construction projects.

Given the above, Table 6.1 shows the summary of the KDs that can enhance the execution of smart sustainable practices as identified via a review of extant literature and through pilot studies. The 30 KDs highlighted in Table are sourced based on the scope definition of this study, as discussed in section 6.2. Subsequent sections of this paper will define the adopted research methodology adopted and examine the perceptions of over 200 survey respondents whose perceptions formed the basis of the identification of the significant KDs of implementing smart and sustainable practices in the built environment.

Table 6.1: Summary of identified KDs for the execution of smart sustainable practices

Code	Key drivers	References
C1	Technical competence of staff	Gu and London (2010); Tsai et al. (2014a); Deutsch (2011)
C2	Greater awareness and experience level within the firm	Chan (2014); Kassem et al. (2012)
C3	More training programs for cross-field specialists in BIM and Sustainability	Wong and Fan (2013); Jalaei and Jrade (2014)
C4	Increased research in the industry and academia	Abdirad (2016); Bolgani (2013)
C5	Government establishment of start-up funding for construction firms to kick-start BIM initiatives	Abubakar et al. (2014)
C6	Adequate construction cost allocated to BIM	Gu and London (2010); Kivits and Furneaux (2013)
C7	Availability of financial resources for BIM software, licenses, and its regular upgrades	Nanajkar and Gao (2014)
C8	Information and knowledge-sharing within the industry	Azhar (2011); Chan et al. (2019b)
C9	Effective collaboration and coordination among project participants	Antón and Díaz (2014); Hanna et al. (2014)
C10	Establishment of a model of good practice for BIM and sustainability execution	Antón and Díaz (2014); Adamus (2013)
C11	Availability and a well-managed in-house database of information on similar projects	Aibinu and Venkatesh (2014); Becerik-gerber and Kensek (2010)
C12	Development of appropriate legal framework for BIM use and deployment in projects	Aibinu and Venkatesh (2014); Azhar (2011)
C13	Security of intellectual property and rights	Kivits and Furneaux (2013)
C14	Shared risks, liability, and rewards among project stakeholders	Chan (2014); Park et al. (2013)
C15	Establishment of BIM standards, codes, rules, and regulations	Redmond et al. (2012)
C16	Appropriate legislation and governmental enforcement & credit for innovative performance	Antón and Díaz (2014); Hope and Alwan (2012)
C17	Increased involvement of project stakeholders in green projects	Alsayyar and Jrade (2015)
C18	Clarity in requirements and measures for achieving sustainable projects	Aibinu and Venkatesh (2014)
C19	Number of subcontractors experienced with BIM projects	Chan (2014)
C20	Client requirement and ownership	Ahn et al. (2014); Chan et al. (2019a)
C21	Early involvement of project teams	Kassem et al. (2012)
C22	Client satisfaction level on BIM projects	Ahn et al. (2014); Chan (2014)
C23	Supportive organizational culture and effective leadership	Yeomans et al. (2006)
C24	Project complexity (regarding building shape or building systems)	Hope and Alwan (2012); Kivits and Furneaux (2013)
C25	Availability and affordability of cloud-based technology	Ahn et al. (2014); Yeomans et al. (2006)
C26	Interoperability and data compatibility	Adamus (2013); Saxon (2013)

Code	Key drivers	References
C27	Standardization & simplicity of BIM and sustainability assessment software	Akinade et al. (2017); Aksamija (2012)
C28	Technical support from software vendors	Redmond et al. (2012)
C29	Availability of BIM and sustainability databases	Abolghasemzadeh (2013); Antón and Díaz (2014)
C30	Open-source software development	Hope and Alwan (2012)

Note: The key drivers were modified from Olawumi and Chan (2019d).

6.4 Research Methodology

The study identified and assessed the key drivers that aid the key construction stakeholders in their execution of smart sustainable practices in the construction study. A quantitative research method was adopted in this study using an empirical questionnaire survey and secondary means of data such as the desktop review of relevant journal articles, online materials, textbooks, official gazettes, and building standards, etc. As pointed out by Olatunji et al. (2017a), the means and instruments of data collection are essential to the achievement of the study's aim and reliability of the collated data. Hence, the use of the empirical questionnaire survey in this study helps to aggregate the opinions of stakeholders in the built environment as regards the 30 KDs. Although opinions of respondents might be subjective based on their experience, locations, etc. the use of several statistical methods helps to minimize these biases.

The targeted survey respondents for the questionnaire were sampled via using both purposive and snowball sampling techniques, and they have requisite direct hands-on experience in smart digital technologies like BIM and the process of achieving sustainability in building projects. Three delivery modes were used in the questionnaire distribution, which is yielded 220 responses from 21 countries as follows: (1) online survey (161 responses), (2) fill-in PDF questionnaires (14 responses), and (3) hand-delivered questionnaires (45 responses). Some of the respondents were sent both the online survey link and an attached PDF survey form. Also, before the survey form distribution, the survey form was pretested. The weblinks to the online survey form and the fill-in PDF survey was posted on relevant LinkedIn groups of different professionals in the built environment, ResearchGate, network groups, email addresses culled from webpages of universities, professional bodies, construction companies, etc., among others social media means. The respondents were told to input their contact details if they are interested in the final result of the survey, which is intended to serve as a motivation for the respondents to participate in the survey exercise. Although the survey exercise yielded responses from 21 countries, no countries, in particular, were targeted. The main goal of the questionnaire distribution is to secure a good representative number of responses from each region of Europe, Asia, Africa, and North & South America. The respondents were also encouraged to share the questionnaire survey link to their colleagues with requisite knowledge of the subject matter.

The first section of the survey form (see Appendix B) solicited basic information about each survey participant (such as their profession, years of experience in the construction industry, their organization type, location, and awareness of BIM and sustainability concepts) and the other sections request the respondent to rate the KDs on a 5-point Likert scale (*1 = strongly disagree, 3 = neutral and 5 = strongly agree*). If a factor is not perceived to be applicable as a CSF, the respondent has the option to tick an 'N/A' box. The gleaned data were analyzed using various statistical methods as explained in the next sub-section and the findings discussed in subsequent sections of this paper.

Meanwhile, prior to the empirical international questionnaire survey, a Delphi survey was conducted involving 14 experts across eight countries towards reaching a consensus on the cross-field research topic. See Olawumi and Chan (2019d) for the published findings of the Delphi survey exercise.

6.4.1 Statistical methods and reliability tests

Inferential and descriptive statistical tools were adopted to evaluate the set of data collated from the study's respondents. These tools included: (1) Reliability using the Cronbach's alpha (α) reliability test; (2) Ranking via mean scores (M) and standard deviations (SD); (3) Analysis of variance (ANOVA), post-hoc Tukey tests, correlation analysis; and (4) Factor analysis and clustering. According to Field (2009), Olawumi et al. (2018) and Olawumi and Chan (2018d), a set of data must undergo reliability testing to evaluate whether the data instruments are measuring the right construct (Olatunji et al., 2017a; Olawumi, 2016).

The Cronbach alpha (α) is useful to measure whether the questionnaire and its associated Likert scale measures the right construct and maintains an internal consistency (Field, 2009; Saka et al., 2019b) value for the study was 0.966 which is significantly higher than 0.70, the minimum threshold for a reliable dataset (Olawumi & Chan, 2019d). This implies that the dataset has good internal consistency, reliable, and suitable for further statistical analysis (Chan et al., 2010; Chan & Choi, 2015). Therefore, for the KD's factor ranking, if there is a case of more than one factor having the same mean value, their SD values will be utilized in ranking them; such that, those with lower SD values are ranked higher (Olatunji et al., 2017a). However, in the case of the factors having the same mean score and SD value, they will be accorded the same factor ranking (Olawumi et al., 2018).

6.4.2 Respondents' demographics

A diverse group of 220 survey participants across 21 countries participated in the study (see Figure 6.1). The respondents are from six varied set of organizational setups as classified in this as follows – academics (40%), public sector clients (25%), main contractors (16%), project consultants (11%), private sector clients (5%), and property managers (3%). It must be noted that personal information, such as the names of their organization or firm, were not solicited from the respondents in the survey form. Hence, the respondents could not be grouped by such means. The respondents were also classified based on their profession, and the results revealed that the quantity surveyors, architects, and project managers were more represented in the study's respondent population with a percentage of 25, 12.7, and 12.3 respectively. The civil engineers (11%) and building services engineers (8%) followed closely. The distribution of the respondents (see Figure 6.1) based on their regions are Asia (56.4%), Africa (29.1%), Europe (9.1%), and America (5.5%). The key countries based on the number of participating respondents in the Asia region are China, Singapore, and Australia; in Africa, we have Nigeria, South Africa, and Egypt. For the European continent, we have the United Kingdom and Germany; and in the American regions (South and North America), we have the United States and Canada.

The respondents have a high level of knowledge and awareness of BIM and sustainability practices with 43% and 53% respectively, while about 37% and 36% of the respondents reported an average level of understanding of BIM and sustainability respectively. Further analysis of the level of awareness of the respondents based on their knowledge of BIM revealed that Europe (70%) and the

America regions (67%) have more than two-thirds of their respective respondents' population with at least a high level of awareness of the BIM process. Meanwhile, Africa and Asia have 47% and 35% respectively with at least a high level of BIM awareness. The findings correspond with the extant literature (Jung & Lee, 2015; Olawumi et al., 2017) which examines the adoption of BIM across various regions. For the sustainability practices awareness, regions such as Africa (67.2%), America (66.7%), and Europe (60%) have more than two-thirds of their respective respondents' population with at least a high level of awareness of the sustainability practices. The respondents from the Asia region have 42.7% with at least a high level of awareness of the sustainability practices. This analysis corresponds with the extant literature (Olawumi & Chan, 2018a) which discusses the trend and implementation of sustainability in different regions and countries.

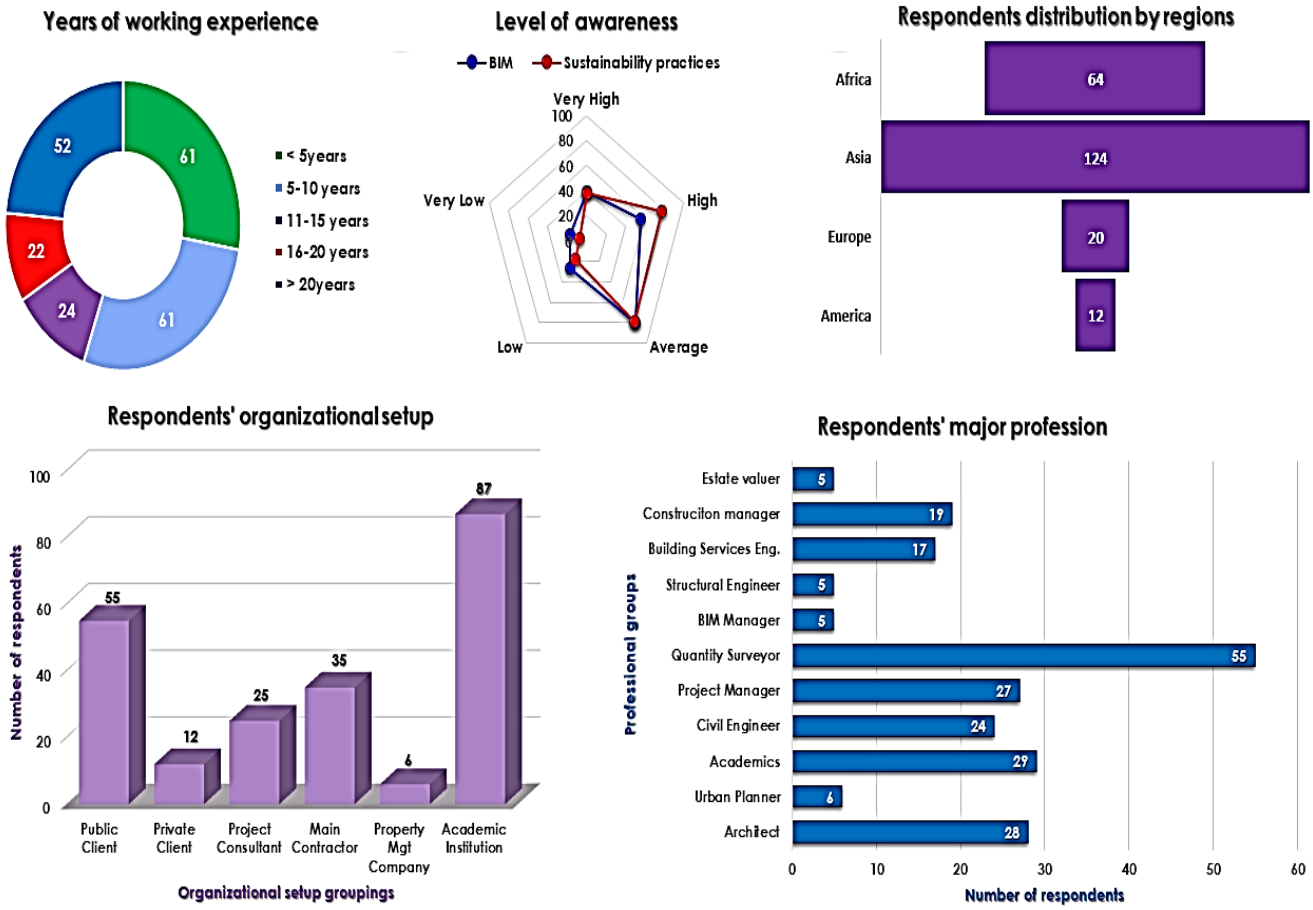

Figure 6.1: Respondents' demographics

The demographics of the respondent (Figure 6.1) based on their level of experience was also evaluated. On average, 44.5% of the respondents have at least 11 years of working experience in the construction industry, of which about 23.6 percent have more than 20 years of working experience. The opinions of the respondents were also solicited on which stage of the project development to implement smart sustainable practices; 57% and 37% of the respondent considers the planning and design stages respectively, while only 6% preferred the construction phase. The result of the statistical analysis of the respondents' demographics revealed that the professionals which supplied the necessary data upon which the study's findings are based have a mixture of both practical experience and theoretical knowledge in the subject matter. Hence, this lends further credence to the data collected and subsequent analysis in this study.

6.5 Results of statistical analyses

This section expatiated on the results of the gleaned data via the survey forms and analyzed using various statistical methods and discusses the survey findings.

6.5.1 Descriptive statistical tests

In ranking the key drivers based on the data collected from the study's respondents, the mean score "M" and standard deviation "SD" was employed. In situations where two or more KDs have the same mean value, their SD values are considered in the ranking as highlighted in Olatunji et al. (2017a) and Olawumi and Chan (2018d) The mean scores for the 30 identified individual KDs range from M= 3.79 (SD= 0.919) for "*C25 - availability and affordability of cloud-based technology*" to M= 4.34 (SD= 0.780) for "*C1 - technical competence of staff*" at a variance of 0.55 (see Table 6.2). A benchmark score of 4 out of 5 on a 5-point Likert scale was used in the study to identify the highly significant KDs of smart sustainable practices in the construction industry. Using this approach, the study pinpointed top-five KDs which include: "*C1 - technical competence of staff*" (M= 4.34, SD= 0.780), "*C3 - more training programs for cross-field specialists in BIM and Sustainability*" (M= 4.27, SD= 0.738). "*C21 - early involvement of project teams*" (M= 4.24, SD= 0.821), "*C2 - greater awareness and experience level within the firm*" (M=4.22, SD= 0.728), and "*C9 - effective collaboration and coordination among project participants*" (M= 4.17, SD= 0.784). The findings revealed that to enhance the execution of smart sustainable practices in the construction industry, it rests on the technical competency and knowledge of the project stakeholders on BIM and sustainability. Also, proper coordination and early involvement of project team members are very significant (Antón & Díaz, 2014; Olawumi & Chan, 2018c). Hence policymakers, local authorities, and other key stakeholders need to prioritize human capital development in their drive for the adoption of smart technologies and implementation of green buildings.

There is a considerable agreement among all the respondents' groups on factor "C3 - more training programs for cross-field specialists in BIM and sustainability" (Olawumi et al., 2018; Wong & Fan, 2013); which was ranked as a key factor and rated among the top five most important factor by all the groups. The finding reveals that when stakeholders in the construction industry have considerable knowledge and skillset in smart sustainable practices, it will ease its execution in the built environment. Also, for factor "C1- technical competence of staff" (Aibinu & Venkatesh, 2014); which was ranked the most significant driver for the execution of smart sustainable practices; the factor was ranked among the top-five key factors by all the respondent's groups except the private clients and academics' groups who both gave it the 7th rank. The result aligns with the findings of Olawumi and Chan (2018c) who recommended to the government and professional bodies in the construction industry to organize regular training workshops and seminars to keep their staff and members abreast of the current trend in the industry and equip them with necessary technical skills as required. The differing rank by the academics and private clients is consistent with the fact that academics are the knowledge of the industry and the private clients generally have the resources to train their staff, although their rankings are still relatively above the average.

Meanwhile, for the factor "C21- early involvement of project teams" (Goedert & Meadati, 2008), the perception of the project consultants and respondents from the main contractors differs significantly from other survey participants from other organization-based respondents. The two respondent's groups ranked the factor as 10th rank as against the top-five rankings achieved by the factor in other respondents' groups. The findings reveal an average recognition of the fact that the early introduction of key stakeholders at the planning stage of a project could influence the achievement of smart sustainable practices in the project. This is because most consultants to the project are primarily involved in the project from its start. However, several issues which vary from poor coordination and collaboration, and difficulty in analysis the sustainability credentials of building plans at the early phase of project development has contributed in a way to hinder the smooth execution of such innovative strategy.

Table 6.2: Key drivers for the execution of smart sustainable practices in the construction industry: inter-group comparisons

KDs	Architects		Civil Engineers		Project Managers		Building Serv. Engr.		Constr. Managers		Overall				
	Mean	Rk	Mean	Rk	Mean	Rk	Mean	Rk	Mean	Rk	Mean	SD	Rk	F	Sig.
C1	4.64	2	4.33	8	4.20	1	4.20	3	4.48	1	4.34	0.780	1	1.137	0.336
C2	4.54	3	4.00	28	3.84	24	3.77	31	4.03	26	4.22	0.728	4	1.040	0.411
C3	4.64	1	4.08	23	3.88	22	4.03	15	4.39	4	4.27	0.738	2	1.770	0.068
C4	4.21	18	4.25	16	4.04	8	3.91	24	4.34	7	4.05	0.803	13	2.491	**0.008**
C5	4.11	23	4.17	19	3.76	30	3.86	27	3.89	32	4.01	0.917	19	1.230	0.273
C6	4.00	29	4.17	19	3.92	19	3.86	28	3.72	30	3.87	0.898	28	0.968	0.473
C7	4.36	10	4.33	8	3.96	16	3.97	21	3.89	31	3.98	0.924	22	1.280	0.243
C8	4.32	15	4.25	16	4.04	7	4.09	10	4.48	2	4.07	0.805	10	1.117	0.351
C9	4.39	8	4.50	3	3.92	17	3.86	29	4.20	13	4.17	0.784	5	0.929	0.507
C10	4.36	12	3.92	31	4.12	3	3.74	32	4.17	19	4.11	0.783	7	1.308	0.228
C11	4.32	15	3.50	36	3.28	30	3.49	36	3.76	34	4.01	0.791	18	1.037	0.413
C12	4.11	22	4.00	28	3.64	33	3.69	33	3.99	30	4.03	0.807	15	1.049	0.403
C13	4.00	28	3.67	35	3.64	34	3.63	34	3.74	35	3.87	0.884	27	1.809	0.061
C14	4.07	26	3.92	31	3.44	35	3.54	35	3.85	33	3.94	0.823	24	1.017	0.430
C15	4.43	6	4.33	8	4.08	5	4.17	5	4.34	8	4.15	0.820	6	1.564	0.119
C16	4.39	9	4.25	15	3.96	13	4.17	5	4.18	15	3.99	0.833	20	2.035	**0.031**
C17	4.21	19	4.42	5	3.92	19	4.14	8	4.41	3	4.02	0.785	17	0.989	0.454
C18	4.14	21	4.33	12	3.92	17	4.03	14	4.31	10	4.03	0.746	14	0.585	0.825
C19	4.00	27	3.75	34	3.96	14	4.06	13	4.02	28	3.93	0.805	25	0.825	0.604
C20	4.00	30	3.83	33	4.00	9	4.09	10	4.02	28	3.98	0.883	21	1.031	0.419
C21	4.46	5	4.08	24	3.96	14	4.26	1	4.20	14	4.24	0.821	3	1.140	0.334
C22	4.11	24	4.08	26	4.08	6	4.23	2	4.34	9	4.05	0.801	12	0.752	0.675
C23	4.39	7	4.00	30	3.84	24	3.89	26	4.08	25	4.07	0.782	9	1.433	0.168
C24	4.11	25	4.17	19	4.00	9	4.11	9	4.16	20	3.91	0.879	26	1.494	0.143
C25	4.21	20	4.25	14	4.00	9	3.91	23	4.21	12	3.79	0.919	30	1.754	0.071
C26	4.36	10	4.42	5	3.80	26	4.00	17	4.18	17	4.06	0.817	11	1.608	0.106
C27	4.36	12	4.00	27	3.88	22	3.89	25	4.10	23	4.08	0.843	8	1.535	0.129
C28	4.36	12	4.42	5	3.80	26	3.83	30	4.14	21	3.95	0.890	23	2.664	**0.004**
C29	4.50	4	4.17	19	3.72	31	4.06	12	4.18	18	4.03	0.883	16	1.394	0.185
C30	4.25	17	4.17	18	3.76	29	3.94	22	4.03	27	3.86	0.926	29	1.591	0.111

Note: Rk = Rank

6.5.2 *Inferential statistical tests*

Parametric statistical methods such as ANOVA test were applied to the collated data to investigate any discrepancies in the perceptions of the different groups of survey participants such as organizational setups (e.g. public and private clients, project consultants, main contractors, etc.) and those categorized based on their professional disciplines (e.g. architects, civil engineers, project managers, etc.). ANOVA test is a parametric tool which measures variance using the mean of scores (Olawumi & Chan, 2019d; Tsai et al., 2014a); and according to Mom et al. (2014a) and Olatunji et al. (2017a), if a factor is significant ($p<0.05$); a post-hoc Tukey test will be conducted. Moreover, before an ANOVA test can be performed on a set of data, the assumption of homogeneity of the sample data must be satisfied (i.e. $p>0.05$) which states that that the variance across groups is equal. Levene's test for homogeneity of variances was employed, and the significance level (p-value) for the KDs was greater than $p > 0.05$, which implies the group variances are equal. Hence, parametric tests (such as ANOVA) will be useful for further analysis of the data.

6.5.2.1 Statistical tests based on organizational setups

The ANOVA test employed on the data (at a significance level <5%) showed no divergence in the perceptions among the groups of respondents based on the organization setups identified in the study. These organizational setups include respondents from the main contractors, academics, public clients, private clients, and project consultants. The findings are consistent with the fact that a good number of the respondents might have been engaged in two or more of these organizational setups in the course of their professional jobs. Also, even those in academics often have a partnership with colleagues practicing in the industry (Olatunji et al., 2017a), and they do share both theoretical and practical experiences. Furthermore, since the concept of smart sustainable practices is an interdisciplinary discipline, there exists a thin line in the workings of the several organizations in the construction industry.

6.5.2.2 Statistical tests based on professional disciplines

The ANOVA statistical method conducted on the survey data revealed some significant differences (at a significance level <5%) in the opinions among the survey participants on three KDs (see Table 6.2). These drivers include two factors with significant differences "C4- increased research in the industry and academia"

[F(10,209)= 2.491, p=0.008]; and "C28- technical support from software vendors" [F(10,209)= 2.664, p=0.004]. The other factor "C16- appropriate legislation and governmental enforcement & credit for innovative performance" [F(10,209)= 2.035, p=0.031] has a moderate significant difference. However, a further test of the three significant factors via a post-hoc Tukey test revealed a moderate divergence (p=0.036) in only one factor "C16- appropriate legislation and governmental enforcement & credit for innovative performance"; with the architects (M= 4.39, SD= 0.685) perceiving it to be of greater importance than the construction managers (M= 3.58, SD= 0.692).

The architects, according to Olawumi and Chan (2019a), are involved early in the construction process when issues relating to smart sustainable practices execution and other concepts are integrated into construction projects. Also, project consultants which include the architects work in conjunction with the clients to ensure the construction project complies with relevant statutory and legal frameworks and standards, which mostly must be adhered to at the planning and design stage of the project. This unique relationship between the client and architect and the fact they are more involved in the early stage of construction projects than their construction managers counterparts, which makes their perception of this factor to be worthy of note. Furthermore, according to Brinkerink et al. (2019), the relevant stakeholders must acquire a good understanding of the applicable legislation which will enable them to develop appropriate plans and strategies to benefit from government subsidies, tax reliefs or other credits for innovation.

6.5.3 Classification of the key drivers based on factor analysis

The basic concept of factor analysis is to identify a few numbers of factors that best represent the structure of relationships among a larger set of variables (Olawumi & Chan, 2019a) and aids the illustration of a complex phenomenon (Xu et al., 2010). In the extant literature, two types of factor analysis are prominent, and these include principal component analysis (PCA) and the Promax rotation method (Chan, 2019; Chan & Hung, 2015). The Promax rotation method allows for the underlying factors to be correlated, that is, in a case when the factors are not independent of each other (Chan & Choi, 2015; Chan & Hung, 2015). However, this study adopted the PCA approach as the factors are expected to be independent and also for the unique data-reduction capacity and simplicity of the PCA method (Olawumi & Chan, 2019a).

A Pearson correlation analysis was carried out on the 30 KDs and none of the factors correlated to another, thus, satisfying the use of the PCA method. Varimax rotation, an orthogonal factor rotation method, was employed in rotating the 30 underlying factors.

Chan and Choi (2015), and Lingard and Rowlinson (2006) posited a provisional requirement that a set of data must meet before it is suitable for factor analysis. An essential requirement is that the sample size of the data and the number of factors must comply with a ratio of 5:1, which was met by this study. This study has 220 responses which are higher than the minimum 150 sample size necessary for factor analysis to be undertaken. Meanwhile, two further tests- Kaiser-Meyer-Olkin (KMO) value and Bartlett's test of sphericity (BTS) were carried out to test the appropriateness of the dataset for factor analysis. KMO values range from 0 to 1 and measure the relative compactness of correlations among the factors. The KMO value for the study is 0.948 which indicates the PCA generated a reliable and distinct cluster (Chan & Choi, 2015; Xu et al., 2010). The BTS examines the correlation among the underlying factors, and the BTS analysis revealed a chi-square test value of 4,926.376 at a very small significance level (p=0.000, df= 435) which implies that the correlation matrix is not an identity matrix (Xu et al., 2010). As the key pre-requirements of factor analysis has been met, PCA can be applied to the dataset, and it also ensures consistent and reliable results.

Five clustered factors were generated from the PCA analysis (see Table 6.3) which represents 68% of the total variance explained which is higher than the minimum eigenvalues of 60% (Chan, 2019; Chan & Choi, 2015; Chan & Hung, 2015; Malhotra, 1996). Also, the underlying factors have a factor loading which ranges from 0.459 to 0.797, and the classification of the underlying factors under each cluster is reasonable and sufficient.

Table 6.3: Factor structure for the PCA analysis of the KDs

Code	KDs for implementing smart sustainable practices	Factor loading	Eigenvalue	Percentage of variance explained	Cumulative percentage of variance explained
Factor 1 – Knowledge & industry-related drivers			15.236	50.786	50.786
C1	Technical competence of staff	0.746			
C3	More training programs for cross-field specialists in BIM and Sustainability	0.745			
C9	Effective collaboration and coordination among project participants	0.668			
C2	Greater awareness and experience level within the firm	0.641			
C11	Availability and a well-managed in-house database of information on similar projects	0.634			
C10	Establishment of a model of good practice for BIM and sustainability execution	0.596			
C23	Supportive organizational culture and effective leadership	0.563			
C8	Information and knowledge-sharing within the industry”	0.546			
C4	Increased research in the industry and academia	0.503			
Factor 2 – Financial, legal & statutory drivers			1.518	5.059	55.845
C7	Availability of financial resources for BIM software, licenses, and its regular upgrades	0.745			
C6	Adequate construction cost allocated to BIM	0.712			
C5	Government establishment of start-up funding for construction firms to kick-start BIM initiatives	0.659			
C12	Development of appropriate legal framework for BIM use and deployment in projects	0.601			
C16	Appropriate legislation and governmental enforcement & credit for innovative performance	0.543			
C15	Establishment of BIM standards, codes, rules, and regulations	0.499			
C13	Security of intellectual property and rights	0.463			
Factor 3 – Organizational & project-related drivers			1.392	4.641	60.486
C22	Client satisfaction level on BIM projects	0.669			
C24	Project complexity (regarding building shape or building systems)	0.646			
C25	Availability and affordability of cloud-based technology	0.604			
C21	Early involvement of project teams	0.572			
C26	Interoperability and data compatibility	0.527			
Factor 4 – Technical drivers			1.301	4.337	64.823
C30	Open-source software development	0.797			
C29	Availability of BIM and sustainability databases	0.762			
C28	Technical support from software vendors	0.700			
C27	Standardization & simplicity of BIM and sustainability assessment software	0.677			

Code	KDs for implementing smart sustainable practices	Factor loading	Eigenvalue	Percentage of variance explained	Cumulative percentage of variance explained
Factor 5 – Information, risks & attitude-related drivers			1.062	3.541	68.363
C19	Number of subcontractors experienced with BIM projects	0.770			
C20	Client requirement and ownership	0.648			
C17	Increased involvement of project stakeholders in green projects	0.616			
C18	Clarity in requirements and measures for achieving sustainable projects	0.567			
C14	Shared risks, liability, and rewards among project stakeholders	0.459			

Source (of the KD's items): Olawumi and Chan (2019d)

6.6 Discussion of survey findings

This section will discuss the findings of this study in three aspects: (i) discussion of the clustered key drivers; (ii) discussion of the perspectives of the respondents on the KDs based on their regions; and (iii) the practical implications of the research findings.

6.6.1 Discussion of the clustered KDs

The factor clusters representing the relationship among the underlying factors are designated with an identifiable and collective label (Sato, 2005), to aid its description (Olawumi & Chan, 2019a). The labels are based on the researcher's perception, and hence are subjective (Chan & Hung, 2015). A metric known as factor scale rating was employed to rank the factor clusters in descending order of relevance (Chan, 2019; Chan & Hung, 2015). The factor scale rating (see Table 6.4) adds up the mean scores of each underlying factor of each cluster and divides the total mean score by the number of the underlying factor (Olawumi & Chan, 2019a). This section discusses the top-three factor clusters to conserve space and provided some recommendations to enhance smart and sustainable practices in construction projects.

Table 6.4: Ranking results of the factor scale rating for the KDs clusters

Clustered factor	Factor label	Factor scale rating	Ranking
1	Knowledge & industry-related drivers	4.1456	1
3	Organizational & project-related drivers	4.01	2
2	Financial, legal & statutory drivers	3.9857	3
4	Technical drivers	3.98	4
5	Information, risks & attitude-related drivers	3.98	4

6.6.1.1 Knowledge & industry-related drivers

Factor cluster 1 consists of nine underlying factors with a factor loading of more than 0.5 and has the highest factor scale rating of M=4.1456. The cluster focuses on issues related to the technical competence of staff, training scheme for specialists in smart sustainable practices, efficiency in the coordination of project stakeholders, firm’s awareness, and experience level among others. Gu and London (2010) and Ma et al. (2018) accentuated that staff of construction firms and government agencies required requisite training on both the technical and non-technical aspects of BIM to ease the implementation of smart sustainable practices in construction projects. Accordingly, they further argued that such training should be continuous because of the new roles and responsibilities emerging each day in the adoption of BIM and implementation of sustainability practices in the construction industry. Meanwhile, Antón and Díaz (2014) and Olawumi and Chan (2018b) emphasized the need for the development and availability of an in-house database to keep track of past and current projects’ data and its organization.

The development of the database, as argued by Gu and London (2010), should align with the project management structure and organization of the firm, as well as suitable to meet the industry needs. However, such a database and its platform must be user-friendly and provide adequate data security. Abanda et al. (2015) advocated for the creation of action learning centers as a practical, knowledge-sharing, and problem-solving environment in which project stakeholders can share their experience, provide technical supports, and learn from each other. Also, an increased level in research and development (R&D) in the academics and industry improved the level of adoption of smart sustainable practices in the construction industry (Aibinu & Venkatesh, 2014; Wong & Fan, 2013).

6.6.1.2 Organizational & project-related drivers

The second most significant factor cluster is factor 3, which comprises of five key factors with a minimum factor loading of at least 0.5 and a factor scale rating of M= 4.01. The factor is concerned with project complexity in terms of its shape and system, client satisfaction level, the early involvement of project stakeholders, data compatibility and interoperability, and availability of affordable cloud-based technology. Ahn et al. (2014) reported that the current industry foundation class (IFC) schema used in the BIM system is inadequate for the integration of relevant information to aid building design simulation and energy modeling. Accordingly, to enhance the execution of smart sustainable practices in the built environment, more efforts need to be deployed by key project stakeholders in ensuring interoperability and data compatibility (Adamus, 2013; Ahn et al., 2014; Olawumi et al., 2018). Meanwhile, Hope and Alwan (2012) and Olawumi et al. (2017) reiterated the need for a clear understanding and evaluation of sustainability criteria in construction projects. there is a need to integrate BIM with sustainability assessment methods. Therefore, it is recommended for project stakeholders, organizations, professional bodies, and the various local authorities to work in sync to enhance the project and organization-related drivers towards improving the adopting of smart and sustainable practices in construction projects.

6.6.1.3 Financial, legal & statutory drivers

Factor cluster 2 consisting of seven key underlying factors and a factor rating of M= 3.9857. The factor is related to the ease of securing funding for the acquisition of BIM software and its associated licenses, government support in the form of start-up funding for construction firms, development of an appropriate legal framework to guide its deployment in projects, the security of intellectual property and rights among others. Nanajkar and Gao (2014) acknowledged the hindrances posed by the high initial cost of procuring BIM software. Hence, to enhance the implementation of smart sustainable practices in construction projects, there must be a conscious effort and commitment by the relevant stakeholders to make the necessary funding available to aid the smooth implementation of smart and sustainable practices in construction projects (Kivits & Furneaux, 2013; Olawumi & Chan, 2018d). Also, top management of construction firms should avoid being hesitant on making long-term future investments and commitment as regards the execution of BIM and sustainability practices in their projects (Gu & London, 2010; Hanna et al., 2013) towards making long-term impacts. The government should endeavor to support small and medium-scale construction firms with funding supports and incentives to aid their adoption of smart sustainable practices in-house and in their construction projects (Bin Zakaria et al., 2013; Olawumi & Chan, 2019d).

6.6.2 Comparative assessment of the KDs based on respondents' regions

It is imperative to examine the significance of the key drivers based on different regions or continents as these regions differ in the level of adoption and implementation of BIM (Jung & Lee, 2015; Olawumi et al., 2017) and sustainability (Olawumi & Chan, 2018a). Also, further analysis of the KDs for each region provides insights into the current state of the implementation of smart and sustainable practices and how the relevant stakeholders can team up to address the identified shortcomings. More so, the comparative assessment of the KDs per region will help avoid the problem of generalization of the research findings as well as provide the similarities. Table 6.5 shows the top-five significant drivers and bottom-three less significant drivers of implementing smart and sustainable practices for each region of the study's respondents. These regions include Africa, Asia, Europe, and America in no particular order.

Table 6.5: Comparative assessment of the KDs based on the respondents' regions

Africa		Asia		Europe		America		Overall		Ranking
Factors	**Mean**	**Factors**	**Mean**	**Factors**	**Mean**	**Factors**	**Mean**	**Factors**	**Mean**	
C1	4.55	C1	4.17	C21	4.70	C1	4.83	C1	4.34	1
C21	4.50	C3	4.11	C9	4.45	C9	4.67	C3	4.27	2
C3	4.48	C2	4.09	C3	4.40	C21	4.58	C21	4.24	3
C9	4.45	C27	4.02	C26	4.40	C4	4.58	C2	4.22	4
C2	4.44	C15	4.02	C12	4.40	C2	4.58	C9	4.17	5
…		…		…		…		…		…
C30	4.08	C14	3.76	C6	3.70	C5	3.92	C6	3.87	28
C19	4.06	C13	3.69	C28	3.65	C30	3.75	C30	3.86	29
C6	3.92	C25	3.52	C7	3.45	C24	3.75	C25	3.79	30

The findings of the analysis for the key drivers for each region reveal some similarities. As shown in Table 6.5, the five most significant for all respondents are drivers C1, C3, C21, C2, and C9. Driver C1 which is concerned with the "technical competence of staff" and C2 – "greater awareness and experience level within the firm" is rated as one of the top-five significant drivers in Asia, Africa, and America regions but not in the European region. Also, factor C3- "training programs for cross-field specialists in BIM and sustainability" is ranked as a top-five driver in the built environment of Africa, Asia, and European regions; similarly, for drivers C9- "effective collaboration and coordination among project participants" and C21- "early involvement of project teams" which are critical KDs for the European, African, and America construction sectors See Table 6.5). The results provided evidence that despite the significant progress made by some countries in Europe and America as regards the adoption of BIM and sustainability (Bernstein et al., 2012; Malleson, 2012; Olawumi & Chan, 2017) such as the United Kingdom, the United States, Canada among others (which are well represented among the study's respondents) issues such as those represented by drivers C1, C2, C3, C9, and C21 are still salient in the construction sectors of these countries. Hence, to enhance the implementation of smart and sustainable practices, stakeholders in these regions must give considerable attention to these drivers.

Also, in the Asia region, drivers C27 and C15, which is concerned with the standardization of BIM and sustainability assessment tools is regarded as an important factor in enhancing smart and sustainable practices in this region. Although, there have been some efforts in this regard, such as the development of BIM standards in Hong Kong (Chan et al., 2019a, 2019b), and development of green rating tools in Hong Kong (HKGBC, 2018), South Korea (IBEC, 2008), and Singapore (BCA, 2015). However, these standards are still insufficient to address some key issues of smart sustainable practices (Illankoon et al., 2017). Respondents from Europe highlighted drivers C26 and C12 as the salient drivers necessary for its adoption in this region. However, respondents from America and the African region gave less importance to driver C30 which implies the availability of open-source software will make little or no significant improvement to the implementation of smart and sustainable practices in these regions. Similarly, in the construction sectors of Europe and Africa, driver C6 is considered as less significant to the adoption of smart and sustainable practices. Meanwhile in Asia, drivers C13 and C14 are given less consideration in these regions.

The comparative evaluation of the perceptions of the respondents based on their regions as discussed in this section has shed more insight and perspectives on the trends and issues relating to the implementation of smart and sustainable practices in the construction industry of these regions.

6.6.3 Practical implementation of research findings

The current study has identified the key drivers that can enhance the implementation of smart and sustainable practices in the construction industry. Also, the research has provided a purview of the significant KDs based on the different regions such as Europe, Asia, Africa, and America as well as based on the respondents' professional and organization setups. The motivation behind the study and the findings of the study aligns with previous studies such as Ahvenniemi et al. (2017) and Allwinkle and Cruickshank (2011) who argued that in the considering buildings or cities as being smart; the evaluation should not be only on the use of smart tools in its design, construction, and operations but only the implementation of sustainability practices. These findings provided valuable contributions to theory and research as well as to industry practice.

In curating the 30 key drivers for the implementation of smart and sustainable practices in the construction industry; the current study has provided an organized list of factors to aid the decision making of relevant stakeholders in the construction industry such as the government agencies, construction organizations, professional bodies, academics, etc. It is advised that more in-depth analysis can be done on these 30 KDs, as to how it can influence the adoption of smart and sustainable practices in each clime, construction projects, and firms. As discussed, these key drivers can form a basis for further discussion by the relevant construction stakeholders.

The KDs and the findings based on the analysis of the different professions and organization setup, as well as regions of the respondents, can form part of a consultation instrument by relevant government agencies in charge of smart cities and sustainable development in designing localized policies and guidelines to aid the implementation of smart and sustainable practices. As revealed in the comparative analysis of the significant KDs for each region; it is imperative for top management of construction firms and professional bodies to place more emphasis on the training of their staff as well as increasing their knowledge and awareness of BIM and sustainability practices through the organization of seminars, workshops, conferences, among others.

The findings across the regions revealed the importance of collaboration and coordination among project stakeholders as well as their early involvement in construction projects. Hence, there is a need for the construction industry to avoid the use of traditional procurement methods and incorporate procurement methods and project management techniques that ensure the critical project stakeholders are involved in the early stages of the planning and design of such projects. However, despite the advantages and preeminence of open-source software development in other fields, the study respondents opined that it might not give construction stakeholders and firms the required leverage in the implementation of smart and sustainable practices in the built environment.

6.7 Conclusions

The study investigated the concepts of smart and sustainable practices based on the extant literature towards identifying the key drivers (KDs) for the implementation of smart sustainable practices in the built environment. The different research approaches helped revealed the different implementation strategies, policies, and meaning of smart sustainable practices – as some countries focus more on the use of smart tools such as BIM, others on eco-issues, and some others tried to create a balance between the two concepts. The review of extant literature also revealed the deep-seated variance in the adoption, trend, and application of BIM and sustainability practices across the various regions, organization setups, and professional disciplines and noted the shortcomings of the existing green rating tools that place more consideration on the environmental sustainability. The key drivers of smart and sustainable practices in the construction industry have opined by the respondents included – the need to organize training programs and workshops for the training of cross-field specialists. Also, featured among the significant drivers is the technical competence of construction organizations' staff; and early involvement and integration of key project personnel in the project.

A factor analysis of the key drivers yielded five-factor clusters. Therefore, based on the findings of the current study, the following recommendations and practical strategies are outlined for the relevant stakeholders in the construction industry towards enhancing the adoption of smart and sustainability practices in the built environment. These include:

- There is a salient need for key project stakeholders, and government agencies to accord higher priority to the human capital development of their staff towards equipping and re-training them to meet up with the current trend of innovation in the industry.
- Government agencies, as well as professional bodies, should provide synergy towards providing adequate and applicable subsidies or financial incentives to small and medium-scale construction firms to aid their adoption of smart sustainable practices in their construction projects.
- Government regulatory agencies and professional bodies should work synchronously towards developing relevant policies and standards to aid the adoption of these concepts within the local context.
- Construction firms should develop their in-house database platforms, which can help such firms in their implementation of smart sustainable practices as well as keep track of their projects' data and information.
- Top management of firms should prioritize the development and establishment of a good working strategy or model to implement smart sustainable practices.
- Academic researchers and industrial practitioners are recommended to synergize their resources, experiences, and skills towards addressing some limitations found in existing smart sustainability tools and the structure of sustainability criteria, as well as providing technical support.
- The development of open-source or affordable cloud-based technologies should be accelerated to mitigate against the potential barriers posed by the cost of purchasing the commercial desktop-based software.

The study has examined the factors influencing the adoption of smart and sustainable practices based on the literature and the perceptions of the respondents, and it is revealed that the construction industry still lags in its adoption and implementation of smart and sustainable practices in the construction industry. The study has attempted to recommend the possible practical ways to overcome the current deficiencies and determined the key drivers that could accelerate its implementation. Nevertheless, for these drivers and practical recommendations to achieve the preconceived goals, there must be synergy among all relevant construction stakeholders, firms, and government agencies towards achieving smart sustainable practices in the built environment.

6.8 Chapter Summary

The construction industry has been evolving in recent years through the adoption of smart tools such as BIM to reduce the complexity in the construction process and optimize the project's goals. This paper aims to identify and assess the key drivers for the implementation of smart sustainable practices in the construction industry. Inferential and descriptive statistical techniques were employed in analyzing the data collected via an international empirical questionnaire survey deployed in soliciting the perceptions of 220 construction professionals across 21 countries in this chapter. Factor analysis was used to categorize the identified key drivers into their underlying clusters for further discussion. Also, the data were analyzed based on the various groups and regions of the study's respondents. The key drivers (KDs) are related to the technical competence of staff, as well as knowledge and awareness level within the industry; issues related to organizational and project's strategy and policies; availability of financial resources, and development of relevant standards and policies to aid its execution among others. A comparative analysis of the perceptions of the different respondents' groups was undertaken and discussed in this chapter. The analysis of the key drivers for the implementation of smart and sustainable practices in the construction industry is expected to aid the decision-making of the relevant stakeholders as well as serve as a consultation instrument for government agencies in their design of localized policies and guidelines to aid smart and sustainable urbanization. The findings revealed the gaps in the implementation of smart and sustainable practices in various climes and organization setups and provided useful and practical strategies for addressing the current hindrances during implementation. The chapter has generated valuable insights into the significant drivers that can enhance the implementation of smart and sustainable practices across regions. It is evident that synergy among the relevant stakeholders in the built environment will help accelerate the implementation of smart sustainable practices in the construction industry. More so, the study findings have provided profound contributions to theory and research as well as to industry practice. The following chapter develops a sustainability assessment method for building projects within the context of the sub-Saharan region of Africa towards fulfilling Objective #2 of the study.

CHAPTER 7: DEVELOPMENT OF A BUILDING SUSTAINABILITY ASSESSMENT METHOD (BSAM) FOR DEVELOPING COUNTRIES IN SUB-SAHARAN AFRICA[7]

7.1 Chapter Overview

The previous chapter analyzed the drivers/CSFs necessary to aid the implementation of BIM and sustainability practices – smart and sustainable practices – in building projects and the built environment. The current chapter based on the findings and deliverables of the previous chapters develops a sustainability assessment method for building projects within the context of the sub-Saharan region of Africa. The developed Building Sustainability Assessment Method (BSAM) scheme and its weighted criteria will be validated using two real-life building case studies. The proposed BSAM scheme will be compared with six widely used green rating systems such as LEED, BREEAM, etc. in this chapter. This chapter also provides an overview of the development of the BSAM scheme and its sustainability criteria.

7.2 Literature review

This section discusses the various literature review and methodological processes, which informed the development of the BSAM scheme.

7.2.1 Establishing the key sustainability assessment criteria

Extant literature and existing GBRS were reviewed as illustrated in Table 7.1 to shows the current trends and the relevant research gaps in these GBRS and the literature. The research gaps in these GBRS and the literature are enormous, however, only those identified in Table 7.1 are resolved in this study. The review of the literature was carried via a content analysis approach (*see* Downe-Wamboldt, 1992; White and Marsh, 2006) to identify the variables or criteria defined and considered by previous studies as important in the assessment of green buildings' sustainability performance.

[7] This chapter is largely based on this published paper:
Olawumi, T.O., Chan, D.W.M., Chan, A.P.C. & Wong, J.K.W. (2020). Development of a Building Sustainability Assessment Method (BSAM) for Developing Countries in sub-Saharan Africa. *Journal of Cleaner Production*, *263(August), Article 121514.* https://doi.org/10.1016/j.jclepro.2020.121514

Table 7.1: Review of relevant sources for the development of the BSAM scheme

S/N	Sources	Publication type	Contributions to existing knowledge that supports the current study	Research gaps
1.	**Review of extant literature**			
a.	Factors affecting green building projects (Ahmad et al., 2019; Cooper, 1999; Olawumi & Chan, 2019a)	Journal articles	• Provided some barriers, benefits, and drivers paradigms affecting green buildings. • Provided recommendations for improving the implementation of green buildings.	• Provided only conceptual descriptions of green building paradigms.
b.	Review of some green rating tools based on key sustainability criteria (Ali & Al Nsairat, 2009; Alyami & Rezgui, 2012; Humbert et al., 2007; Illankoon et al., 2017)	Journal articles	• Provided in-depth reviews of the development of some green rating systems – credit points, methodology, data collection. This provided insight into the development of the BSAM scheme. • Description of some key sustainability criteria. These criteria were modified for the development of the BSAM scheme.	• Revealed that there are no suitable green rating tools for the African continent.
c.	Development of green building assessment methods. (Atanda, 2019; Banani et al., 2013; Gething & Bordass, 2006; Mahmoud et al., 2019)	Journal articles	• Developed green building rating systems for some developing countries. • Utilize several aggregation techniques in the development of the assessment methods.	• Little or no emphasis on the social and economic sustainability. • No related green rating system suited for the local context of countries in Africa.
d.	Implementation of green rating tools and review of its practices. (AlWaer & Kirk, 2012; Bunz et al., 2006; Chew & Das, 2008; Kaur & Garg, 2019; Sev, 2009)	Article	• Provided in-depth reviews of the development of some green rating systems across North America, Asia, and Europe. • Discussed some key sustainability criteria and shows how the construction industry practices can lead to sustainable development.	• Revealed that there are no suitable green rating tools for the African continent.
e.	Issues with adopting the existing green rating tools (Ding, 2008; Ding et al., 2018; Dwaikat & Ali, 2018; Olawumi & Chan, 2019d)	Journal articles	• Revealed the salient challenges hindering use of the existing green rating tools. • Expatiate on the economic performance of green buildings.	• Revealed the need to bridge the current limitations in the development of new green rating tools.

S/N	Sources	Publication type	Contributions to existing knowledge that supports the current study	Research gaps
2.	**Green rating systems**			
a.	**LEED green rating system** i. LEED (v. 4) for Homes Design and Construction (USGBC, 2017) ii. LEED v4 for Interior Design and Construction (USGBC, 2018c) iii. LEED v4 for Building Operations and Maintenance (USGBC, 2018b) iv. LEED v4.1 Operations and Maintenance (USGBC, 2018a) v. LEED v4 for Neigbourhood Development (USGBC, 2018d)	Scheme documentation	• Features a three-level hierarchical structure of sustainability criteria • Use of experts' surveys to determine its credit points • Different schemes for the various building development stage • Greater emphasis on environmental sustainability such as IEQ and Energy, etc. • Relevant schemes for countries in North and South America, and Europe.	• Little or no emphasis on the social and economic sustainability. • No related scheme suited for the local context of countries in Africa.
b.	**BEAM Plus** i. BEAM Plus New Buildings V2.0 (HKGBC, 2018) ii. BEAM Plus Existing Buildings Version 2.0 - Comprehensive Scheme (HKGBC, 2016)	Scheme documentation	• Features a three-level hierarchical structure of sustainability criteria • Involved the participation of experts and industry practitioners in developing the scheme. • Scheme available only for new and existing buildings. • Solely considers environmental sustainability.	• No emphasis on the social and economic sustainability. • Applicable for use solely in Hong Kong
c.	**BREEAM** i. BREEAM UK New Construction (BRE, 2018) ii. BREEAM In-Use International (BRE, 2016)	Scheme documentation	• Features a three-level hierarchical structure of sustainability criteria • Use of experts' surveys and consultation to determine its credit points • Different schemes for the various building development stage • Greater emphasis on environmental sustainability such as IEQ and Energy, etc. • Relevant schemes for the UK and other countries in Europe.	• Little or no emphasis on the social and economic sustainability. • No related scheme suited for the local context of countries in Africa.
d.	**CASBEE** for New Construction (IBEC, 2004, 2008)	Scheme documentation	• Features a two-throng assessment category of quality and load • Divides the building project using hypothetical internal and external boundary.	• No emphasis on the social and economic sustainability. • Applicable for use solely in Japan • Sole emphasis on a few environmental sustainability

S/N	Sources	Publication type	Contributions to existing knowledge that supports the current study	Research gaps
				criteria.
e.	**Green Mark** i. Green Mark for Residential Buildings (BCA, 2015) ii. Green Mark Certification Standard for New Buildings (BCA, 2010)	Scheme documentation	• Features a three-level hierarchical structure of sustainability criteria • Involvement of more than 130 industry members and academics in the setting of metrics, assessment methods, and performance levels • Different schemes for the various building development stage • Greater emphasis on environmental sustainability.	• No emphasis on the social and economic sustainability. • Applicable for use solely in Singapore • Sole emphasis on a few environmental sustainability criteria.
f.	**IGBC** Green New Buildings Rating System (IGBC, 2014)	Scheme documentation	• Features a three-level hierarchical structure of sustainability criteria • Involvement of more than 1,923 industry experts in its development. • Sole emphasis on environmental sustainability.	• No emphasis on the social and economic sustainability. • Applicable for use only in the Indian context.
3.	**Green building technical notes**			
a.	Environmental design guide (CIBSE, 2007)	Technical note	• Provided some data values, equations, and reference tables, which were used in the evaluation of some environmental sustainability criteria for the BSAM scheme.	• Focused on environmental sustainability aspects.
b.	GSA Lighting (GSA, 2019)	Technical note	• Provided some data tables which were referenced in some IEQ criterion in the development of the BSAM scheme.	• Focused only on an environmental sustainability criterion.
c.	Energy and Use of Energy: Calculation and Application of OTTV and U-value (HKIA, 2012)	Technical note	• Provided some equations, and reference tables which were used in the evaluation of some energy criterion for the BSAM scheme.	• Focused only on an environmental sustainability criterion.
d.	Green Mark i. Handbook on Energy Conservation in Buildings and Building Services (BCA,	Technical note	• Provided some data values, equations, and reference tables, which were used in the evaluation of some energy criterion for the	• Focused only on an environmental sustainability criterion.

S/N	Sources	Publication type	Contributions to existing knowledge that supports the current study	Research gaps
	1986) ii. Guidelines on Envelope Thermal Transfer Value for Buildings (BCA, 2004)		BSAM scheme.	

More so, as shown in Table 7.1, a review of existing and leading green rating systems was conducted, such as BREEAM, LEED, BEAM Plus, CASBEE, Green Mark, Green Star, IGBC among others. These rating systems were sourced from their publicly available repository.

The four steps of the review process highlighted above informed the identification of the three levels of the sustainability criteria. The levels of classification of the sustainability criteria of the BSAM scheme is based on the format of other well-established rating systems such as LEED, BREEAM, etc. which utilized similar system. Hence, the sustainability criteria consist of eight (8) key sustainability indicators – which are the level 1 criteria. For the sustainability attributes (level 2 criteria) – which are the subsets of their respective indicators, there are thirty-two (32) attributes; and lastly, for the sustainability sub-attributes – which are the sub-sets of their respective attributes, there are 136 sub-attributes. Most green rating systems whether designed for country-wide use (Ali & Al Nsairat, 2009; Ameen & Mourshed, 2019; Berardi, 2012; Escolar et al., 2019; Mahmoud et al., 2019) or regions (BCA, 2015; USGBC, 2018b, 2018a) only evaluate the existing building. However, the BSAM scheme proposed in this study is designed to assess the "greenness" and sustainability performance of both new and existing buildings, a similar model is used by the BREEAM system (BRE, 2016, 2018). Designing the BSAM scheme to cater for both new and existing buildings will ensure the sustainability potential of building projects in developing countries which can be forecasted in the early stages of the building project development.

7.2.2 Review of the selected existing green building rating systems

This section provides an overview and justifications for the selection of six existing GBRS used for comparative assessment along with the proposed BSAM scheme. The primary criteria for selecting these GBRS is that they are developed by members of the World Green Building Council (WGBC). According to the WGBC directory, there are 66 green building council members of three membership levels – established (38), emerging (10), and prospective (18) (WGBC, 2019). The "established" level members are defined as one with "*a fully developed and operational organization that is running impactful green building programs of work*" (WGBC, 2019). These green building councils are all independent, non-profit organizations with interest in the sustainability of the built environment and advance green building in their own countries. The six green rating tools selected for comparative evaluation in this paper are developed and implemented by established green building council members based on the WGBC classification.

The second criteria in selecting these GBRS are identifying the number of building projects that have received green certification based on these rating tools. The six green rating systems and the number of certified green projects include BREEAM (>560,000) LEED (>90,000), Green Mark (>3000), IGBC (>1800), Green Star (>1500), and BEAM Plus (>467). Apart from these listed rating tools, CASBEE with over 14,000 certified green projects was excluded in the comparative analysis because this rating tool does not allocate credit points to each of its sustainability criteria but instead uses the Building Environment Efficiency score to rate projects (Illankoon et al., 2017). Although there are several green rating tools (Bernardi et al., 2017; Nguyen & Altan, 2011), but most of them are not members of the WGBC and are not widely used.

Among these GBRS, three tools namely – BEAM Plus, IGBC, Green Mark are country-specific systems; while BREEAM, LEED, Green Star have been adopted and their criteria have been modified for more than one country (see Table 7.4). It is noted that BREEAM and LEED are the most widely used worldwide (Banani et al., 2013; Illankoon et al., 2017; Nguyen & Altan, 2011) and widely accepted. Hence, the six GBRS were reviewed in this paper and explained in Table 7.2.

Table 7.2: BSAM scheme and the six selected green building rating systems

GB rating systems	Year	Region	Countries
LEED	1998	North America	United States of America, Canada
		South America	Argentina, Brazil, Chile, Peru
		Europe	Germany, Turkey, Spain, Poland, Sweden, Italy
		Asia	mainland China, Korea Republic, India, Jordan, Chinese Taipei, United Arab Emirates
BEAM Plus	1996	Asia	Hong Kong
BREEAM	1990	Europe	United Kingdom, Croatia, Germany, Netherlands, Poland, Spain, Sweden, Turkey, Norway, Switzerland, Austria, Luxembourg
		Asia	
IGBC	2001	Asia	India
Green Mark	2005	Asia	Singapore
Green Star	2003	Oceania	Australia, New Zealand
		Africa	South Africa
BSAM scheme (*current study*)	2019	Africa	Target countries – *sub-Saharan African countries*

Source: The data was sourced from the respective websites of the six GBRS.
Note: BEAM Plus – Building Environmental Assessment Method (Hong Kong); IGBC – Indian Green Building Council Rating (India); GB – Green Building

More so, most of the six selected green rating systems have different schemes available for the certification of different buildings types. For instance, BREEAM has five main schemes available, namely (1) Communities (2) Infrastructure (3) New construction (4) In-Use (5) Refurbishment and Fit-out.

7.3 Research methods and data collection

This section further discusses the research method and data collection approaches for the study.

The methodological approach employed for the development of the proposed BSAM scheme as shown in Figure 7.1. Firstly, a comprehensive desktop review of relevant guidelines and technical notes on green building practices was undertaken, as well as a holistic review of the existing green building rating systems through peer-reviewed journal articles and web pages using a content analysis approach (step A). These reviews formed the basis of the identification and establishing the key sustainability criteria (indicators, attributes, and sub-attributes) of the BSAM scheme (step B).

Using a similar approach adopted by the established green building councils for the development of existing green rating systems such as LEED, BREEAM, etc.; the current study utilized experts' consultations and surveys to provide a quantitative measure suitable for the determination of credit points (score-weighting) and significance for the key sustainability criteria (step C). Hence, a set of questionnaire survey forms were distributed to the invited green building experts. The data collated from expert surveys and consultation help in establishing the ranking of the key BSAM scheme criteria based on the allocated credit points (steps B and C).

More so, these preceding steps help to deduce the overall sustainability ranking of the 'benchmark' building project; and to establish the certification grade system of the BSAM scheme (step D and E). Lastly, towards justifying the contributions of the BSAM to address the particular context of the sub-Saharan region – it was validated using two building projects situated within the region (step F). Meanwhile, to show the precedence of the BSAM scheme over the existing green rating tools – a comparative assessment of selected green rating systems with the BSAM scheme was undertaken via comparing the score-weight distributions of the key criteria of the respective green building rating systems (step G).

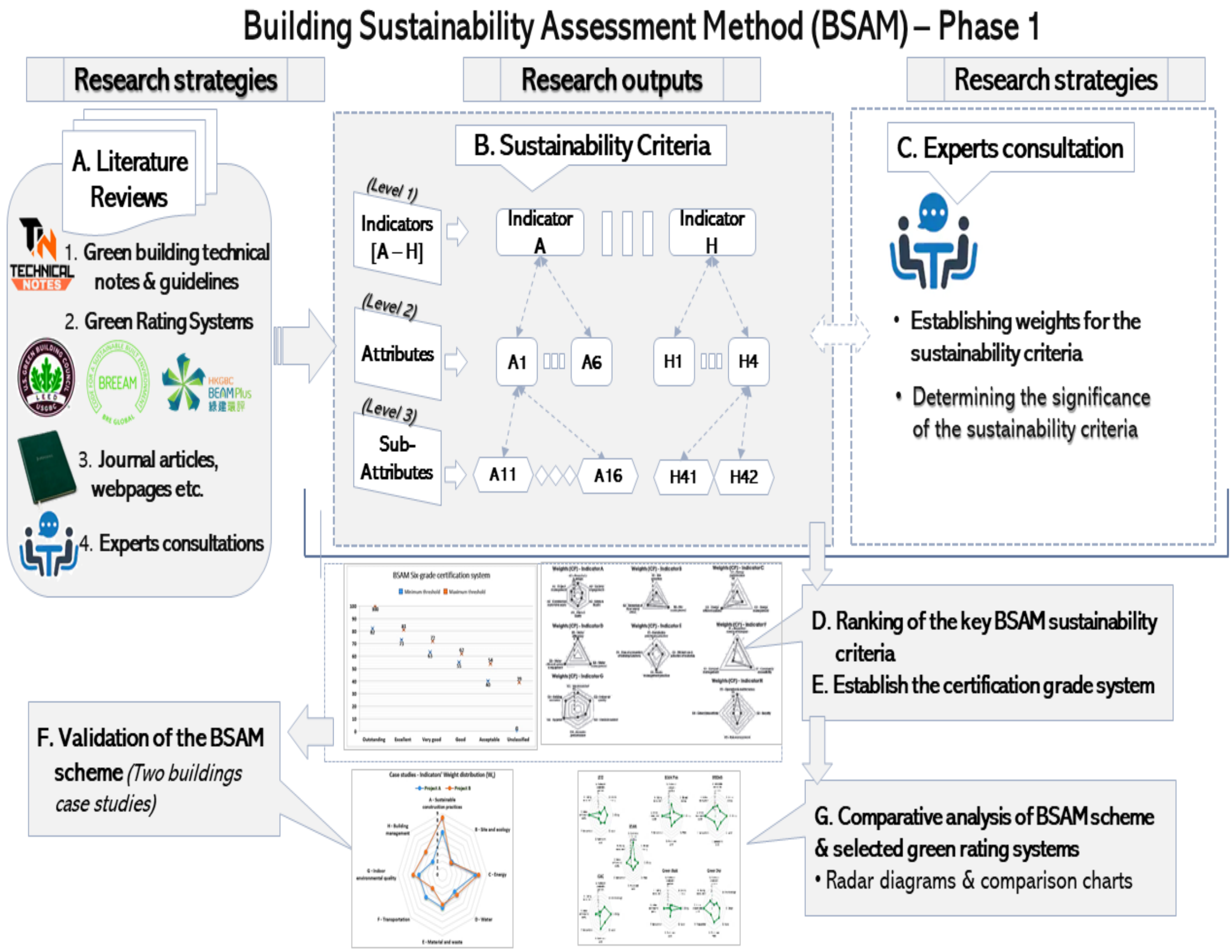

Figure 7.1: Methodological approach to BSAM scheme development

Note: Step A → Step B; there is a continuous loop between step C and step B until step B is established; step B → step D and step E. Step E → step F and step G. "→" = "leads to"

7.3.1 BSAM scheme: Its documentation and experts' consultation

The eight key sustainability indicators which are criteria to the sustainability performance of buildings and identified through the four stages of the review process include – 'sustainable construction practices', 'site and ecology', 'energy', 'water', 'material and waste', 'transportation', 'indoor environmental quality', and 'building management'. As mentioned, these sustainability indicators consist of sub-sets called attributes as illustrated in Figure 7.2, which are evaluated in the determination of the sustainability performance of buildings. The attributes also contain sub-sets called sub-attributes – which are numerous (136) and open to future improvement. A complete structure and components of the proposed BSAM scheme are given in Appendix A. The sustainability indicator "*sustainable construction practices*" is only assessed for new buildings and excluded in the sustainability assessment for existing building projects. Also, there are some subsets (sub-attributes) of the sustainability attributes which will not be evaluated for either new or existing buildings (Olawumi & Chan, 2019c). Readers can check the full documentation of the BSAM scheme for more details on which of the sub-attributes evaluate for new buildings and those that solely evaluate existing buildings.

Indicators	(A) Sustainable Construction Practices	(B) Site and Ecology	(C) Energy	(D) Water	(E) Material and Waste	(F) Transportation	(G) Indoor Environmental Quality (IEQ)	(H) Building Management
Attributes	Project Site & Design	Site Selection	Energy Performance	Water Efficiency	Sustainable Purchasing Practice	Alternative Means of Transport	Visual Comfort	Operation & Maintenance
	Societal Engagement	Site Management	Energy Management	Water Management	Efficient Use & Selection of Materials	Community Accessibility	Indoor Air Quality	Security
	Safety & Health	Reduction of Heat Island Effect	Energy Efficient Systems & Equipment	Water Efficient Systems & Equipment	Waste Management Practice	Transport Management	Thermal comfort	Risk Management
	Ethics & Equity				Ease of Conversion of Building Functions		Acoustic Performance	Green Innovations
	Construction Material & Waste						Hygiene	
	Project Management						Building Amenities	

Figure 7.2: Key sustainability indicators (A-H) and their associated attributes

For the evaluation of the sustainability criteria in building projects, it is recommended that the assessment be carried out by an independent third-party assessor.

7.3.2 Data collection and experts' demographics

Country-wide experts' consultations were undertaken in seven major cities in Nigeria via a structured questionnaire surveys for six months which featured the engagement of 189 experts in the built environment towards the development of the BSAM scheme. In some instances, discussions and interviews were held with some experts who require clarification on the identified sustainability criteria. It is worthy of note, that other well-established green building rating systems utilized surveys and interviews in developing the credit points for their rating systems. The participating experts were selected via a purposive sampling technique and snowball sampling. As shown in Table 7.3, the experts were requested to supply their personal details such as – their profession, years of experience in the construction industry, and whether the experts or their organization have been involved in making sustainability decisions (minor/major) in a building project. The questionnaire survey form is not the regular Likert scale-type survey form but provides spaces for the experts to input numerical values for the credit points, grading system levels, etc.

Table 7.3: The experts' demographics

Description	Frequency	Percentage (%)
Major profession or occupation		
Architects	35	18.5
Civil Engineers	31	16.4
Project Managers	25	13.2
Quantity Surveyors	42	22.2
Structural Engineers	7	3.7
Building Services Engineers	18	9.5
Estate Surveyors	17	9.0
Urban Planners	7	3.7
Mechanical and Electrical Engineers	4	2.1
Land Surveyors	3	1.6
Total	**189**	**100.0**
Years of working experience in the built environment		
< 5 years	38	20.1
5-10 years	53	28.0
11-15 years	33	17.5
16-20 years	40	21.2
> 20 years	25	13.2
Total	**189**	**100.0**
Expert's organizations involved in sustainability decisions?		
Yes	173	91.5
No	11	5.8
Not sure	5	2.6
Total	**189**	**100.0**

The analysis of the invited experts revealed ten varied sets of key experts and stakeholders in the built environment who participated in the development of the BSAM scheme. Ali and Al Nsairat (2009) recommended that multi-stakeholders should be involved in developing green rating tools which was accomplished in this research. More so, ninety-eight experts who represented more than 50% of the total number of participating experts have more than 11 years of working experience in the built environment. Also, it is worthy of note that more than 91% of the experts have been involved in making sustainability-related decisions in either current or previous building projects.

Meanwhile, comparing the statistics of experts demographics of the current study with previous studies where authors have developed native green rating systems for a country – such as (i) Ali and Al Nsairat (2009) only employed four sets of stakeholders where invited namely academicians, project managers, field and design engineers; of which a total of 60 experts participated. (ii) For Mahmoud et al. (2019) only five sets of stakeholders participated namely civil engineers, mechanical and electrical engineers, sustainability experts, facility managers, and architects; of which 20 experts participated. (iii) Also, in Ahmad and Thaheem (2017), the study involved a higher proportion of its respondents from the academics, with a little percentage from the design and construction consultancy.

In total 120 respondents participated in the study presented by Ahmad and Thaheem (2017). It can be concluded that the invited experts for this current study are well experienced (regarding their years of working experience and involvement in sustainability implementation in the built environment). Hence, this lend credence to the analyzed data. More so, the inputs of the key stakeholders in the built environment are well represented in the development of the BSAM scheme. The larger number of the participating experts for this study, when compared to the previous studies, validate the adequacy of the sample size.

7.3.3 Composition of the BSAM scheme - Repository

The composition and full documentation for the BSAM scheme as developed in the course of this research is publicly available via a repository (Olawumi & Chan, 2019c) and as an e-supplement to this study (see Appendix A). The BSAM scheme is a 77-page documentation.

7.4 Results and discussion

7.4.1 BSAM Scheme: Analysis of its key sustainability assessment criteria and case study validation

This section presents the analysis of the data collected via the multi-expert consultations. The results in this section while fulfilling one of the primary objectives of the study, also focus on the suitability of the BSAM scheme in practice within the built environment – especially in developing countries. Hence, this section includes the validation of the proposed BSAM scheme using a case study analysis involving two building projects – a residential building and a commercial building.

7.4.1.1 Key sustainability assessment criteria – score-weight determination and distribution

The determination of the credit points (score-weights) for each of the sustainability sub-attributes was undertaken in consultation with industry experts in the built environment across seven states in Nigeria. The invited experts were asked to assign credit point scores to each of the sustainability sub-attributes. The invited construction industry experts were provided information as regards the importance of the credit point that is to be allocated to each sub-attribute and provided a guide based on the earlier four-stage review process. The ratio of the mean average of the credit scores of the sustainability criteria to the nearest unit is presented in Appendix D1, and Figure 7.3 shows the score-weight distribution for each sustainability indicator (A – H) in terms of the weightings of their sustainability attributes.

The summation of the credit points of the respective sub-attributes gives its total credit point for its attribute. Equation (i) is used to establish the score-weight (credit point) of each indicator and it is based on the mean score metric which divides a set of values by the number of values in that set. The mean score metric was also employed in other well-established rating systems such as LEED, BREEAM, etc. The set of values are the numerical values inputted by the invited experts within the spaces provided in front of each sustainability criteria.

$$W_z = \ Weight\ (credit\ point) = \frac{\sum CP_a}{N} - - - eqn\ (i)$$

Where $\sum CP_a$= summation of the credit points of the attributes of sustainability indicator (z)

N = the number of attributes for the sustainability indicator (z)

W_z= score-weight [credit points (CP)] of the sustainability indicator (z)

For example, the W_z (F) for sustainability indicator F is 5.333 CP (see Appendix D1) which is a resultant of the average of its three attributes (F1= 7; F2= 7; F3= 2 *credit points*). Appendix D1 reveals that sustainability indicators "*sustainability construction practices*," "*energy*," "*indoor environmental quality*," and "*building management*" (A=11.5 CP; C= 10.67 CP; G= 7.0 CP; and H= 6.5 CP, respectively) are rated critical to the sustainability performance of the project based on the score-weight (W_z) of the attributes.

The score-weights of the sustainability criteria are vital to establishing the ranking of each sustainability assessment indicator and the overall sustainability rating of buildings.

7.4.1.2 Determination of the significance of the sustainability sub-attributes

This section discusses and presents the results of the importance of each sustainability sub-attribute based on their classification as either "*required*," "*optional*," or "*negligible*." The classification of the sub-attributes is basically for the comparison or ranking of building projects; and not to exclude the assessment of the sustainability sub-attribute when evaluating a building project's sustainability performance, especially if the sub-attribute is marked "*optional*." However, if a sub-attribute is marked "negligible," it will be excluded in project ranking or comparison. The industry experts invited to participate in the development of the BSAM were also asked to classify the 136 sustainability sub-attributes and rate the level of significance of the sub-attributes in respect of each sustainability attributes using a three-point scale ("*required*," "*optional*," and "*negligible*").

The "classification by percentage score" adopted by Olatunji et al. (2017) was modified for use in this study. The classifications are as follows: (1) if ≥65% of the experts rated the sub-attribute as "required" or less than 40% of the experts rated the sub-attribute as "optional," it was classified as a *required sub-attribute*. (2) if less than 65% of the experts rated the sub-attribute as "required" and between 40 and 65% of the experts rated it as "optional", the sub-attribute was classified as *optional*;

and (3) if less than 50% of the experts ranked the sub-attribute as required, and less than 40% rated it optional, the sub-attribute was classified as *negligible.*

Based on these classification criteria, Appendix D2 presents the classification of the significance of each sustainability sub-attribute; seventy-three (73) sub-attributes were classified as *required*, while 63 sub-attributes were classified as an *optional attribute*. No sub-attribute was classified as negligible. Column “*inference*” in Appendix D2 shows the resultant significance of each sub-attribute based on the classification criteria.

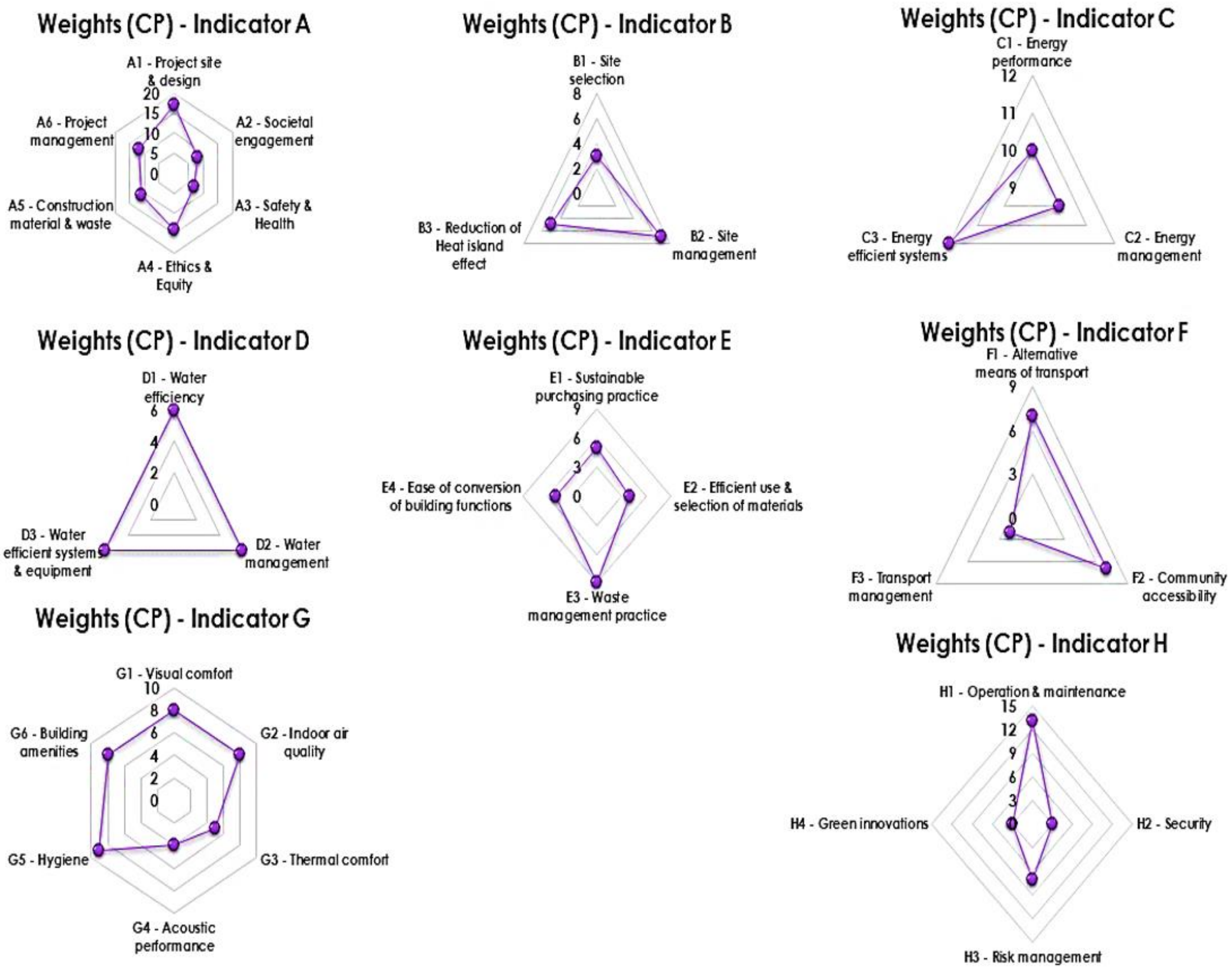

Figure 7.3: Score-weight distribution for each of the key sustainability assessment criteria

7.4.1.3 Establishing the ratio of each sustainability indicator

As shown in Figure 7.4, sustainability indicators A, C, and G were regarded by the experts as the sustainability criteria that should be given the highest priority in the evaluation of a building sustainability performance compared to the other five criteria.

Further, the percentage contribution (ratio, S_r) of each sustainability indicator (A – H) to the overall sustainability performance of a building project is evaluated using equation (ii) and as shown in Figure 7.4. The overall sustainability status (S_p) of the building project is deduced by calculating the score-weights between the $\sum W$ of the benchmark and the proposed case using equation (iii). The benchmark case – is a building project demonstrating the optimum sustainability performance – that has achieved the maximum score-weight (credit point) for the sustainability criteria. The proposed case – is the building project under observation or being assessed.

$$S_r = \frac{W_z}{\sum W_z} X\ 100 - - - eqn\ (ii)$$

Where $\sum W_z$ = summation of the score-weights of the sustainability indicator (z)

W_z= score-weight [credit point] of the sustainability indicator (z)

S_r = Percentage contribution of each sustainability indicator

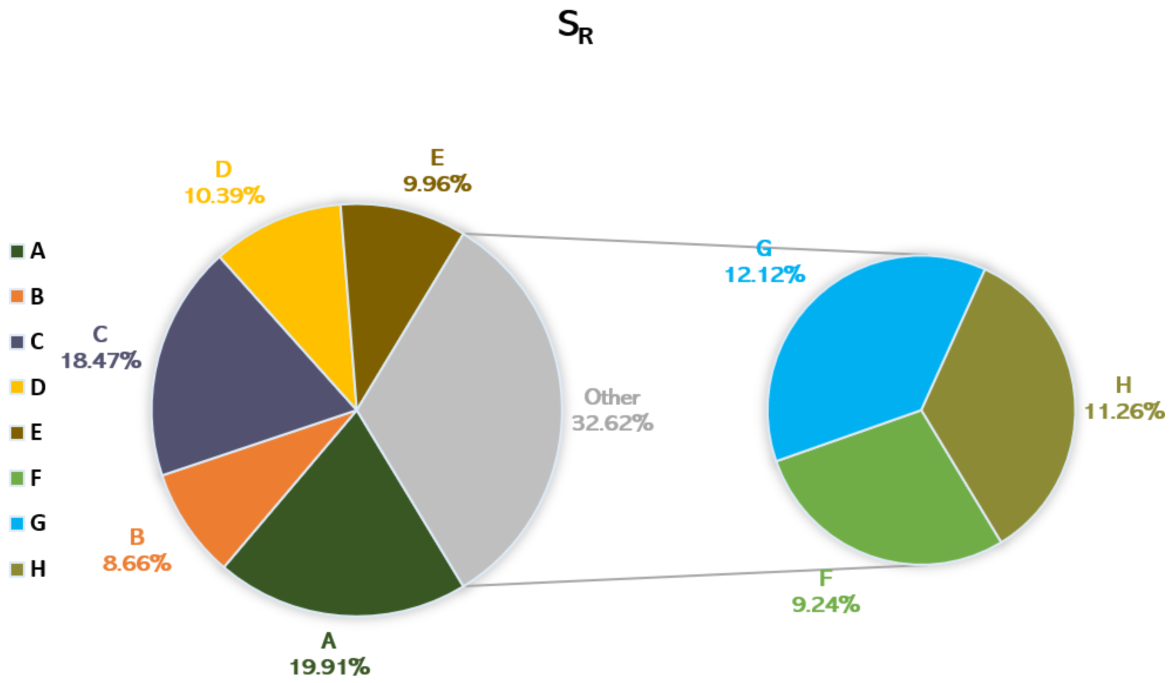

Figure 7.4: Percentage contribution of each of the key sustainability assessment criteria

Note: A – 'Sustainable construction practices'; B – 'Site & Ecology'; C- 'Energy'; D – 'Water'; E – 'Material & waste'; F – 'Transportation'; G – 'Indoor environmental quality' (IEQ); H – 'Building management'.

$$S_p = \frac{\sum W_s}{\sum W_i} X\ 100 - - - eqn\ (iii)$$

Where $\sum W_s$ = summation of the score-weights of the sustainability indicator (*proposed case*)

$\sum W_i$ = summation of the score-weights of the sustainability indicator (*benchmark case*)

S_p = The overall sustainability performance (in percentage, %)

7.4.1.4 The BSAM certification grading system

The grading system for the BSAM scheme was derived by soliciting from the invited experts to input two numerical values (minimum and maximum thresholds) in the questionnaire survey form for the six identified performance levels (outstanding, excellent, very good, good, acceptable, and unclassified) of the BSAM scheme. The six performance levels have been earlier identified by the authors based on a similar approach adopted by the other green rating systems such as LEED, Green Star, BEAM Plus, BREEAM, etc. The experts were asked to provide the two numerical values (thresholds) which must be within the range of 0 and 100. The mean value of these thresholds for the individual performance level was calculated as shown in Figure 7.5.

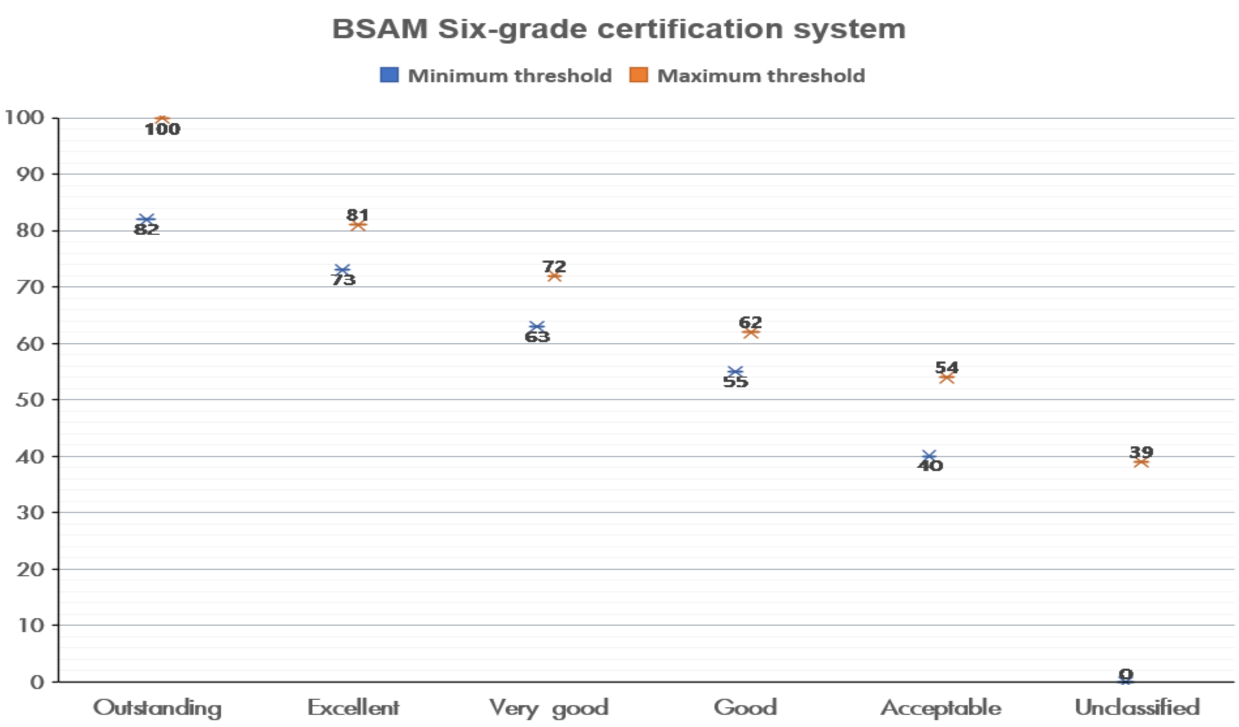

Figure 7.5: BSAM Six-grade certification system

Hence, to calculate the certification grade level for a green building, the result of the evaluation of equation (iii) which assesses the overall sustainability performance (S_p) of the building project is used. The BSAM certification grade system is based on the performance level on which the resultant S_p, falls. The BSAM certification grade system is a scale from 0 to 100, which represents the six performance levels. Therefore, based on the thresholds of the six performance levels of the BSAM scheme (see Figure 7.5), a green building project must have a S_p value of 40 ("*acceptable*" grade) before it can be green certified under the proposed BSAM scheme. The highest performance level for the BSAM tool is the "*outstanding*" grade level, which is from 82 – 100%.

7.4.1.5 Case study validation for the BSAM scheme

Two case study of projects were used to validate the suitability, adequacy, reliability, and appropriateness of the BSAM scheme in practice within the built environment – especially in developing countries of sub-Saharan Africa. These include a residential building and a commercial building. These two case studies share similar tropical climate classification with varying rainy and dry seasons. The first case study is a residential building (a duplex) project (Project A) located within the south-eastern part of Nigeria. It is classified as a "new building" based on BRE (2018) classification as the building is still less than one year of occupancy. The second case study is a commercial building project (Project B) located within the south-western part of Nigeria – which featured three laboratories and other offices at the ground floor and include two meeting halls, a conference room among other offices at the first floor – and can also be classified as a "new building".

The two case studies (projects A and B) were assessed using the BSAM scheme documentation (Olawumi and Chan, 2019b) and sustainability criteria weights, and the results are shown in Appendix D3 and Table 7.4. The result revealed in Appendix D3 shows the weighting average at the sustainability attributes and indicators levels (Table 7.4) because results at these levels help understand where the building projects perform well and where it is inadequate. However, it must be noted that the two case study projects were assessed based on their score-weights at the sub-attributes level – which is the building block of the BSAM scheme. A radar diagram shown in Figure 7.6 maps the standing of the case study building projects (projects A & B) in terms of their sustainability indicators' weightings (W_s).

The analysis of the weightings (W_s) for the sustainability indicators for the case studies – projects A and B (Table 7.4) reveals that project A outperforms project B in three sustainability criteria. These are criteria B, E, and F with weighting values of 2.67, 4.88, and 4.67 respectively. Also, project B outperforms project A in five sustainability criteria which are A, C, D, G, and H with weighing values of 8.42, 7.33, 4.17, 5.92, and 4.75 respectively.

Hence, to improve the projects' sustainability performance of projects; the clients, designers, and other key stakeholders need to critically assess the projects' credit points (score-weights) of the sustainability attributes level of the individual projects as shown in Appendix D3. This will help to evaluate where the building is performing well and where there is a need to improve the overall sustainability performance. The overall sustainability performance (S_p) of the case study projects is also presented in Table 7.4. Project A has a 62.6% overall sustainability performance when its score-weights ($\sum W$) is normalized with the benchmark case, while project B has a better overall sustainability performance status of 69.11%. Based on the BSAM scheme grade certification system, project A can be classified as a "*good*" rated green building and project B as a "*very good*" rated green building.

Table 7.4: Weighting average for the sustainability indicators and the overall sustainability performance (S_p) values for the case study projects

Sustainability Indicators	Maximum Weight (W) [*Benchmark case*]			Project A			Project B		
	∑CP_i	W_i	S_r (%)	∑CP_s	W_s	S_r (%)	∑CP_s	W_s	S_r (%)
A	69	11.50	19.91	37.5	6.25	17.28	50.5	8.42	20.89
B	15	5.00	8.66	8	2.67	7.37	7.5	2.50	6.20
C	32	10.67	18.47	20	6.67	18.43	22	7.33	18.20
D	18	6.00	10.39	10.5	3.50	9.68	12.5	4.17	10.34
E	23	5.75	9.96	19.5	4.88	13.48	17.5	4.38	10.86
F	16	5.33	9.24	14	4.67	12.90	8.5	2.83	7.03
G	42	7.00	12.12	28.75	4.79	13.25	35.5	5.92	14.68
H	26	6.50	11.26	11	2.75	7.60	19	4.75	11.79
Total (∑)		**57.75**	100.00		**36.17**	100.00		**40.29**	100.00
S_p			**100%**			**62.63%**			**69.77%**

Note *∑$CP_{i,s}$ = total of each sustainability indicator' attribute weights; S_p = The overall sustainability performance (in percentage, %); $W_{i,s}$= score-weight of the indicator; S_r = Percentage contribution of each indicator. A – 'Sustainable construction practices'; B – 'Site & Ecology'; C- 'Energy'; D – 'Water'; E – 'Material & waste'; F – 'Transportation'; G – 'Indoor environmental quality' (IEQ); H – 'Building management'.*

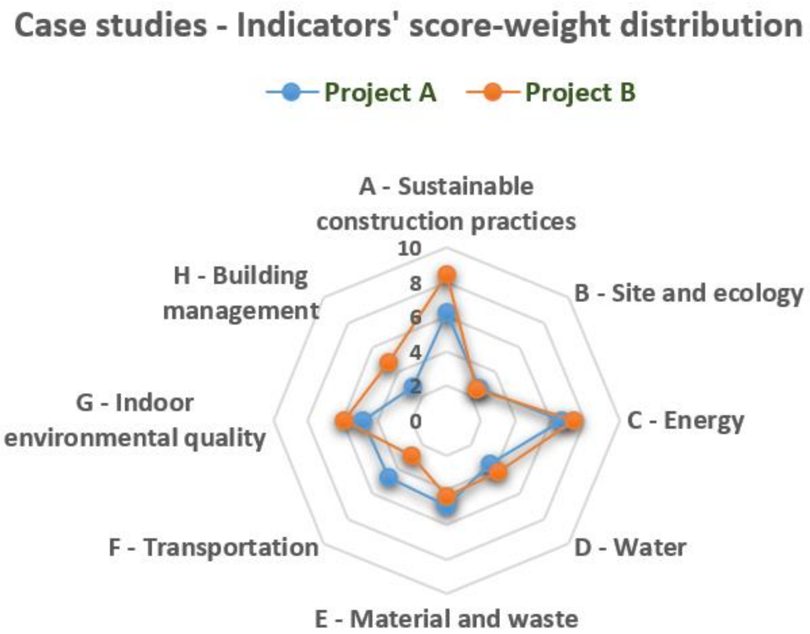

Figure 7.6: Comparison of the score-weight distribution of the two case study projects (A & B) in terms of their sustainability indicators

The results and analysis presented in this section offer key stakeholders and decision-makers a convenient and efficient means and methods for assessing the sustainability performance of a building project. The breakdown of the analysis into the sustainability attributes and indicators levels also help in understanding how the green building project functions at each sustainability assessment criteria level and assist in pinpointing where it fails to perform adequately.

7.4.2 Comparison of the proposed BSAM scheme with the six selected existing green building rating systems

This section compares the BSAM scheme with the six well established GBRS. This paper focuses on the ‘new construction’ schemes and latest versions of the six selected green rating tools for uniformity purpose (Illankoon et al., 2017). The different sustainability criteria and the scheme of the six selected GBRS used in this study are identified in Table 7.5.

7.4.2.1 Allocating credit points to the key sustainability assessment criteria

The proposed BSAM scheme and the six selected GBRS identified in the previous section have different sustainability criteria (Table 7.5). Specific sustainability criteria are identical in some of the rating tools such as ‘energy’ and “IEQ”; IEQ is addressed in BREEAM and BEAM Plus as “health and wellbeing” (Table 7.5). Sustainable sites (or land use), materials, and waste are another set of sustainability criteria addressed directly in most of the green rating tools (BRE, 2018; GBCA, 2017; HKGBC, 2018; IGBC, 2014; USGBC, 2017); except in Green Mark where ‘waste’ and ‘materials’ are addressed under the “resource stewardship” criterion while the sustainable sites are termed ‘tropicality’ under the “climatic responsive design” criteria of the Green Mark (BCA, 2015). Also, all the selected GBRS has the ‘innovation’ criterion embedded as a key criterion or as a sub-level of other criteria; and it is intended to reward innovative techniques employed in the projects. In BEAM Plus, the ‘innovation and additions’ criterion is addressed as a bonus criterion (BRE, 2018).

Table 7.5: Distribution of the credit points for key sustainability assessment criteria of BSAM scheme and the six selected green building rating tools

LEED v4. (Design & Construction - 101 credit points)	**BEAM Plus v2.0** (New Building - 133 credit points)	**BREEAM 2018** (New Construction - 149 credit points)	**IGBC v3.0** (New Buildings - 100 credit points)
Integrative process (2)	Integrated design and construction management (25)	Management (21)	Sustainable architecture and design (5)
Location and transportation (15)	Sustainable sites (20)	Health and wellbeing (20)	Site selection and planning (14)
Sustainable sites (7)	Materials and waste (14)	Energy (31)	Water conservation (18)
Water efficiency (12)	Energy use (31)	Transport (12)	Energy efficiency (28)
Energy and atmosphere (29)	Water use (12)	Water (9)	Building materials and resources (16)
Indoor environmental quality (16)	Health and wellbeing (21)	Materials (14)	Indoor environmental quality (12)
Innovation (5)		Waste (11)	Innovation and development (7)
Regional Priority (4)		Land use and ecology (13)	
		Pollution (12)	
		Innovation (10)	

Green Mark v5.0 (Residential building - 140 credit points)	**Green Star v1.2** (Design & As-built - 100 credit points)	**BSAM v1.0** (New Buildings - 241 credit points)
Climatic responsive design (30)	Management (14)	Sustainable construction practices (69)
Building energy performance (30)	Indoor environmental quality (17)	Site and ecology (15)
Resource stewardship (30)	Energy (22)	Energy (32)
Smart and healthy building (30)	Water (12)	Water (18)
Advanced green efforts (20)	Materials (14)	Material and waste (23)
	Land use and ecology (6)	Transportation (16)
	Emissions (5)	Indoor environmental quality (42)
	Innovations (10)	Building management (26)

More so, the seven green building rating tools have differing sustainability criteria (see Table 7.5) and to provide a common basis to compare these rating tools – this study adopts the eight key sustainability criteria of the BSAM scheme to allow uniformity in the comparative assessment of the seven rating tools. Furthermore, in the review of the selected rating tools, it was observed that for instance – in Green Mark®, some sub-levels of the sustainability criteria such as 'sustainable construction practices,' 'transportation,' 'site and ecology,' and 'water' identified in BSAM was evaluated under the 'climatic responsive design' criterion in Green Mark rating tool (BCA, 2015).

In LEED®, 'non-toxic pest control' was identified in 'sustainable sites' criterion but was attributed under 'IEQ' criterion in the BSAM scheme as the credit point helps to provide a better IEQ; also, ‘regional priority’ criterion in LEED (USGBC, 2017) was attributed under ‘site and ecology’ in the BSAM scheme as it includes credit points that have an impact on site and designs. Similar re-arrangement of the credit points of the sustainability criteria of the selected green rating tools was undertaken to conform with the structure of the eight BSAM scheme sustainability criteria. As a result, the credit points of the criteria for the six selected green rating tools were separately attributed based on the BSAM criteria (Table 7.6).

Based on these normalized credit points, radar diagrams (Figure 7.7) and a comparison chart (Figure 7.8) were developed to further compare the key sustainability criteria and the seven green rating tools.

7.4.2.2 Similarities in the radar diagrams for the green building rating tools in comparison to the BSAM scheme

As illustrated in Figure 7.7, LEED and BEAM Plus have a similar pattern in the structure of their diagram based on the credit point allocation among the key sustainability criteria except for the ‘sustainable construction practices’ criterion which was considered in a greater context in BEAM Plus. Also, the pattern of the BREEAM and Green Star radar diagrams is quite similar except for the ‘sustainable construction practices’ criterion, which was considered in a little more detail in BREEAM. These findings are akin to the normative literature (Fowler & Rauch, 2006; Illankoon et al., 2017) which reported that Green Star was developed based on the BREEAM scheme. The BEAM Plus which was also developed based on the BREEAM system also share similar pattern except for the less evaluation of the ‘building management’ in the former.

Table 7.6: Allocation of the credit points for the eight key sustainability assessment criteria (A - H) for each of the green rating tools

Sustainability criteria		A	B	C	D	E	F	G	H	Total
LEED	CP	2	14	17	15	11	7	30	5	101
	%	1.98	13.86	16.83	14.85	10.89	6.93	29.70	4.95	100.00
BEAM-Plus	CP	18	9	31	13	15	4	27	6	123
	%	14.63	7.32	25.20	10.57	12.20	3.25	21.95	4.88	100.00
BREEAM	CP	16	11	27	14	20	12	35	18	153
	%	10.46	7.19	17.65	9.15	13.07	7.84	22.88	11.76	100.00
IGBC	CP	3	14	27	16	20	3	13	4	100
	%	3.00	14.00	27.00	16.00	20.00	3.00	13.00	4.00	100.00
Green Mark	CP	8	12	55	8	22	0	33	2	140
	%	5.71	8.57	39.29	5.71	15.71	0.00	23.57	1.43	100.00
Green Star	CP	4	8	12	15	16	10	23	12	100
	%	4.00	8.00	12.00	15.00	16.00	10.00	23.00	12.00	100.00
BSAM Scheme (*current study*)	CP	69	15	32	18	23	16	42	26	241
	%	28.63	6.22	13.28	7.47	9.54	6.64	17.43	10.79	100.00

Note: A – 'Sustainable construction practices'; B – 'Site & Ecology'; C- 'Energy'; D – 'Water'; E – 'Material & waste'; F – 'Transportation'; G – 'Indoor environmental quality' (IEQ); H – 'Building management'. CP – Credit points; % - the percentage of each criterion of the total score of the scheme.

Also, the pattern of the IGBC and BREEAM system radar diagrams is similar except for the better consideration for the 'building management' and 'sustainable construction practices' criteria in BREEAM. The pattern of the BSAM scheme, however, is somewhat similar to most of the other selected green rating tools (except Green Mark), though the massive consideration of the 'sustainable construction practices' criterion in the BSAM scheme is an exception. The 'sustainable construction practices' criterion is a massive improvement on the existing GBRS to suit the local context of the developing countries with the sub-Saharan region of Africa.

7.4.2.3 Differences in the radar diagrams for the green building rating tools in comparison with the BSAM scheme

An evaluation of the comparison of the selected green building rating tools shows that the 'IEQ' criterion has the highest consideration in most of the rating tools except for BEAM Plus and the proposed BSAM scheme where it receives a little lesser attention (Figures 7.7 and 7.8). The normalized credit points for the 'IEQ' for the rating tools range from 13% to 29.7%. The 'IEQ' criterion is given the highest priority in LEED, with about 29.7% of the total credit points, followed closely by BREEAM (22.88%). In the BSAM scheme, the 'IEQ' criterion is given the second priority behind the 'sustainable construction practices' criterion. Illankoon et al. (2017) reported that there is an increased concern about occupant satisfaction in buildings that IEQ denotes due to the prevalence of 'sick building' syndrome. However, a survey by El Asmar et al. (2014) reveals a weak link between the intended performance of the building as regards IEQ at the design stage and its actual performance during occupancy. Berardi (2012) identified IEQ as an essential criterion in the assessment of green buildings.

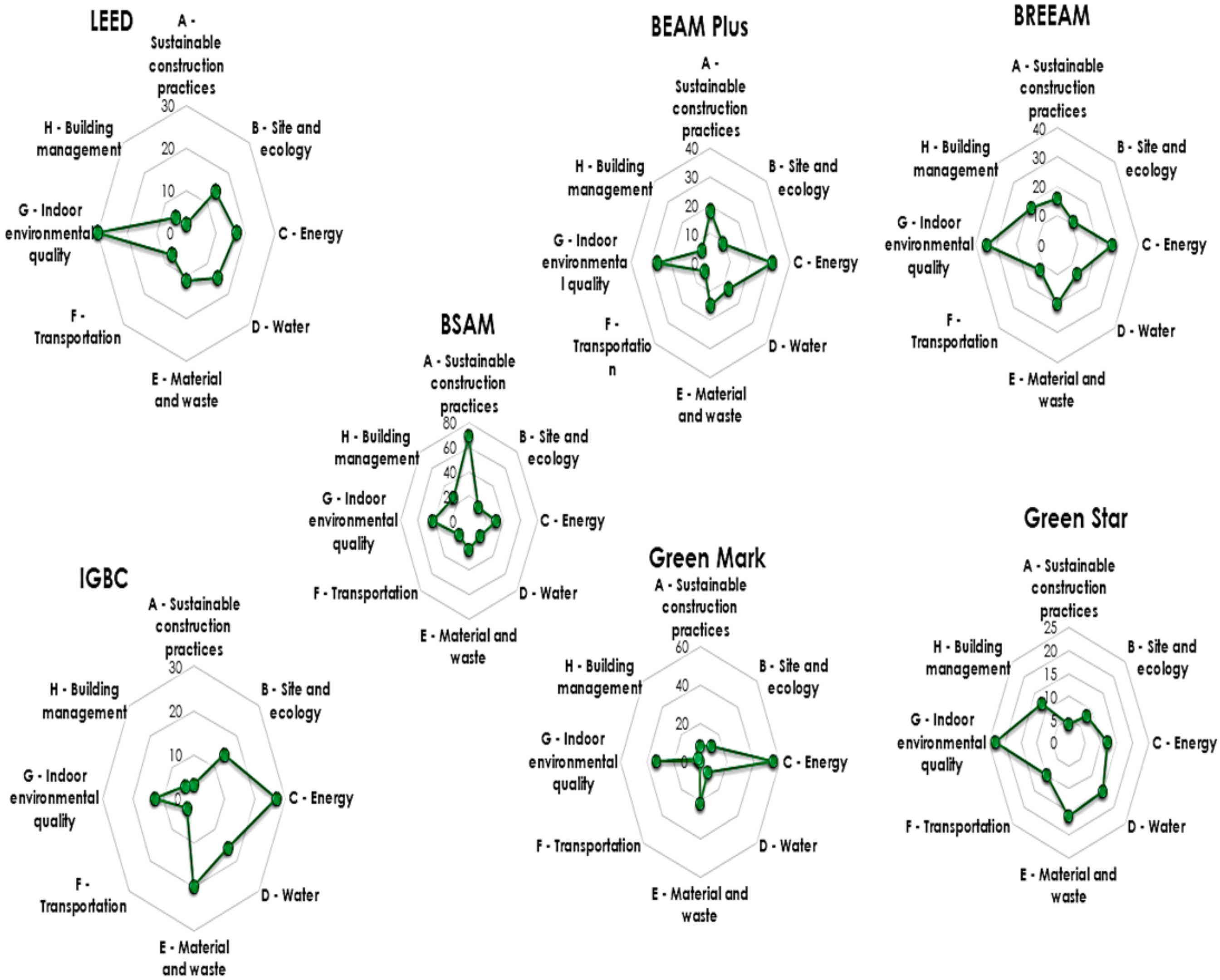

Figure 7.7: Radar diagrams for the green building rating tools based on the credit points of their key sustainability assessment criteria

Next in line is the ‘energy’ criterion, which is given second priority, except in BEAM Plus, IGBC, and the Green Mark, where it receives the highest consideration. Also, the normalized credit points for the ‘IEQ’ for the rating tools range from 12% to 39.29% of the total score. The ‘energy’ criterion receives 39.29% of the overall credit point in Green Mark when compared to the 16.83% in LEED. A review of the Green Mark rating system shows that the ‘energy’ criterion is distributed across three out of the five credit criteria in Green Mark® with each criteria receiving a very high credit allocation (BCA, 2015). This finding corresponds with one of the main objectives of Green Mark to achieve “increased energy effectiveness”; which explains the higher percentage weighting of the ‘energy’ criterion in Green Mark compared to the other rating tools (BCA, 2015). The ‘energy’ criterion is rated as a third priority within the BSAM scheme after the ‘sustainable construction practices’ and ‘IEQ’ criteria. Berardi (2012) and Kamaruzzaman et al. (2016) reported that the ‘IEQ’ and ‘Energy’ criteria are the salient sustainability criteria in all green building rating tools which correlate with the findings reported in this paper.

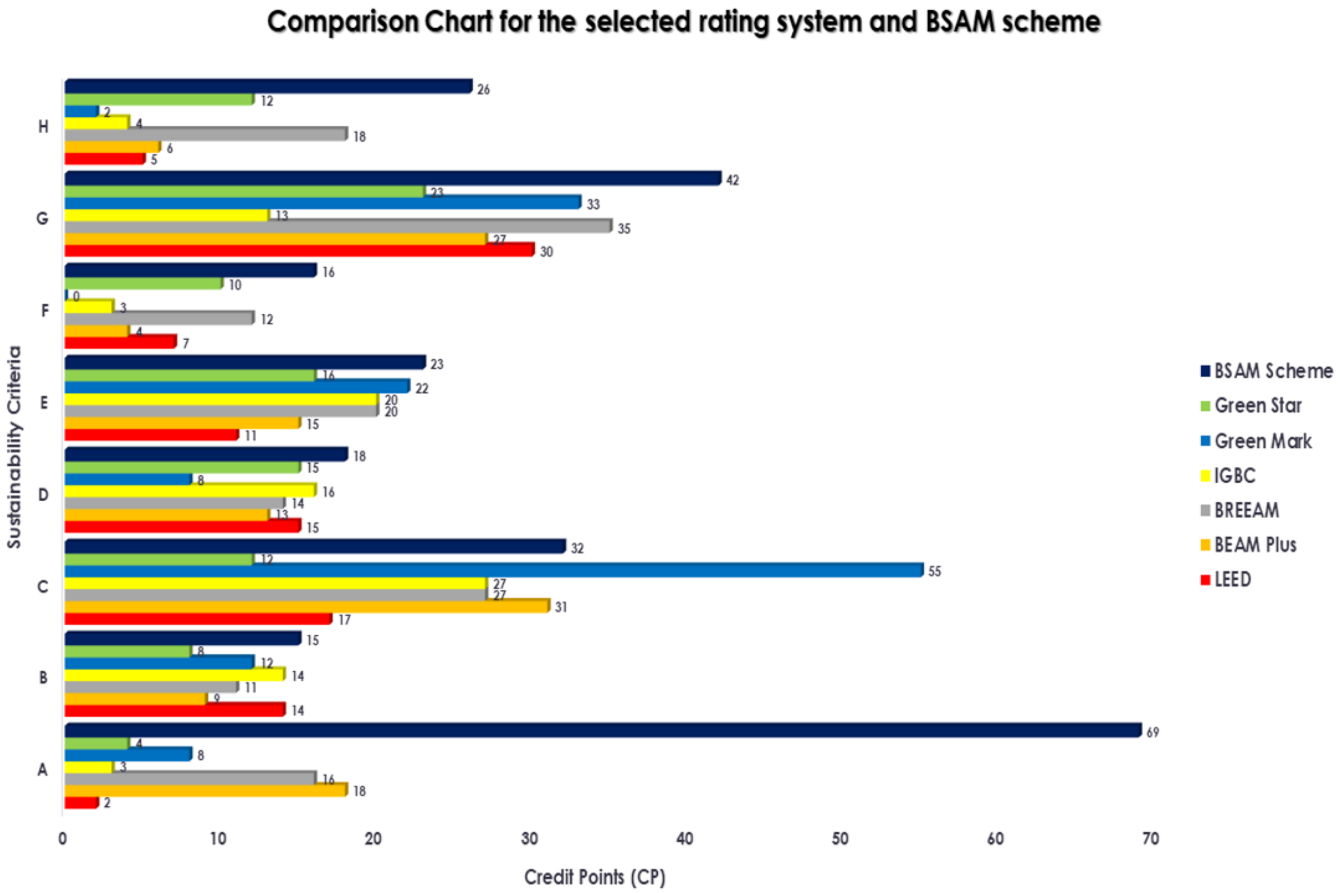

Figure 7.8: Comparison chart for the green building rating tools based on the credit points of their key sustainability assessment criteria

Note: A – 'Sustainable construction practices'; B – 'Site & Ecology'; C- 'Energy'; D – 'Water'; E – 'Material & waste'; F – 'Transportation'; G – 'Indoor environmental quality' (IEQ); H – 'Building management'.

Nevertheless, an analysis of 490 buildings from the green building council database by Berardi (2012) revealed that the 'energy' criterion is the most difficult to achieve. In line with one of the main objectives of Green Mark to "increased energy effectiveness"; which explains its higher percentage weighting compared to the other rating tools. Kamaruzzaman et al. (2016) reported that the 'IEQ' and 'Energy' criteria are the salient sustainability criteria in all green building rating tools which correlate with the findings reported in this paper.

The 'material and waste' criterion also receives some consideration by all the rating tools with its normalized credit points ranging from 9.54% to 20% of the total score. The 'material and waste' criterion received its highest priority in the IGBC scheme, followed closely by the Green Star. Zhang et al. (2017) stressed that there is a need for an increased focus on the recycling of building materials and waste to promote a sustainable material performance, as well as encourage the use of local materials. The Australian Bureau of Statistics (2012) also reported that the building construction works contribute about 26% of total waste in the ecosystem; hence, it is important to evaluate this criterion in buildings to ensure an optimal sustainable performance. Each of the rating tools gives the 'water' criterion some focus on the radar diagram except for the Green Mark system, where it receives the lowest credit point of 5.71% of the total score. It gets the highest score in the IGBC scheme with a normalized credit point of 16%. Berardi (2012) revealed that the 'water' criterion has the highest percentage of fulfillment in most certified green buildings.

Meanwhile, among the selected green building rating system, only the BSAM scheme considers 'water conservation' as a priority criterion. Cheng et al. (2016), in an analysis of buildings in Taiwan, reported that green buildings achieved 60% water savings than non-green buildings. Alwisy et al. (2018) stressed that the use of water-efficient equipment could help buildings achieve significant reductions in water usage. Also, per Tam et al. (2019a) who stated that the use of sustainable water facilities rather than the conventional ones can help improve water efficiency.

The 'material and waste' criterion also receive some consideration by all the green rating tools with its normalized credit points ranging from 9.54% to 20% of the total score. The 'material and waste' criterion received its highest priority in the IGBC scheme, followed closely by the Green Star. For the transportation' criterion, the Green Mark scheme has given no priority or credit point to the 'transportation' criterion, and it also gave less than 2% of its total score to the 'building management' criterion.

7.4.2.4 Precedence of the BSAM scheme over the existing green building rating tools

This section highlights and discusses certain key sustainability criteria that are not identified in the six GBRS, but which were identified in the extant literature. It is noteworthy that these key sustainability criteria were considered in developing the BSAM scheme. Also, the BSAM scheme embeds virtually all the criteria in the six selected green rating tools, but the inclusion of these key criteria in the BSAM scheme is based on their importance within the local context of developing countries in sub-Saharan Africa.

Olawumi and Chan (2018a), Olawumi and Chan (2019c) and ISO 15392 reported that for a building project to be regarded as a green building it needs to fulfill the triple-bottom pillar of sustainability – that is, must be environmentally, socially, and economically sustainable. However, with reference to the findings of the review of the six selected green rating tools and as reported in the extant literature (*see* Ali & Al Nsairat, 2009; Illankoon et al., 2017; Sev, 2009); these existing green building rating tools considers only the factors pertaining to the minimization of the environmental impacts of buildings while ignoring the key social and economic criteria in the evaluation of buildings. Illankoon et al. (2017) and Gibberd (2005) further stressed the need for the future development of green rating tools especially in developing countries to address this shortcoming in the existing GBRS.

Shari (2011) identified some key social sustainability criteria such as education and awareness, local people and employment, and inclusiveness of opportunities which were not considered by the selected green rating tools. Also, Liu et al. (2013) highlighted 'stakeholder relation' as another social criterion that should be considered by green rating tools, but which are not currently included in the existing rating tools. All these social sustainability criteria were given significant consideration in the newly developed BSAM scheme under the 'sustainable construction practices' criterion. Social sustainability criteria identified under the BSAM scheme include ‘engagement of local firms’, ‘local employment opportunities’, ‘public participation’, ‘compliance with social standards’, ‘education and skills development’ among many other key social sustainability attributes. Berardi (2012) argued further that the neglect of social sustainability criteria in existing rating systems makes these GBRS incomplete as it contradicts a key pillar of the sustainable development dimension.

For the economic sustainability criteria, the extant literature (Ali & Al Nsairat, 2009; Liu et al., 2013; Wei et al., 2011) has discussed extensively the need for an increase in the consideration of economic criteria in the development of building projects which are currently lacking in the existing green building rating systems. The proposed BSAM scheme considered economic criteria such as ‘enhanced local economy,’ ‘reuse of construction materials’ among others. Zhang et al. (2017) reiterated the need to link the economic and environmental criteria of green buildings to allow for harmony in its assessment. Another key sustainability indicator (cultural aspect) identified in the literature (Banani et al., 2013; Salehudin et al., 2012; Shari, 2011) is the ‘protection of cultural heritage’ which is not provided in most green rating tools except in BEAM Plus. The criterion is catered for in the proposed BSAM scheme as ‘integration of cultural heritage in design.’

More so, the ‘management’ criterion is given less consideration in the existing green rating tools; even though this sustainability criterion has been much discussed in the literature (Illankoon et al., 2017; Sev, 2009). In the BSAM scheme, the ‘management’ criterion is given due consideration to about 11% of the total credit point, which gave the criterion the fourth priority among the eight key sustainability criteria identified in BSAM. Also, as regards the ‘materials and waste’ criterion, none of the existing green rating tools consider this key criterion for assessment at the construction stage of the green building development. Another key sustainability criteria unavailable in the existing GBRS but given consideration in the proposed BSAM scheme are the ‘safety and health’ and ‘ethics and equity’ criteria. Also, as regards the ‘materials’ criterion, the existing GBRS focus on the material type (category) while the BSAM scheme focuses both on the former as well as whether the materials are locally sourced.

Meanwhile, Ali and Al Nsairat (2009) reported that unlike developing countries are typically conscious of the economic and social pillars of sustainable development than the environmental construct. Hence, this study addressed the imbalance by developing a holistic GBRS towards achieving sustainable development goals.

7.6 Conclusions

Green building rating systems provide a means to create and monitor the development of sustainable buildings and infrastructure. The relevance of the development of the proposed BSAM scheme lies in addressing the shortcomings of the existing green building rating systems and providing a holistic green rating tool suitable to the local context of developing countries in sub-Saharan Africa. The research established the key sustainability criteria of the proposed BSAM scheme based on a four-step review process discussed in the study's methodological approach. A review of the extant literature using the content analysis approach identified the need for green building rating systems to focus on the three pillars of sustainability. The eight key criteria were identified for inclusion in the BSAM scheme. The full documentation of the BSAM scheme documentation is provided as a supplementary data and multi-expert consultations helped in determining the credit weighting of each of the BSAM sustainability criteria.

The sustainability assessment criteria weights and the significance of each sustainability sub-attributes were also established based on the analysis of the data collected via the experts' consultations. The criteria-based ranking of the BSAM scheme is generated by aggregating the credit points of its sustainability attributes and sub-attributes. Also, the percentage of the total score-weights for each sustainability criterion and the certification grading system scales – outstanding, excellent, very good, good, acceptable, and unclassified, which are measured on the scale of 0-100% was established. Forty percent is the minimum threshold before a building can receive green certification under the BSAM scheme. Two case studies of building projects (residential and commercial buildings) were employed to validate the suitability, practicality, and appropriateness of the BSAM scheme in practice within the built environment.

Furthermore, to validate and demonstrate the improvement of the proposed BSAM scheme over the existing green building rating systems, a comparative analysis of the BSAM scheme with six selected common green rating tools – LEED, BEAM Plus, BREEAM, IGBC, Green Mark, and Green Star – was carried out in this study. An analysis of the existing green rating tools reveals a different set of sustainability criteria and to allow for uniformity of comparison of the green rating tools in this paper; the credit points of these rating tools were re-assigned based on the eight key sustainability criteria of the BSAM scheme. Based on the comparison of these green rating tools, the following conclusions were derived – (1) The existing green building rating tools place more emphasis on the environmental aspect of sustainability and overlooked the social and economic parameters; while the BSAM scheme gave a steady consideration to the three aspects of sustainability; thereby providing a better holistic evaluation of green buildings. (2) The BSAM scheme embeds virtually all the key sustainability criteria required for the assessment of green buildings based on the local context, while some green rating tools fail to cater for some of the key sustainability criteria adequately.

More so, (3) There are some similarities in the credit points allocation among the green rating tools, as shown in the patterns of their radar diagrams while there are differences. (4) The BSAM scheme, BREEAM, and Green Star shows a more balanced consideration in the allocation of credit points for the key sustainability criteria. (5) The ‘management’ and ‘sustainable construction practices’ criteria were given higher priority in the BSAM scheme when compared to the other selected green rating tools; although, these criteria are of vital to the sustainability performance of buildings. (6) All the green building rating tools place more significant consideration to the ‘IEQ’ and ‘energy’ criteria, although the ‘energy’ criterion was found to be the most difficult to achieve while the ‘water’ criterion is the easiest to achieve.

As evidenced by the findings in this paper, the BSAM scheme encompasses the necessary key sustainability criteria as well as an improvement of the existing green rating tools. Limitations to the proposed BSAM scheme, includes that the scheme like the other green rating tools, fails to address the complex relationships among the key sustainability criteria. Also, another limitation of the study is the use of aggregation of points which limits the expressions of the key sustainability criteria. These two shortcomings are addressed in chapter 8.

In summary, the following are the significant contributions of the study. (1) The proposed BSAM scheme includes effective guidelines towards evaluating green buildings as well as the documentary evidences to be assessed and verified to ascertain the fulfillment of the key sustainability criteria. (2) It also covers the maintenance and improvement of the sustainability performance of the buildings throughout their lifecycles. (3) Implementing the proposed BSAM scheme can promote greener buildings and sustainable urban development and guide the design team as well as the construction team to employ greener technologies. (4) It also fulfills the need for a technical scheme through the experience-based ranking of the key sustainability criteria.

It is recommended for each developing country in the sub-Saharan region to establish their own green building councils towards joining the global body. More so, countries using the existing green rating systems such as LEED, BREEAM, BEAM Plus, etc. which emphasizes the environmental sustainability are implored to examine the social and economic sustainability criteria in the BSAM scheme updating their respective GBRS. Also, stakeholders in the built environment are encouraged to adopt and test the proposed BSAM scheme in evaluating their building projects to accelerate the implementation of this green rating tool. Future research can focus on expanding the scope of the key sustainability criteria and adding more variables at each sub-level – attributes and sub-attributes. Conclusively, the study has contributed to the existing body of knowledge by developing the BSAM scheme for developing countries as a step towards establishing a universal working green building rating system for future use.

7.7 Chapter Summary

The consideration of the regional context in the development of green building rating systems is well established in the previous literature, and this informs the development of a sustainability assessment method for sub-Saharan Africa. Hence, a multi-expert consultation method was carried out in Nigeria – which is the largest economy in the region. This was performed via a structured questionnaire survey and interview approaches to identify the key sustainability assessment criteria, assign score-weights to the various criteria, and establish the certification grading system of buildings. The developed Building Sustainability Assessment Method (BSAM) scheme and its weighted criteria were validated using two real-life building case studies. The established BSAM scheme was compared to six widely used green rating systems. The comparative analysis reveals that the score-weights and priorities of the BSAM scheme were remarkably different from the existing rating systems. The study findings also show the increasing focus on the indoor environmental quality and energy criteria by all the rating systems. The developed BSAM scheme, meanwhile, has adequately considered the three main pillars of sustainable development unlike the existing green rating tools. Hence, it is expected for the proposed BSAM scheme to promote greener buildings and enhance sustainable urban development in the region. This chapter provided an overview of the development of the BSAM scheme and its sustainability criteria. The following chapter attempts to use a more robust weighting methodology to address the two limitations of the conventional “aggregation of points” method adopted in this chapter.

CHAPTER 8: APPLICATION OF GENERALIZED CHOQUET FUZZY INTEGRAL METHOD IN THE SUSTAINABILITY RATING OF GREEN BUILDINGS BASED ON THE BSAM SCHEME[8]

8.1 Chapter Overview

The previous chapter developed a sustainability assessment method for building projects within the context of the sub-Saharan region of Africa using the conventional “aggregation of points” approach. The current chapter addresses this limitation and others by employing a MCDM technique – the generalized Choquet fuzzy integral (GCFI) method – to determine the weights of the sustainability criteria and develop the sustainability evaluation index of the BSAM scheme, while solidifying the development of the BSAM scheme. The developed sustainability rating model (BSAM scheme) will then be validated in four real-world building case studies to demonstrate its usefulness and robustness in practice. More so, the significance of the GCFI technique over other weighting methodology and MCDM tools will be discussed.

8.2 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, 2018a). 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

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[8] This chapter is largely based on this published paper:
Olawumi, T.O. & Chan, D.W.M. (2020a). Application of Generalized Choquet Fuzzy Integral Method in the Sustainability Rating of Green Buildings based on the BSAM Scheme. *Sustainable Cities and Society, 61, Article 102147.* https://doi.org/10.1016/j.scs.2020.102147

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 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, 2019c). 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.

8.3 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 8.2 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).

8.3.1 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.

8.3.2 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 8.4.1.1, 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.

8.3.3 Advantages of the GCFI methods 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 8.4. Meanwhile, to minimize round-off error and ease the speed of running the GCFI algorithm in this study as illustrated in section 8.4, 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.

8.4 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 8.1 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 8.4 are based on the General Choquet Fuzzy Integral (GCFI) methodology as adopted from the extant literature (*see* Dong et al., 2016; Huang et al., 2010a; Kurt, 2014; Ozdemir & Ozdemir, 2018).

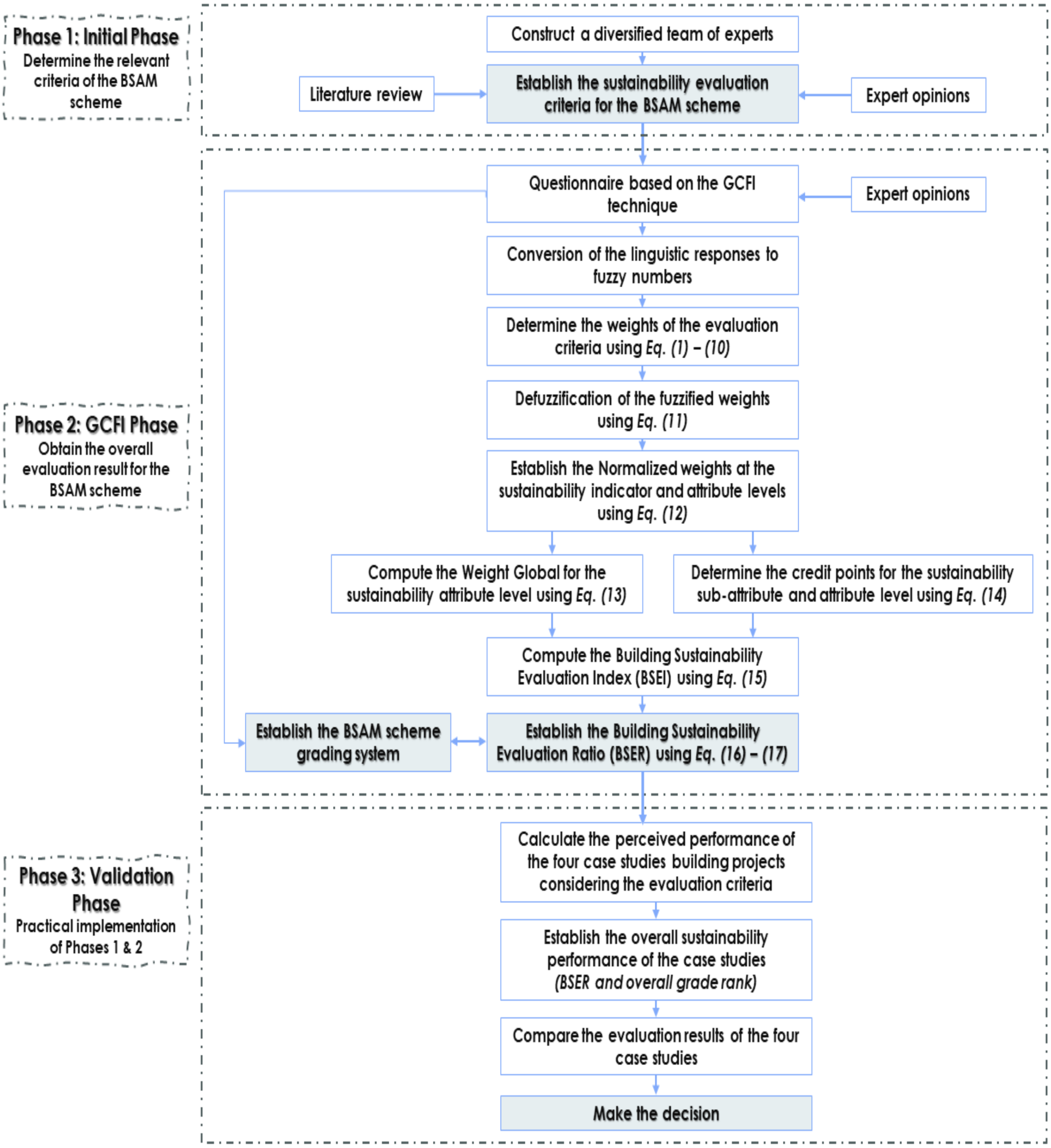


Figure 8.1: Overall framework of the research methodology

8.4.1 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 (see Appendix A) – a green building rating system specifically designed for countries in the sub-Saharan region of Africa

(Olawumi & Chan, 2019c). The structure of the BSAM scheme framework is illustrated in Figure 8.2. 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.

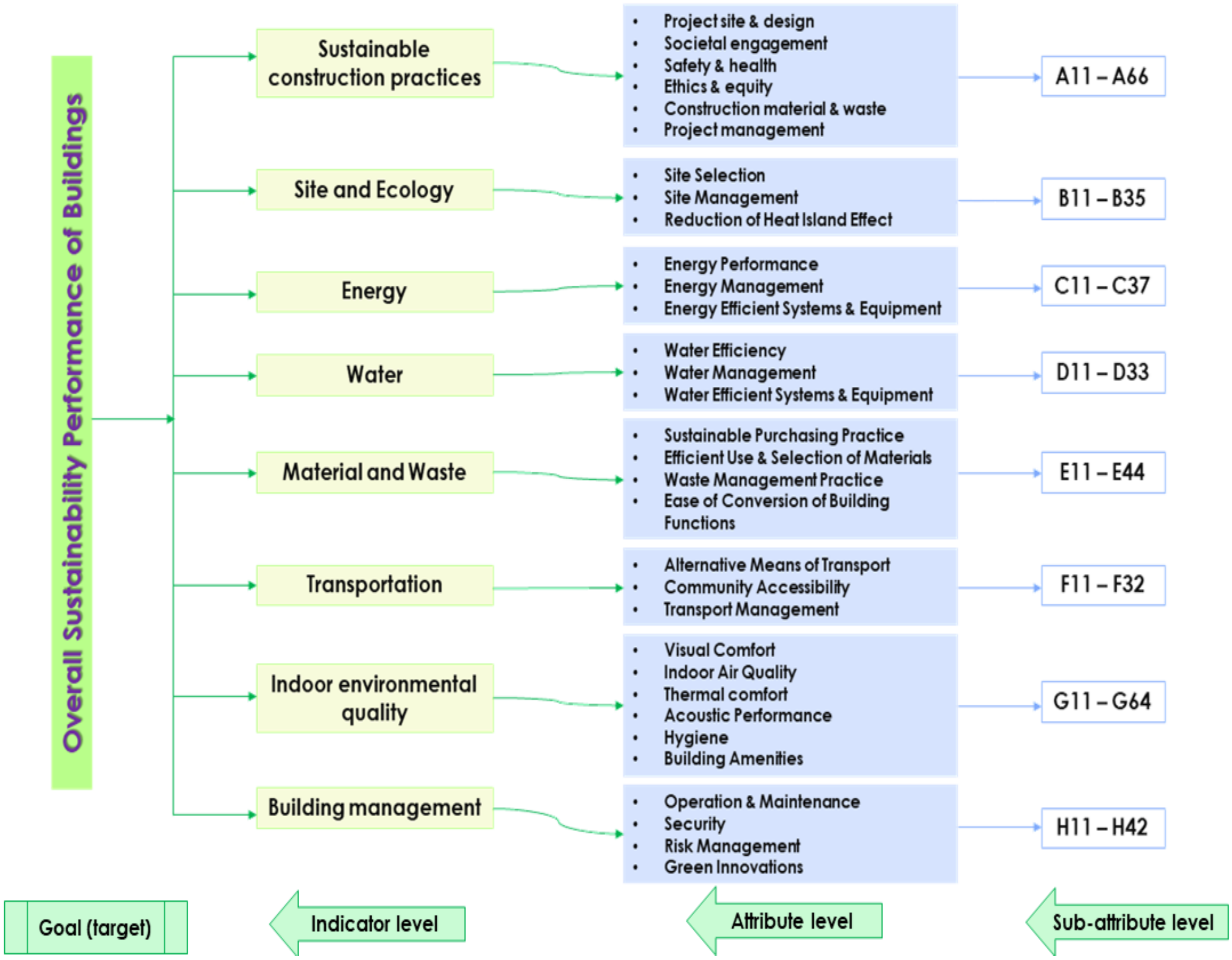


Figure 8.2: Hierarchical structure of the sustainability evaluation criteria of the BSAM scheme

8.4.1.1 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 8.3 for the analysis of the demographics of the experts. As shown in Figure 8.3, 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.

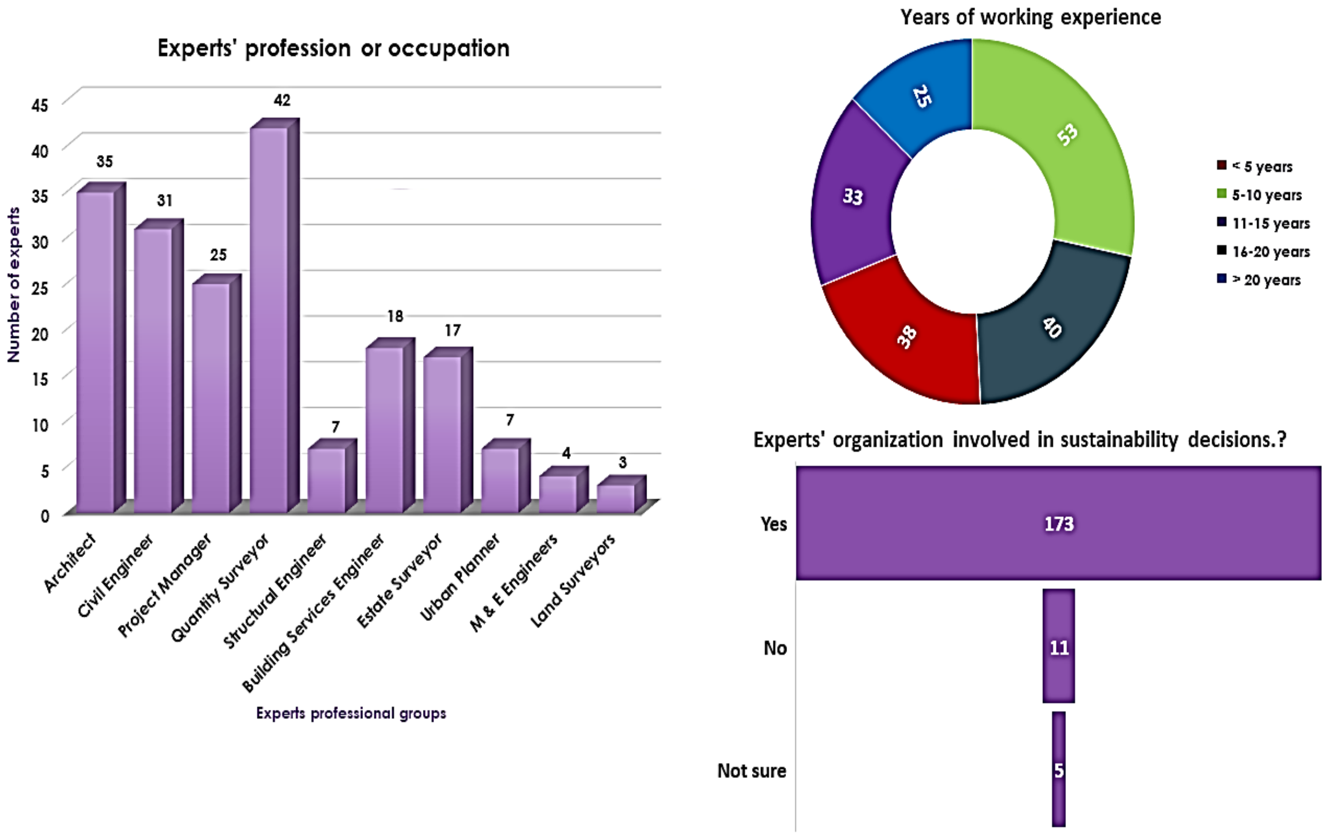


Figure 8.3: The experts' demographics

8.4.1.2 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 C1*). 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 8.1 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 8.1 and, as represented in Figure 8.4, 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 $\tilde{P}_i$.

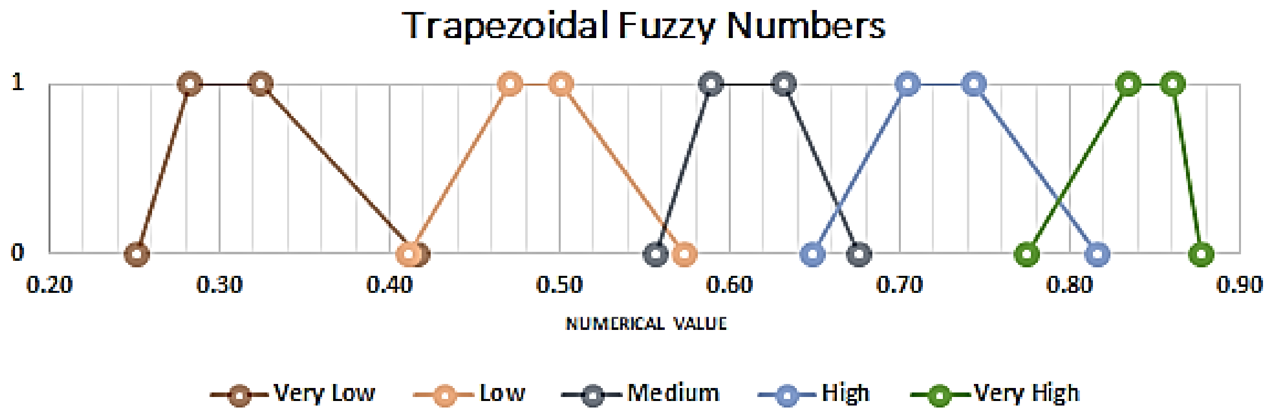


Figure 8.4: Representation of the Trapezoidal Fuzzy Numbers

Table 8.1: Relationship between the 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)

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 8.2).

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 C2*) using the five-linguistic-term scale was calculated using Eq. (1) and as presented in Table 8.2.

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 C3*). (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 8.2) 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 8.2 – 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 8.2 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 8.1 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).

Table 8.2: 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 ($\tilde{P}_i$)	Min. Tolerance Value	Max. Tolerance Value	Tolerance Zone ($\bar{e}_i^{\propto}$)	RON values ($\tilde{R}_i$)	Average 'degree of significance' value (*Best Alternative*) ($\tilde{T}_i$)
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)
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)

Sustainability Criteria (Attributes)	Average 'degree of significance' value for each criterion ($\tilde{P}_i$)	Min. Tolerance Value	Max. Tolerance Value	Tolerance Zone ($\bar{e}_i^{\propto}$)	RON values ($\tilde{R}_i$)	Average 'degree of significance' value (***Best Alternative***) ($\tilde{T}_i$)
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)

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).

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

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).

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

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).

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

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

Table 8.3 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 8.2. For instance, the TFN for criteria "A1" in Table 8.2 ($\tilde{T}_i$) 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 8.3):

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

$$= \left[\frac{(0.516 - 0.876 + 1)}{2}, \frac{(0.584 - 0.556 + 1)}{2}\right] = [\mathbf{0.320}, \mathbf{0.514}] \quad for\ (\propto = 0)$$

Table 8.3: Evaluation result of the GCFI algorithm for the fuzzy valence function, $\tilde{f}_i^{\propto}$ for $\propto = 0$

Criteria code	Individual significance (T_i^0)	$\tilde{f}_i^{\propto}$ Value for the 'BA' $[\int \tilde{f} d\tilde{g}]$ / $(\tilde{f}_i^-, \tilde{f}_i^+)$	Criteria code	Individual significance (T_i^0)	$\tilde{f}_i^{\propto}$ Value for the 'BA' $[\int \tilde{f} d\tilde{g}]$ / $(\tilde{f}_i^-, \tilde{f}_i^+)$
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)			

More so, Table 8.4 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 8.2 – as the "individual significance" column in Table 8.4. 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 8.4):

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

Table 8.4: Evaluation result of the GCFI algorithm for the fuzzy valence function, $\tilde{f}_i^{\propto}$ for $\propto = 1$

Criteria code	**Individual significance** (T_i^1)	**$\tilde{f}_i^{\propto}$ Value for the 'BA'** $[\int \tilde{f} d\tilde{g}]$ / $(\tilde{f}_i^-, \tilde{f}_i^+)$	**Criteria code**	**Individual significance** (T_i^1)	**$\tilde{f}_i^{\propto}$ Value for the 'BA'** $[\int \tilde{f} d\tilde{g}]$ / $(\tilde{f}_i^-, \tilde{f}_i^+)$
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)			

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

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

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

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

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

Eq. (8) is used for solving for λ for $\propto = [0,1]$ (see Tables 8.5 & 8.6); 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 8.5, 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 8.2 (*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], [0.528, 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: $\lambda = [\mathbf{-0.9963,\ -0.9997}] \quad for\ \propto = 0$. Hence, See Tables 8.5 and 8.6 for the λ values for the sustainability indicators (A – H) for $\propto = [0,1]$ respectively.

More so, to calculate the fuzzy measures $\mathrm{g}(\mathrm{A}_{(\mathrm{i})}), \text{for } 1{=}1, 2, 3, \ldots, \mathrm{n}$ for the sustainability attributes (A1 – H4); Eq. (6) and (7) are employed and results presented in Tables 8.5 and 8.6 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 8.2, 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 8.3 and 8.4 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 8.5 and 8.6. 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 8.2) 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 8.5) using Eq. (6) and (7) as follows:

$$\lambda^- = -0.9963$$

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

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

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

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

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

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

Table 8.5: For $\propto = 0$, 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 8.6: For $\propto = 1$, 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					

8.4.1.3 The defuzzification process, normalization process and results

Having calculated fuzzy measures $\mathrm{g}(\mathrm{A}_{(\mathrm{i})})$ 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 i ≠ 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:

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

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

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 8.5 and 8.6; 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 8.3 and 8.4. 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 8.3, taking $\propto = 0$.

The $g^{-}\left(A_{(i)}\right)$ for criteria A1 – A6 (see Table 8.5) are first sorted, as shown below:

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

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

Meanwhile, the corresponding fuzzy valence functions $f_{i,0}^{-}$ (see Table 8.3) to these $g^{-}\left(A_{(i)}\right)$ values are:

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

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

$\int \tilde{f} d\tilde{g} = [0.327, 0.650]$ $\qquad$ $taking\ \propto = 0;$ for criteria A $\qquad$ (see Table 8.3)

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 8.7; 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 8.7).

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

In Table 8.7, 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 8.7 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 8.7) 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 8.7, 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:

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

Table 8.7: Defuzzification and normalization results for the sustainability criteria (SI & SA) using GCFI method

Criteria code	Fuzzy numbers for the 'best alternative' $(\widetilde{V})$	Defuzzied Value $F(\widetilde{A})$	Normalized weights – for NB $N(\widetilde{A})$	Weights global (*SA*) – for NB WG_j	Normalized weights – for EB $N(\widetilde{A})$	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**	

Criteria code	Fuzzy numbers for the 'best alternative' $(\widetilde{V})$	Defuzzied Value $F(\widetilde{A})$	Normalized weights – for NB $N(\widetilde{A})$	Weights global (*SA*) – for NB WG_j	Normalized weights – for EB $N(\widetilde{A})$	Weights global (*SA*) – for EB WG_j
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.

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.

8.4.1.4 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 8.4.1.5). 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).

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

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

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

8.4.1.5 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 C4. The proposed BSAM certification grade system is a scale from (0) to (100) which accommodates the six sustainability certification grades. Figure 8.5 shows the six certification grades and their respective BSER values (grade 1= unclassified; 2= acceptable; 3= good; 4= very good; 5= excellent; 6= outstanding).

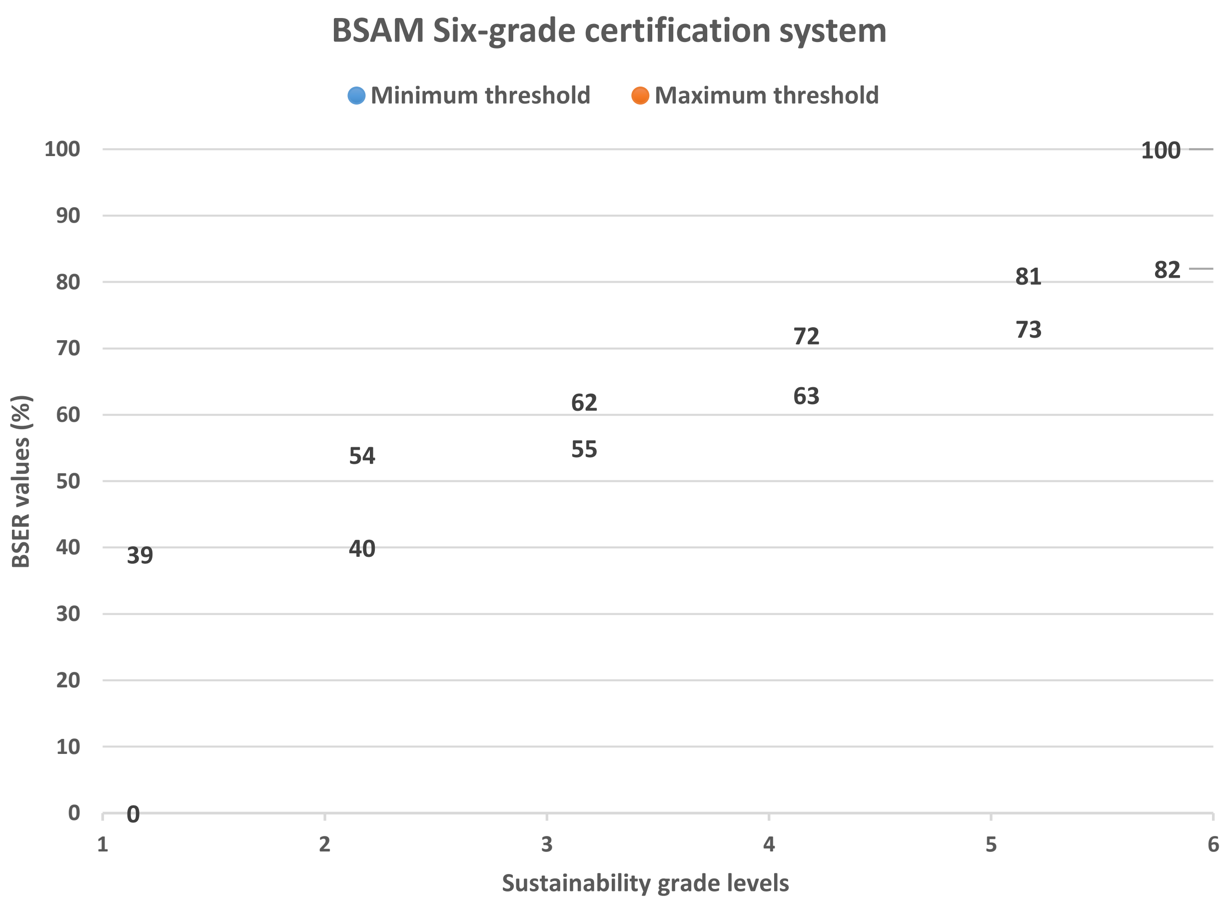


Figure 8.5: BSAM Six-grade certification system: showing the grade levels and corresponding BSER values

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).

8.4.2 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.

8.4.2.1 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 composed of two units of duplex apartments. The SNN building has a gross area of 896.041m^2 consisting 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, 2019c) forms an integral part of the assessment process.

8.4.2.2 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 8.8 for the NB case studies and Table 8.9 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.

Table 8.8: Building Sustainability Evaluation Index (BSEI) – for the two New Buildings Case Studies

Sustainability Indicators (SI)	SI Normalized Weight $N(\widetilde{A})$	Sustainability Attributes (SA)	SA Normalized Weight $N(\widetilde{A})$	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 8.9: Building Sustainability Evaluation Index (BSEI) – for the two Existing Buildings Case Studies

Sustainability Indicators (SI)	SI Normalized Weight $N(\tilde{A})$	Sustainability Attributes (SA)	SA Normalized Weight $N(\tilde{A})$	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	0.1361	2	3	0.0907	0.1361
		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
Energy (C)	0.1469	C1	0.3240	0.0476	6.5	10	0.3093	0.4758	7.5	10	0.3569	0.4758
		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
Water (D)	0.1318	D1	0.3713	0.0489	6	6	0.2937	0.2937	3.5	6	0.1713	0.2937
		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
Material and Waste (E)	0.1463	E1	0.2572	0.0376	4	5	0.1506	0.1882	5	5	0.1882	0.1882
		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
Transportation (F)	0.1486	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
Indoor Environmental Quality (IEQ) (G)	0.1425	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
Building Management (H)	0.1409	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%**	

8.4.3 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 8.8.10 for further illustration.

Table 8.10: 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 (2019c)
Key social sustainability criteria - like *education, awareness, stakeholder relation, inclusiveness, employment*	None	In detail	Liu et al. (2013); Shari (2011)
Key economic sustainability criteria - *like local economy, re-use etc.*	Little or no focus	In detail	Ali and Al Nsairat (2009); Liu et al. (2013); Wei et al. (2011)
Cultural aspect - such as *cultural heritage in design*	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 (2019c); Sev (2009)
Material and waste criterion (*at the construction phase*)	None	In detail	Olawumi and Chan (2019c)
Weighting methodology – *robustness and capability of the method to express the interaction among the sustainability criteria*	"aggregation of points" method – *incapable of expressing interaction*	GCFI method *– see section 8.3.3*	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)

8.5 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 8.5.1).

(ii) The BSER values and sustainability grade levels of the four case studies (section 8.5.2) based on the determination of the BSEI (model validation).

8.5.1 Weights of the key sustainability criteria

The weights of the key sustainability criteria (A – H) are presented in Table 8.7 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 8.7, 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 8.5 and 8.6, 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.

8.5.2 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 8.8 and 8.9, 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 8.8. 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 8.8, and for the FT building, the values are 4.6595 and 6.6288 respectively as presented in Table 8.9. 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 8.8; where for the SNN and FT buildings, the BSER values are 75.33% and 70.29% respectively as shown in Table 8.9. Therefore, the two new buildings such as CE duplex and RA lab 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 8.5 and discussed in section 8.4.1.5.

More so, for the new buildings as shown in Table 8.8, 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 8.9), 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 8.8 and 8.9. 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

8.6 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 allows for the comparative assessment of building designs and models which can help stakeholders 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 the 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.

8.7 Chapter Summary

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 GCFI method was employed to determine the importance weights of the sustainability assessment criteria in this chapter. 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. The following chapter focuses on the development of a cloud-based system to enable a dynamic and automated assessment of the sustainability performance of building projects.

CHAPTER 9: DEVELOPMENT OF A CLOUD-BASED SUSTAINABILITY DECISION SUPPORT SYSTEM (C-SDSS): A DIGITALIZED AUTOMATED GREEN BUILDING SUSTAINABILITY ASSESSMENT TOOL[9]

9.1 Chapter Overview

The previous chapter employed the generalized Choquet fuzzy integral (GCFI) method – to determine the weights of the sustainability criteria and develop the sustainability evaluation index of the BSAM scheme. The current chapter develop a Cloud-based Sustainability Decision Support System (C-SDSS) to facilitate the assessment of the sustainability performance of green buildings. The C-SDSS platform will be developed using various high-level programming languages such as PHP, Jscript, etc. and relational databases. The primary green building rating system to be used on the C-SDSS platform is the BSAM scheme – which was developed in chapters 7 and 8 and purposely designed specifically for the sub-Saharan region of Africa and which holistically considered the social, economic, and environmental sustainability criteria. Also, the proposed C-SDSS platform will permit the comparison of green building projects' sustainability credentials on the cloud-based system.

9.2 Development and methodology of C-SDSS platform: Main features and graphical user interfaces (GUI)

The C-SDSS platform is a dynamic and automated tool developed in this study with the intent to facilitate the evaluation of the sustainability performance of green buildings within the context of the sub-Saharan region of Africa. The C-SDSS platform as an automated and dynamic digital (web-based) tool is programmed and developed using a high-level language such as PHP (Hypertext Pre-processor), Jscript, and other open-source languages such as HTML, CSS, etc.

The C-SDSS platform is regarded as a decision support system as it is designed to aid relevant project stakeholders, and assessors in the evaluation of the sustainability performance of green building projects. Apart from its key functionality to establish the sustainability rating or performance of a building project; the C-SDSS

[9] This chapter is fully reported in this working paper:
Olawumi, T.O., & Chan, D.W.M. Development of a Cloud-based Sustainability Decision Support System (C-SDSS): A Digitalized Automated Green Building Sustainability Assessment Tool.

platform has the functionality to compare the sustainability performance of two or more building models or design (*as later illustrated via case studies of building projects in Section 9.3.2.3*) which can help the users/assessors to decide on the most or better building design or model for a construction project. Also, government agencies or clients can use this ‘compare projects’ functionality of the C-SDSS platform (see Figure 9.3) to decide on the most suitable project bid for their building projects.

Also, the developed C-SDSS platform is available for use in any operating system, whether for computers, mobile phones, tablets, etc. since the C-SDSS platform is designed to be accessible by any web browser. The PHP high-level language is used basically to handle the server-side functionalities for the C-SDSS platform while the Jscript handles both the server-side and client-side functionalities. The HTML is a mark-up language while the CSS is a style sheet language.

More so, as discussed in chapters 7 and 8, the BSAM scheme – which was developed specifically for the sub-Saharan region of Africa – is the primary green rating system adopted and integrated within the C-SDSS platform. However, the BSAM scheme has a limitation common to the existing green rating tools such as LEED, BREEAM, etc. – which is the use of aggregation of points methodology in their sustainability assessment of green buildings; which does not cater for the interdependence and interactions among the sustainability criteria (Ahmad & Thaheem, 2018; Mahmoud et al., 2019).

Hence, to ameliorate this limitation of the BSAM scheme before its integration within the C-SDSS platform developed in this study – the BSAM scheme green rating system’s sustainability assessment algorithm was improved using the Generalized Choquet Fuzzy Integral (GCFI) technique. See Dong et al. (2016), Kurt (2014), and Ozdemir and Ozdemir (2018) for more details on the GCFI methodology and its advantages. Therefore, the GCFI techniques were coded using PHP programming languages during the development of the green building sustainability assessment interfaces of the C-SDSS platform as later discussed in Section 9.2.1.3 and illustrated partly in Figure 9.7.

9.2.1 C-SDSS main features

The C-SDSS platform was coded on the Adobe Dreamweaver software and hosted on WampServer – which serves as the local server for the C-SDSS during the development phase of the C-SDSS platform. Apart from the Dreamweaver software, WampServer, the C-SDSS, also integrates a relational database – MySQL – which all were used for the coding and optimization process, data entry and storage management, green building sustainability assessment, information and documentation, and output displays. The C-SDSS platform only requires the installation of web-browsers – which comes pre-installed on all mobile devices, desktop computers, and laptops; and it requires access to Wi-Fi access to utilize the dynamic tool. Its functionality is not dependent on the type of web browser used, or any software or operating system deployed.

Hence, the C-SDSS platform can be divided into five tiers based on its features as follows.

9.2.1.1 Coding and optimization process

The coding, design, and development of the C-SDSS platform is undertaken within the Dreamweaver software using the various programming languages (PHP, Jscript, etc.). Codes were written to design and handle the data entry and storage in the MySQL relational database and to develop the C-SDSS platform – where the actual green building sustainability assessment, display of various outputs, and the documentation of the BSAM scheme is resident. Meanwhile, optimization and verification procedures were undertaken to ensure the various coded and designed features of the C-SDSS platform perform effectively (as designed) on all web browsers such as Google Chrome, Microsoft Edge, Internet Explorer, Mozilla Firefox, Opera, etc.

9.2.1.2 Data entry and storage management

This feature links the C-SDSS platform and its process interfaces with the server-based MySQL databases which allow the input of the various weightings of the BSAM scheme green rating system into the MySQL databases; and also allows for users to enter the relevant project information necessary for the sustainability assessment of such projects as well as the comparative assessment of alternative building designs. Hence, during the automated calculation of the sustainability performance of a green building project, these data in the relational databases are systematically linked and used in the evaluation process. Two main relational databases were used, which has a combined 138 data-filled tables.

The first one – with 129 relational tables – stores data relating to the BSAM scheme green rating system such as the weightings for the BSAM criteria (that is, its three-level hierarchical structure of sustainability indicators, attributes, and sub-attributes); and other results of the GCFI algorithm which were used to calculate the building sustainability evaluation ratio (BSER) of the BSAM scheme. The second database – with nine (9) relational tables – stores information related to the users, project details (description, GFA, owner, project type, etc.), browser cookies, results of the sustainability assessment based on the BSAM scheme, among others. When a project is being registered on the C-SDSS platform, a project identification (ID) is generated for such a project, and the project ID is used in subsequent evaluations of such building project. The data entry feature also includes the 'user registration' and 'sign-in' pages as well as the 'project registration' page (see Figure 9.6). The 'Delete projects' page (Appendix E1) also provides an interface for the user or assessor to delete a building project details and sustainability assessment results from the second relational database of the C-SDSS platform.

9.2.1.3 Green building sustainability assessment

This feature is one of the key features of the C-SDSS platform as it automatically handles the assessment of the sustainability assessment of the building projects based on the BSAM scheme green rating system. It consists of a few interfaces highlighted and illustrated in Section 9.2.2.2. One of the interfaces, the "*Indicator (A-H)*" (steps D and E, as shown in Figure 9.4) allows the green building project assessor to input values (using the drop-down options list) for the sustainability criteria A-H based on the BSAM scheme documentation (Olawumi & Chan, 2019c) (see Appendix A). Before assessing the sustainability performance of a building project, the user must select the project classification type (step B, Figure 9.4) – whether it is a new building or an existing building – based on BRE (2018) classification. For each sustainability criteria, an excerpt of the BSAM documentation is provided; the excerpts contain a brief description of the sustainability criteria, the total points attainable under the criteria, how the points are allocated, and the relevant documentary evidence required for the attainment of such sustainability criteria of the BSAM scheme.

A button, "*Submit Assessment*" (step D, Figure 9.4) is provided at the end of each web interface of the criteria A-H, once this button is clicked; two project-specific metrics are automatically calculated for each of the sustainability criteria based on the GCFI algorithm (Ozdemir & Ozdemir, 2018) which are – the calculated points and factor indexes. After the building project has been evaluated based on the eight BSAM sustainability criteria; the C-SDSS platform automatically calculates the BSER value, the Building Sustainability Evaluation Index (BSEI) for the green building, its overall certification grade, and plot the line graph (*using the project's sustainability indicators' BSER*), and the gauge graph (*using the overall project's BSER*) for the building project (see Figure 9.2). The BSAM scheme green rating scheme (Olawumi & Chan, 2019c) has a six-grade certification system which are Outstanding (82-100); Excellent (73-81); Very good (63-72); Good (55-62); Acceptable (40-54); Unclassified (0-39).

9.2.1.4 Information and documentation

This information and documentation feature of the C-SDSS platform provides general information about the overall project aim, scope, and objective; it also details the full documentation of the BSAM scheme green building rating system designed for the sub-Saharan region (including a PDF plug-in for the BSAM scheme documentation) as well as a link to the online repository for the BSAM scheme. This feature also entails the "About" webpage, which provides information about the authors and their profiles, and include a "Contact" page to get necessary feedback about the C-SDSS from the authors.

9.2.1.5 Output displays

This C-SDSS key feature display three sets of relevant information and outputs which are presented on the 'View Project SER,' 'Compare Projects,' and 'Green projects' interfaces. The 'Green projects' interface (see Figure 9.1) is the main homepage of the C-SDSS platform (see Section 9.2.2.1); once the user sign-in into the C-SDSS, the user will be led to this interface. The 'Green Projects' page is populated by building projects which been registered by the user on the C-SDSS platform via the ‘project registration’ interface. For each project registered on the cloud platform, an identifiable project ID is generated for each building project. More so, the ‘Green Projects’ interface has four main gateways (buttons) to the C-SDSS platform, which are the “Assess Project,” “View Project SER,” “Compare Project,” and the “Delete Project(s)” buttons (see Figure 9.4). Each populated and registered building project on the ‘Green Projects’ interface has an attached ‘checkbox’ (*on the left-top corner of the building project details*) which must be checked to assess the project, view its assessment result, compare the projects, or the delete project(s). If a building project is not checked before clicking on the four main buttons on the ‘Green projects’ interface, an error message is displayed.

The ‘View Project SER’ interface (see Figure 9.2) allows the user to view the sustainability assessment result of the ‘checked’ building project. For the user to navigate to this interface, the “View Project SER” button on the ‘Green projects’ interface must have been clicked. On the ‘View Project SER’ interface, relevant sustainability assessment results such as the BSER values for the sustainability indicators and attributes are presented as well as the factor indexes for the sub-attributes. Also, presented on the ‘View Project SER’ interface is the overall certification grade, the line graph (*which is plotted based on the project’s sustainability indicators’ BSER*), and the gauge graph (*plotted using the overall project’s BSER*) of the assessed green building project.

9.2.2 C-SDSS graphical user interfaces (GUI)

This section illustrates the various GUI of the C-SDSS main features highlighted and described in Section 9.2.1.

9.2.2.1 Output displays GUI

As discussed in Section 9.2.1.5, the output displays feature presents three sets of relevant outputs which are the ‘View Project SER’ (Figure 9.2), ‘Compare Projects’ (Figure 9.3), and ‘Green projects’ outputs pages; of which the ‘Green projects’ is the main homepage (see Figure 9.1) of the C-SDSS platform.

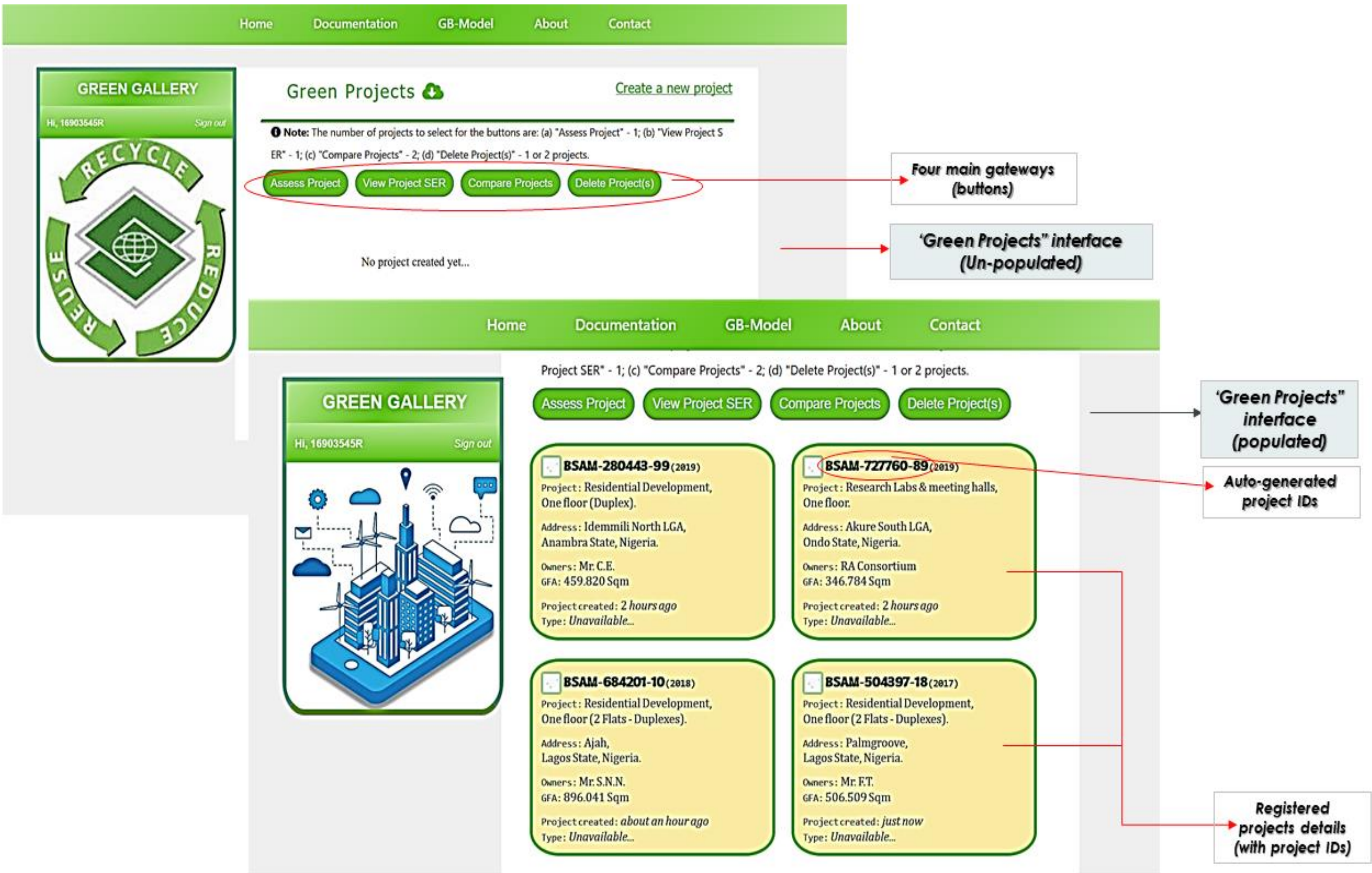


Figure 9.1: "Green Projects" GUI

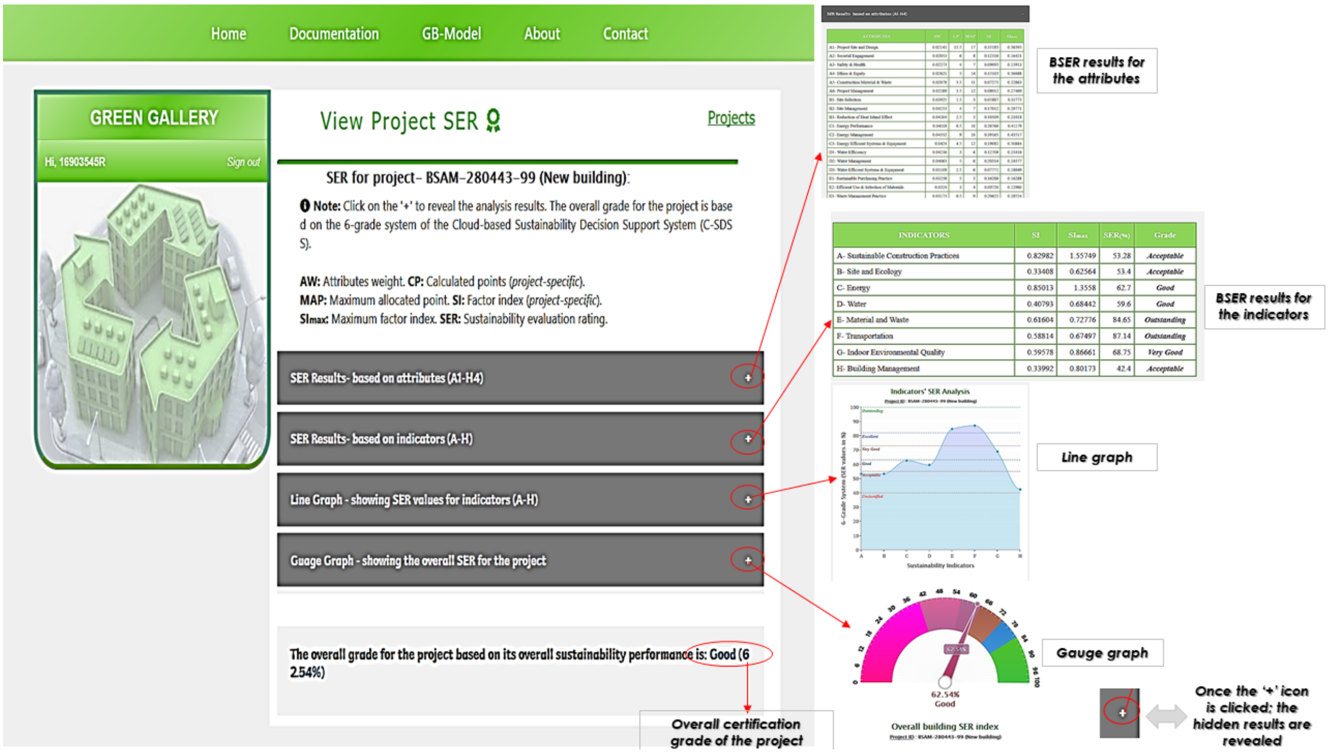


Figure 9.2: "View Project SER" GUI

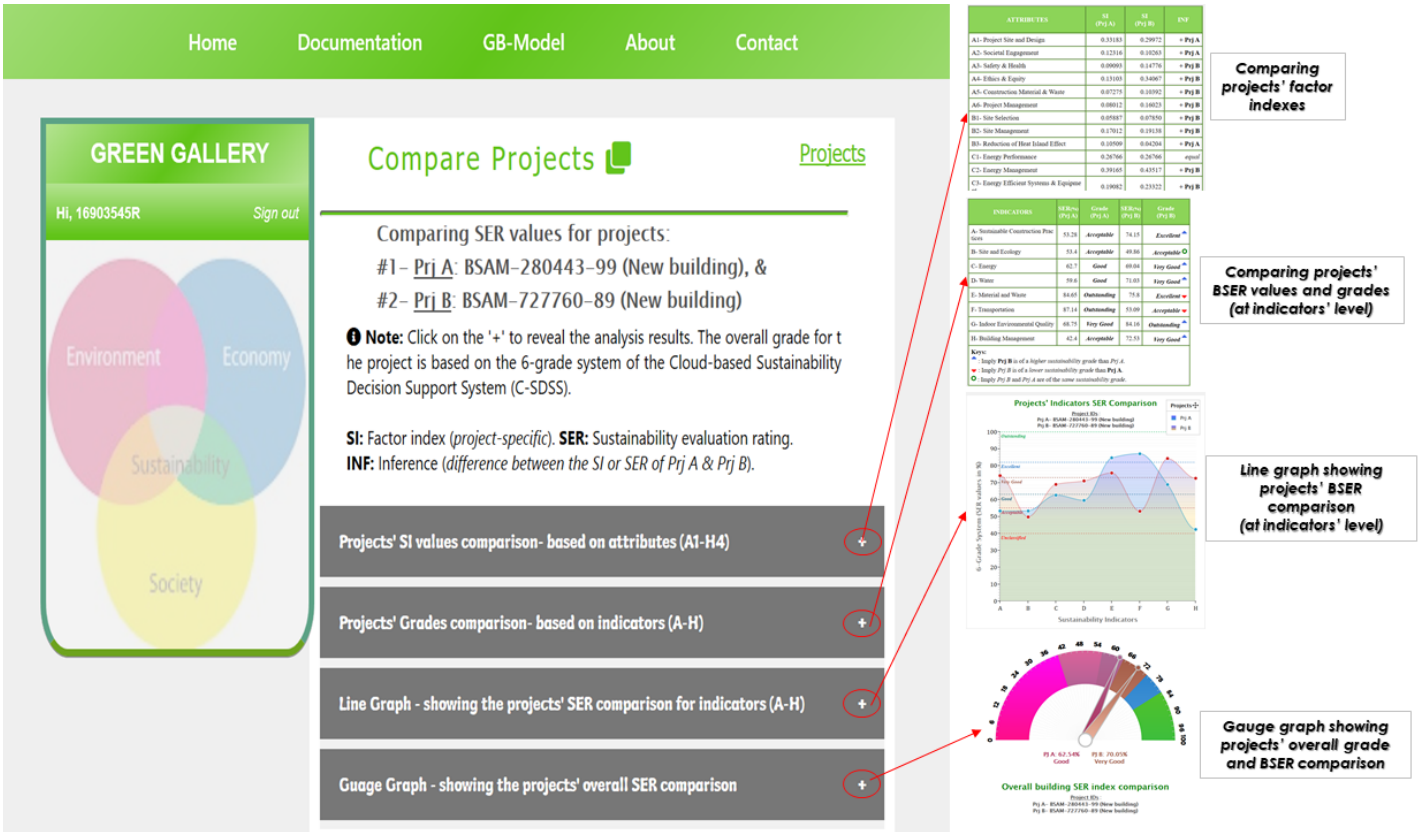


Figure 9.3: "Compare Projects" GUI

9.2.2.2 Green building sustainability assessment GUI

As expatiated in Section 9.2.1.3, towards assessing the sustainability performance of a building project registered under the C-SDSS platform and based on the developed BSAM scheme for the sub-Saharan region, a number of processes (steps A – G) are involved as illustrated in Figure 9.4. In step A (see Figure 9.4), on the "Green Projects" GUI which displays the C-SDSS registered projects; the user or assessor needs to select the building project to be assessed and clicked the "Assess Project" button which will lead the user to the next interface – "building classification" GUI. At the step B (see Figure 9.4), which is the "building classification" interface; the user selects the building project classification type – whether it is a new building or an existing building – based on BRE (2018) classification; and then the user must click the "Start Assessment" button to navigate to the next stage of assessment.

The next phase of assessment (step C) occurs at the "Green Indicators" interface, which contains eight weblinks for the eight sustainability criteria of the BSAM scheme as shown in Figure 9.4. Each link leads the user to eight interfaces (steps D

& E) where the building project can be evaluated based on the BSAM documentation (Olawumi & Chan, 2019c). Once a sustainability indicator has been assessed for a building project – say indicator A as shown in step F (Figure 9.4) – a green mark appears in front of the sustainability indicator weblink. As discussed in section 9.2.1.3 and as shown in step E (Figure 9.4), for each sustainability criteria being assessed, an excerpt of the criteria from the BSAM documentation is provided.

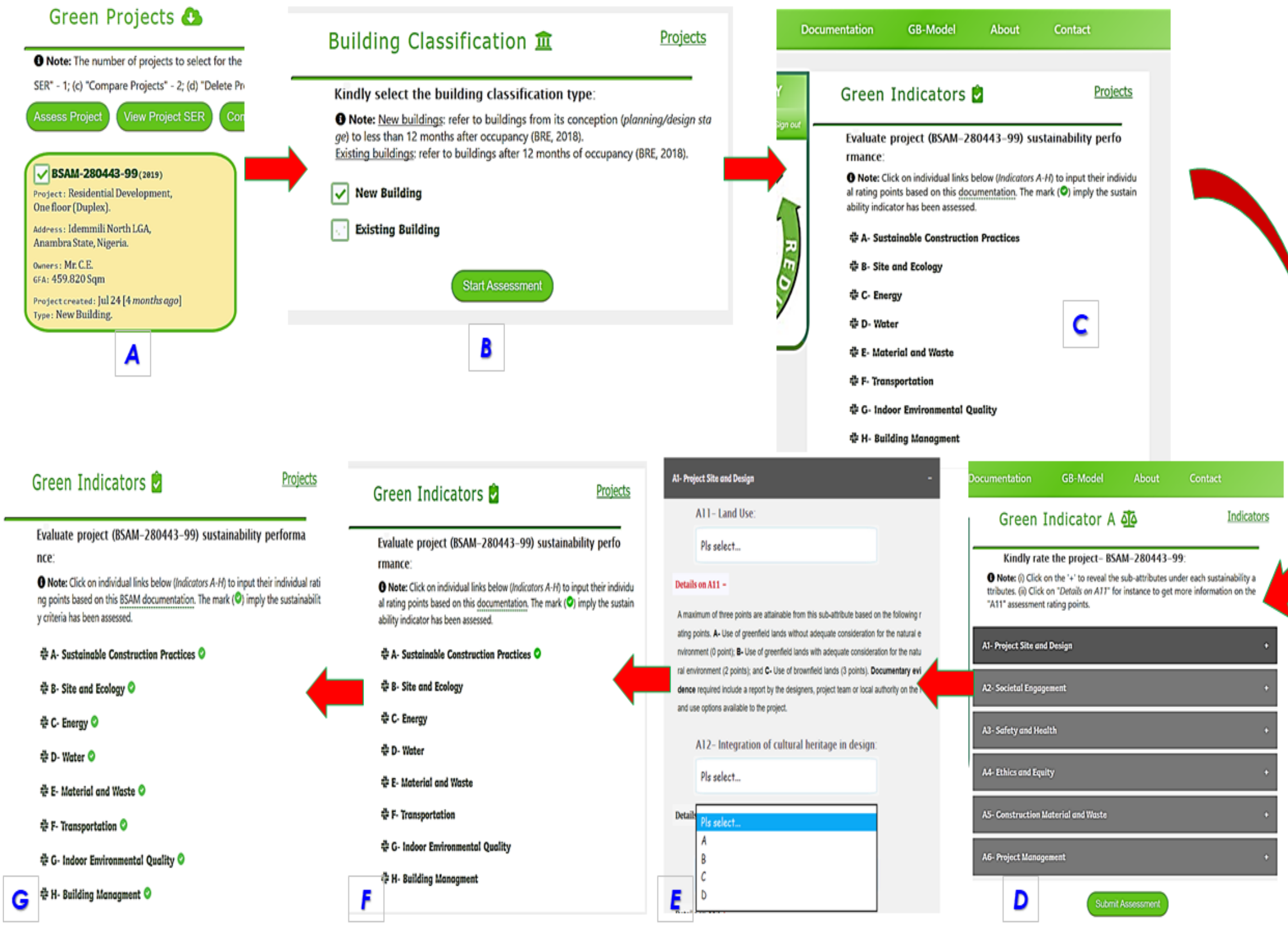


Figure 9.4: Green Building Sustainability Assessment GUIs

9.2.2.3 Data entry and storage management GUI

As discussed in Section 9.2.1.2, these GUI illustrates how the various data entries and their storage within the two MySQL relational databases are integrated with the C-SDSS platform. Figure 9.5 shows the MySQL relational databases of the C-SDSS platform while the “Project Registration” interface – a data entry GUI – is illustrated in Figure 9.6. Once the “Register Project” button on the “Project Registration” GUI is clicked, the building project details are registered in the MySQL database of the C-SDSS platform. All the other data entries GUI are illustrated in Appendix E1.

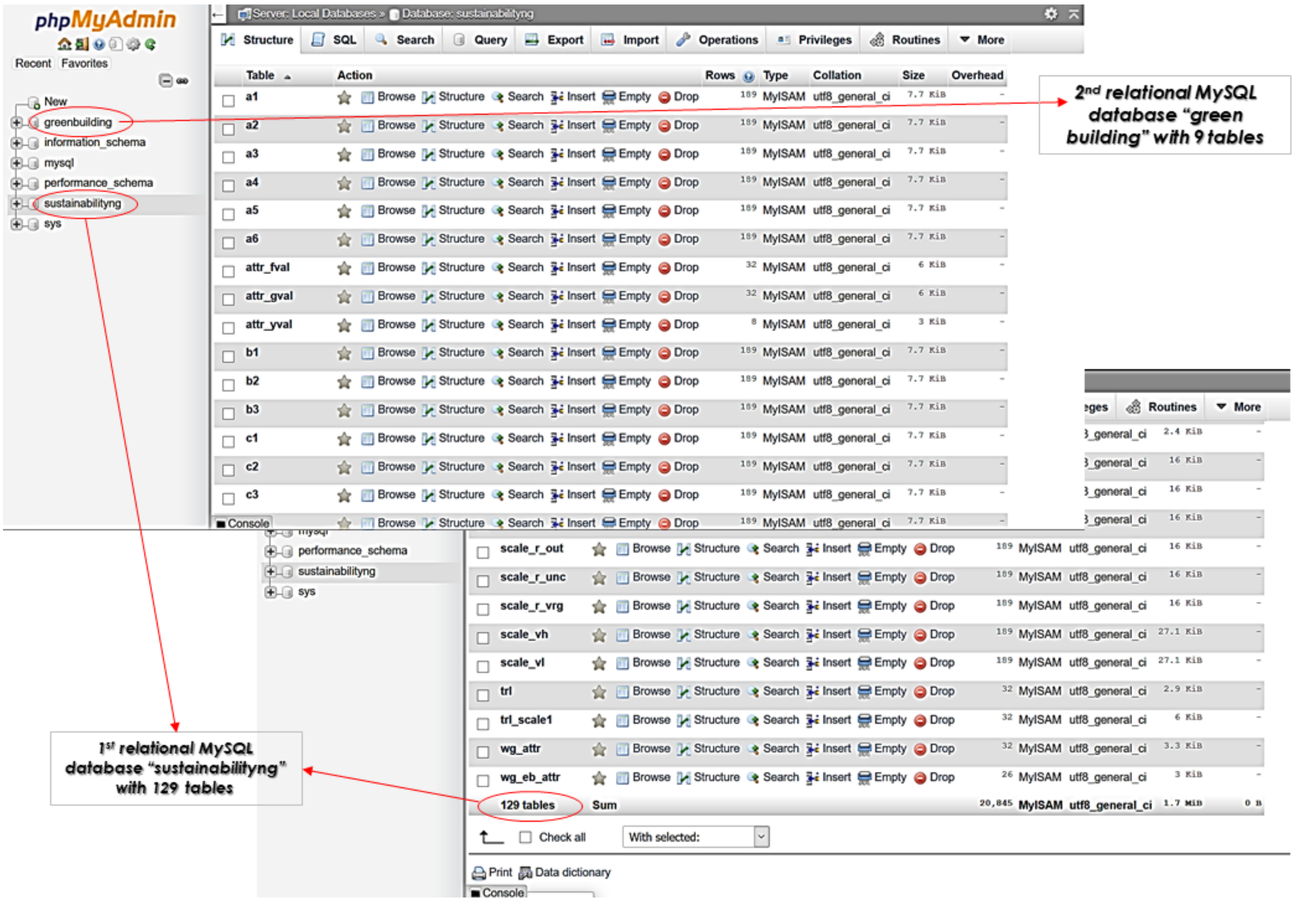


Figure 9.5: MySQL relational databases GUI for the C-SDSS platform

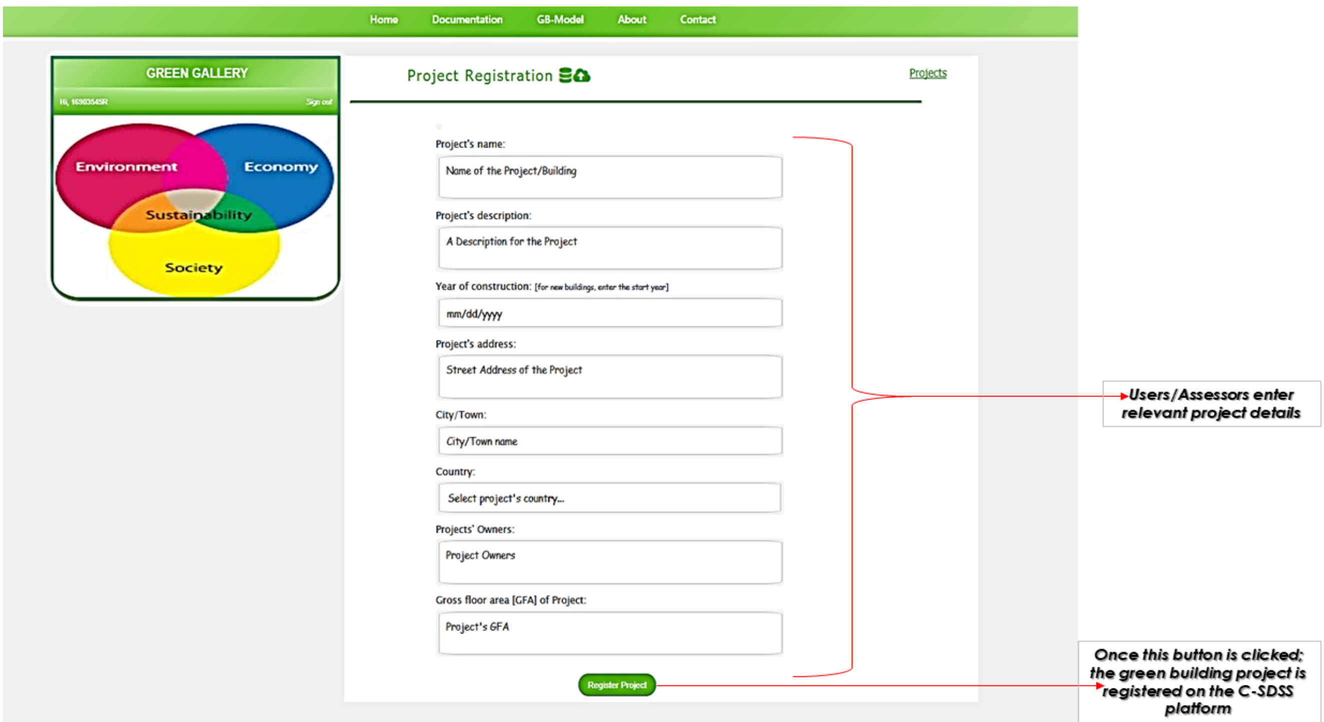


Figure 9.6: "Project Registration" GUI

9.2.2.4 Coding and optimization process GUI

As explained in Section 9.2.1.1, the coding, development, and optimization of the C-SDSS platform were undertaken within the Adobe Dreamweaver software using PHP (version 5.6), Jscript, and other programming languages. Figure 9.7 shows a part of the coding for the calculation of the fuzzy measures based on the GCFI algorithm which was used to calculate for the BSEI and BSER values of the BSAM scheme green rating system. Appendix E2 reveals the interfaces of other GUI of the coding and optimization process.

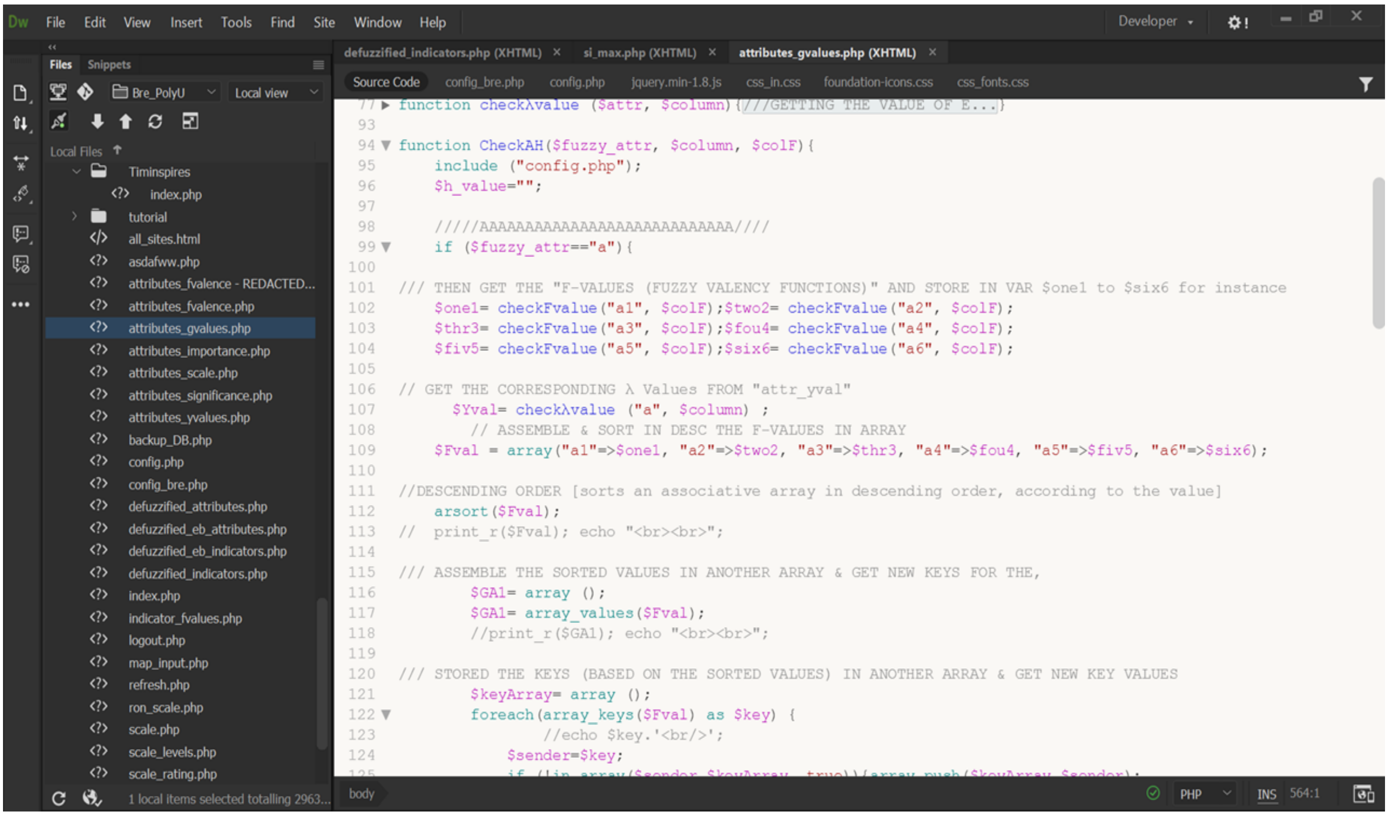


Figure 9.7: Code reading for the calculation of the fuzzy measures (GCFI algorithm)

9.3 Validation and Verification of the C-SDSS platform

This section discusses the verification and validation processes undertaken to confirm the suitability, adequacy, and practicality of the C-SDSS platform as a dynamic and automated tool for the evaluation of the sustainability performance of green buildings in the sub-Saharan region of Africa. As discussed in Section 9.2, the C-SDSS platform consisted of five key features of which the BSAM scheme is the primary green rating system on which the building projects are assessed and certified on the C-SDSS platform. According to Yang et al. (2011), verification means "doing things right," while validation means "doing the right things."

Hence, both the BSAM scheme and C-SDSS platform verification and validation processes are discussed here – which are (1) the verification of the C-SDSS platform; (2) use of four real-life building project case studies to validate the C-SDSS platform; and (3) Experts' validation of the C-SDSS platform (*inclusive of the BSAM scheme*).

9.3.1 Verification of the C-SDSS platform

Verification has defined in terms of computerized systems (*of which the C-SDSS platform is one*) means – ensuring that the codes, design, and program of the developed computerized model and its implementation are appropriate and correct (Kleijnen, 1995; Yang et al., 2011).

In verifying, the authors utilize the in-built code verification function of Adobe Dreamweaver software, which helps to check for and locate probable errors in the codes used in the development of the C-SDSS platform. Also, the default error reporting value in the PHP Apache configuration file was not overridden, which allows the authors to effectively review and address likely errors from the coding of the C-SDSS platform using the PHP high-level language. Also, the C-SDSS platform was optimized using appropriate codes to ensure the C-SDSS works effectively and smoothly on every web browsers and operating systems. Finally, the C-SDSS platform codes, interfaces, and design were optimized and verified to ensure they are correct, free of flaws, and errors.

9.3.2 Case study building projects' validation exercise

In order to validate the developed C-SDSS platform and its features, the study utilized four real-life building projects – two of which can be classified as "new buildings" (NB), and the other two can be classified as "existing buildings" (EB) according to BRE (2018) classification. As earlier mentioned, the BSAM scheme is the primary green rating system on the C-SDSS platform (see Section 9.2). More so, the BSAM scheme has eight sustainability indicators (A – H); while, the eight indicators are assessed for new buildings, only sustainability indicators B – H are evaluated for the existing buildings.

9.3.2.1 Case study building projects' descriptions and documentary evidences

Table 9.1 shows the descriptions and project details of the four-case study building projects. More so, as part of the requirements to use the BSAM scheme green rating system to assess the sustainability performance of a building project, necessary documentary evidence must be secured (Olawumi & Chan, 2019c). Part of the documentary evidence is the BIM model, CAD drawing, utility records (e.g. energy, water, waste, etc.), building specifications, site layouts, etc. More so, according to Mahmoud et al. (2019) and has evidenced in the sustainability assessment process of the existing green rating systems such as LEED, BREEAM, etc., reasonable assumptions can be made if a piece of documentary evidence is missing. The necessary documentary evidences for the four-case study building projects were secured, and the C-SDSS platform (along with the BSAM scheme) was then used to assess the sustainability performance of the projects, as discussed in Section 9.2.1.3 and Section 9.2.2.2.

Table 9.1: Descriptions of the four-case study building projects

Description	**New Buildings**		**Existing Buildings**	
Code	**CE duplex**	**RA labs**	**SNN building**	**FT building**
Description	One-storey residential building	One-storey commercial facility	One-storey buildings (2 units of duplexes)	One-storey buildings (2 units of duplexes)
Location	Anambra State, south-eastern region, Nigeria	Ondo State, south-western region, Nigeria	Lagos State, south-western region, Nigeria	Lagos State, south-western region, Nigeria
Gross Floor Area (GFA, m^2)	$459.820m^2$	$346.784m^2$	$896.041m^2$	$506.509m^2$
Green Area (m^2)	$183.928m^2$ (40% of the GFA)	$34.581m^2$ (10% of the GFA)	$89.604m^2$ (10% of the GFA)	$202.581m^2$ (40% of the GFA)
Paved Area (m^2)	$141.483m^2$	-	$420.064m^2$	$101.403m^2$
Project IDs (***as generated on the C-SDSS platform***)	BSAM-280443-99	BSAM-727760-89	BSAM-684201-10	BSAM-504397-18

9.3.2.2 Sustainability assessment of the case study projects on the C-SDSS platform

The sustainability assessment of the four-case study projects was undertaken on the C-SDSS platform based on the BSAM scheme green rating system. Figures 9.8 and 9.9 reveals the result of the sustainability analysis of the NB and EB case study projects respectively after the “View Project SER” button on the “Green Projects” interface is clicked; while Figure 9.10 revealed the comparative assessment of the case study projects after the “Compare Projects” button on the “Green Projects” interface is clicked – as discussed in Section 9.2.1.5 and Section 9.2.2.1. More so, after these four case study projects were registered on the C-SDSS platform, identifiable project IDs were generated for each of the projects, as presented in Table 9.1.

As shown in Figure 9.8, the two NB projects – CE duplex and RA labs have an overall BSER value of 62.54% and 70.05% and certification grade of “*Good*” and “*Very Good*” respectively based on the sustainability evaluation result of the two building projects undertaken on the C-SDSS platform (see gauge graphs “C”, Figure 9.8). Similarly, as shown in Figure 9.9, the two EB projects – SNN building and FT building have an overall BSER value of 75.33% and 70.29% and certification grade of “*Excellent*” and “*Very Good*” respectively based on the sustainability evaluation result of the two building projects undertaken on the C-SDSS platform (see “C”, Figure 9.9).

SER Results- based on indicators (A-H)

INDICATORS	SI	SImax	SER(%)	Grade
A- Sustainable Construction Practices	0.82982	1.55749	53.28	Acceptable
B- Site and Ecology	0.33408	0.62564	53.4	Acceptable
C- Energy	0.85013	1.3558	62.7	Good
D- Water	0.40793	0.68442	59.6	Good
E- Material and Waste	0.61604	0.72776	84.65	Outstanding
F- Transportation	0.58814	0.67497	87.14	Outstanding
G- Indoor Environmental Quality	0.59578	0.86661	68.75	Very Good
H- Building Management	0.33992	0.80173	42.4	Acceptable

SER Results- based on indicators (A-H)

INDICATORS	SI	SImax	SER(%)	Grade
A- Sustainable Construction Practices	1.15493	1.55749	74.15	Excellent
B- Site and Ecology	0.31192	0.62564	49.86	Acceptable
C- Energy	0.93605	1.3558	69.04	Very Good
D- Water	0.48615	0.68442	71.03	Very Good
E- Material and Waste	0.55166	0.72776	75.8	Excellent
F- Transportation	0.35837	0.67497	53.09	Acceptable
G- Indoor Environmental Quality	0.7293	0.86661	84.16	Outstanding
H- Building Management	0.58153	0.80173	72.53	Very Good

Figure 9.8: C-SDSS results of the sustainability analysis of the NB case study projects

Note: SI: Factor index (*project-specific*); **SI$_{max}$:** Maximum factor index; **SER:** Sustainability evaluation ratio; **Grade:** Based on the BSAM scheme certification grade system.

More so, to better present the results of the sustainability assessment of the projects, "A" and line graphs "B" in Figures 9.8 and 9.9 reveals the breakdown of the results for each of the sustainability indicators (of the BSAM scheme) for the NB and EB building projects respectively; it shows the BSER value and certification grade for the four building projects' sustainability indicators as well as a line graph (see "B", Figures 9.8 & 9.9) plotting the BSER value of the projects' sustainability indicators (on the x-axis) against the certification grade levels (y-axis). The six shades of color as seen in the gauge graphs "C" in Figures 9.8 and 9.9 are the six-grade certification grade system of the BSAM scheme.

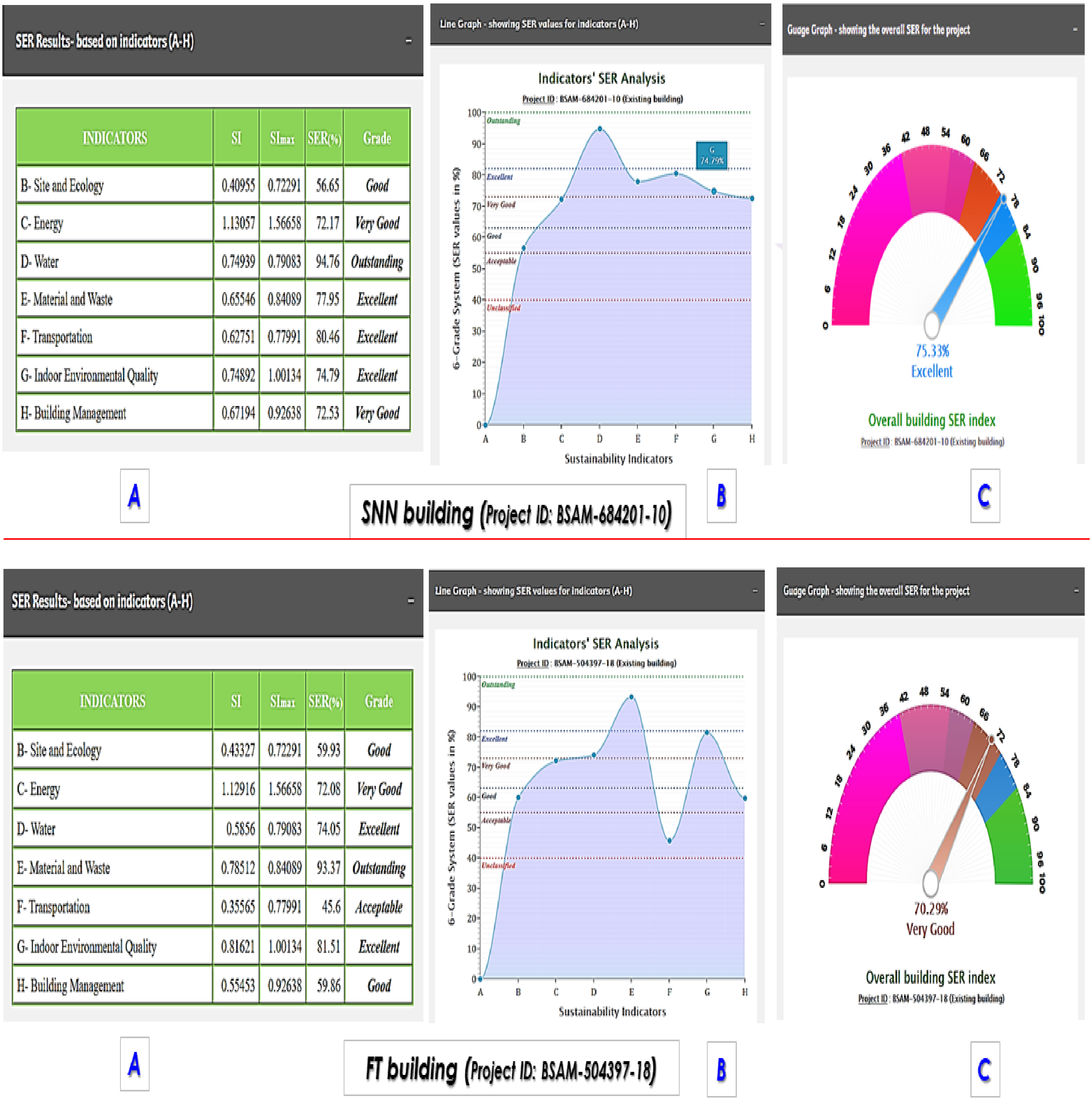


Figure 9.9: C-SDSS results of the sustainability analysis of the EB case study projects

9.3.2.3 Comparative sustainability assessment of the case study projects

The C-SDSS platform (based on the BSAM scheme green rating system) can be used to compare two green building projects at a time. The comparative assessment of the green building projects on the C-SDSS platform are based on a three-tier of comparison, which are – (1) comparing the factor indexes (SI) values of the sustainability attributes of the green building projects; (2) comparing the BSER values and grades of the sustainability indicators of the building projects (see “A” & line graphs “B”, Figure 9.10); and (3) comparing the overall BSER values and grades for the green building projects (see gauge graphs “C”, Figure 9.10).

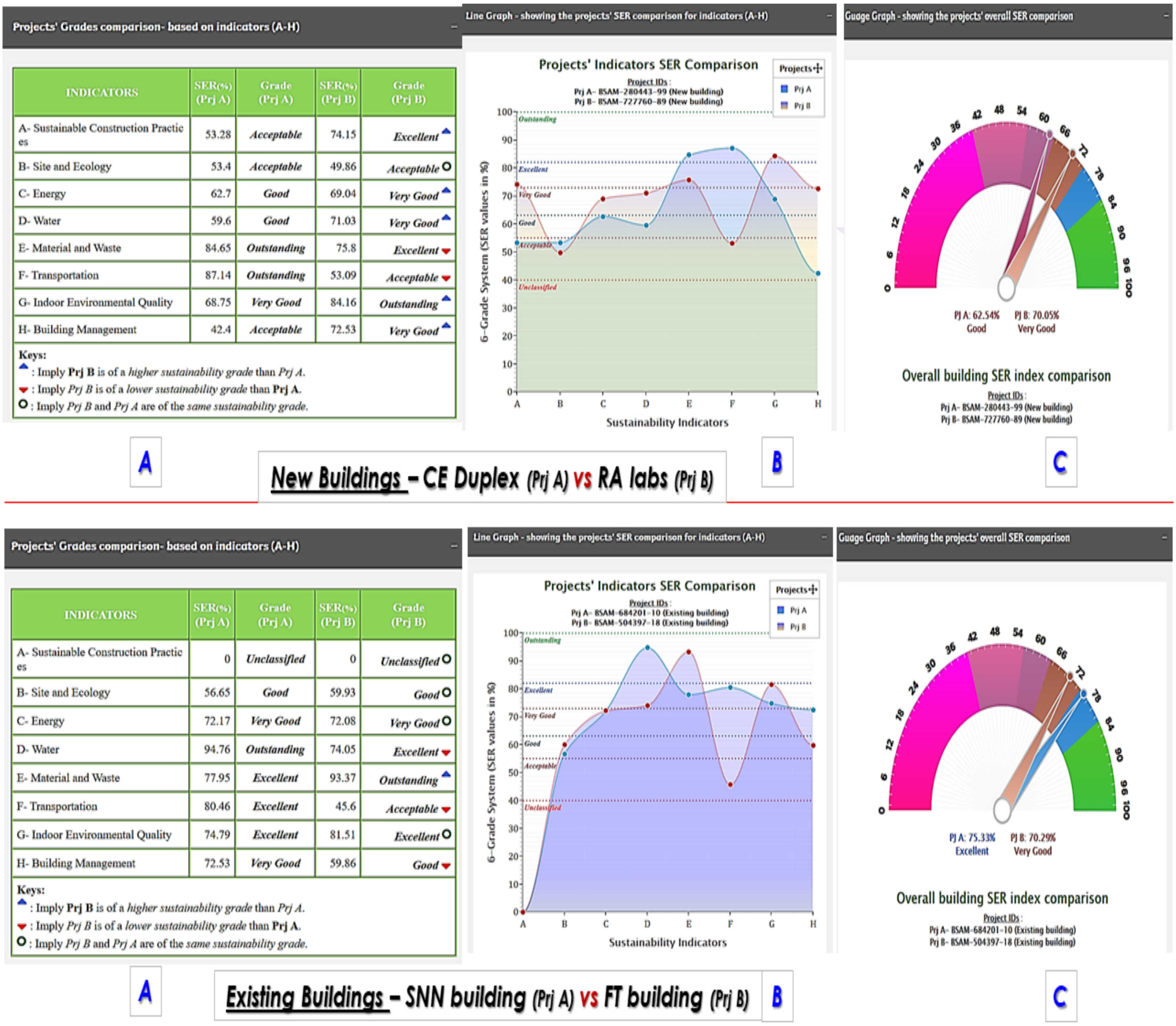
For the first tier of the comparative assessment of the NB and EB case study projects as revealed in Appendix E3. The two NB case study projects – CE duplex and RA labs – have the same SI values (SI = 0.26766) for the sustainability attribute “C1- Energy Performance”. Also, based on the SI values, the RA labs with 20 sustainability attributes of higher SI is preferable compared to the CE duplex with 11 attributes. Moreover, the EB case study projects – SNN building and FT building – have the same SI values in six sustainability attributes (B1, C2, E4, G3, H3, & H4) with SI values of 0.09070, 0.50282, 0.17301, 0.17301, 0.14991, and 0.07165 respectively. However, for the two EB projects, unlike the NB projects, the EB case study projects have 10 sustainability attributes, each with a higher SI than the other. Hence, no difference between the sustainability performance of the EB projects based on SI’s values of their sustainability attributes.

Furthermore, for the second tier of the comparative assessment of the NB and EB case study projects as revealed in “A” and plotted in line graphs “B” in Figure 9.10; the two NB case study projects – CE duplex and RA labs – have different BSER values for the eight sustainability indicators. Hence the building project grades at the indicators’ level were used. As shown in “A” Figure 9.10, the two NB projects have the same certification grade (‘*Acceptable*’) for sustainability indicator “B- Site and Ecology.” More so, based on the NB project indicators’ grade; RA labs have five indicators (A, C, D, G, & H) with higher sustainability grades than CE duplex building – with just two sustainability indicators (E & F) with higher grades. Hence, the RA labs building has superior sustainability performance than the CE duplex.

Moreover, the EB buildings projects – SNN building and FT building – have the same certification grades in three sustainability indicators (B, C, & G); while FT building has only one sustainability indicator (“*E- Material and Waste*”) with a greater certification grade than the SNN building. The SNN building, meanwhile, has three indicators (D, F, & H) with greater certification grades than the FT building. Hence, the FT building has a lower sustainability performance than the SNN building.

Lastly, for the third tier of the comparative assessment of the NB and EB case study projects as revealed in the gauge graphs “C” in Figure 9.10. The two NB case study projects – CE duplex and RA labs – have overall BSER values of 62.54% and 70.05% as well as certification grades of “*Good*” and “*Very Good,*” respectively. These results show the RA labs building has a greater overall sustainability performance than the CE duplex building. Meanwhile, for the two EB case study projects – SNN building and FT building – have overall BSER values of 75.33% and 70.29% as well as certification grades of “*Excellent*” and “*Very Good*” respectively. The comparative assessment for the EB case studies shows the SNN building with a better sustainability performance than the FT building.

Overall, the comparative assessment of the NB and EB case study projects across the three tiers of comparison reveals salient and significant findings at each level of comparative assessment. Across the three-tier of comparative assessment for the NB case study projects, the RA labs building shows increasing record of a higher sustainability performance than the CE duplex building. Meanwhile, for the EB case study projects, the SNN building has a greater sustainability performance than the FT building in the second and third levels of comparative assessment except for the first tier.



Projects' Grades comparison- based on indicators (A-H)

INDICATORS	SER(%) (Prj A)	Grade (Prj A)	SER(%) (Prj B)	Grade (Prj B)
A- Sustainable Construction Practices	53.28	Acceptable	74.15	Excellent ▲
B- Site and Ecology	53.4	Acceptable	49.86	Acceptable O
C- Energy	62.7	Good	69.04	Very Good ▲
D- Water	59.6	Good	71.03	Very Good ▲
E- Material and Waste	84.65	Outstanding	75.8	Excellent ▼
F- Transportation	87.14	Outstanding	53.09	Acceptable ▼
G- Indoor Environmental Quality	68.75	Very Good	84.16	Outstanding ▲
H- Building Management	42.4	Acceptable	72.53	Very Good ▲

Keys:
▲ : Imply Prj B is of a higher sustainability grade than Prj A.
▼ : Imply Prj B is of a lower sustainability grade than Prj A.
O : Imply Prj B and Prj A are of the same sustainability grade.

Projects' Grades comparison- based on indicators (A-H)

INDICATORS	SER(%) (Prj A)	Grade (Prj A)	SER(%) (Prj B)	Grade (Prj B)
A- Sustainable Construction Practices	0	Unclassified	0	Unclassified O
B- Site and Ecology	56.65	Good	59.93	Good O
C- Energy	72.17	Very Good	72.08	Very Good O
D- Water	94.76	Outstanding	74.05	Excellent ▼
E- Material and Waste	77.95	Excellent	93.37	Outstanding ▲
F- Transportation	80.46	Excellent	45.6	Acceptable ▼
G- Indoor Environmental Quality	74.79	Excellent	81.51	Excellent O
H- Building Management	72.53	Very Good	59.86	Good ▼

Keys:
▲ : Imply Prj B is of a higher sustainability grade than Prj A.
▼ : Imply Prj B is of a lower sustainability grade than Prj A.
O : Imply Prj B and Prj A are of the same sustainability grade.

Figure 9.10: Comparative assessment of the NB and EB cases study projects respectively on the C-SDSS platform

In practice, in a case of a building design or model, a client or project team might prefer to use the second tier of comparative assessment (the sustainability indicators) to choose the best building design for their construction project. For instance, for the NB case studies, (*let's assume they are both building designs and not completed projects*); although RA labs 'design' has the best overall BSER value and grade than the CE duplex 'design', the project team or client might prefer the CE duplex 'design' if they prefer a building design with better sustainability performance in either "*E- Material and Waste*" or "*F- Transportation*" or both.

The three-tier comparative assessments obtainable on the C-SDSS platform can provide the project team, client, government agencies, and other key project stakeholders necessary and details information on the sustainability performance or potentials of the green building projects or building designs respectively.

9.3.3 Experts' validation of the CDSS platform and its integrated BSAM scheme

The experts' validation of the study findings is comprised of two parts – the first one is the developed C-SDSS platform itself, and the second one being the BSAM scheme, which is the primary green rating system used for the sustainability assessment of green buildings on the C-SDSS platform. The BSAM scheme was developed as part of a larger research project. According to Lucko and Rojas (2010), validation of research work is critical and serves as a means to ensures the research process including the methodology conforms to the highest quality standards.

Several techniques have been adopted in the extant literature to conduct research validation work, which includes case studies, questionnaire surveys, simulations, experiments, etc. (Hu et al., 2016a; Pyett, 2003; Sousa, 2014). Case studies validation has discussed in section 9.3.2 was earlier carried out while this section will discuss the experts' validation exercise carried out using expert questionnaire surveys. Meanwhile, according to El-Diraby and O'Connor (2004) there exists no single definition for validation, and per Lucko and Rojas (2010) and Sargent (1991), there is no established methodology to determine the validation approach to be adopted or technique to use. However, according to Law (2007) and Yang et al. (2011), a validation process must be able to affirm that a proposed framework can be a proper and realistic representation of the system in the real-world and/or can predict the real-world performance of the system.

The validation process can be classified into six key areas, which are construct, content, internal, external, face, criterion validity (Lucko & Rojas, 2010). The descriptions and details of these validation types are well discussed in extant literature (*see* Field, 2009; Leedy & Ormrod, 2001; Lucko & Rojas, 2010; Taherdoost, 2016). More so, based on previous studies – four validation types, such as internal, construct, external, and content validity were adopted in designing the validation questionnaire for this study, as discussed in Section 9.3.3.1.

9.3.3.1 Validation survey and experts' demographics

Validation questionnaire survey forms were designed to validate the proposed C-SDSS platform and its integrated BSAM scheme based on a set of validation statements to validate the suitability, effectiveness, credibility, ease of use, efficiency, usefulness of the C-SDSS platform and the BSAM scheme to facilitate the sustainability assessment of green buildings and promote the implementation of sustainability practices in buildings and real estate development. The invited experts based within the sub-Saharan region of Africa were invited via purposive sampling and snowball sampling techniques. Two modes of questionnaire distribution were adopted – (1) online survey forms; and (2) PDF fill-in survey forms (Olawumi & Chan, 2019a). Links to the online survey and PDF fill-in survey forms were also sent to the experts via email. These modes of questionnaire distribution according to Andrews et al. (2003) helps to saves time and cost.

The validation questionnaire comprises of three sections. The first section of the survey form asked for background details from the invited experts. The second section presents the C-SDSS platform template and the weightings of the BSAM scheme criteria (sustainability indicators, attributes, and sub-attributes) as well as the BSER value for an ideal green building (benchmark building). The last section of the survey form presented the eight validation statements or questions which relate to the external, internal, content, and construct validity; and solicits for the experts to rate their level of agreement on these validation questions (VQ) based on a 5-point Likert scale (1= strongly disagree; 3= Neutral; and 5= strongly agree).

Key criteria the experts must have before they are invited to participate in the validation exercise include – they must have adequate experience and knowledge in sustainability issues in construction and green building implementation in the built environment. Based on these criteria, the targeted experts who are based within the sub-Saharan region of Africa were identified and sent the survey forms via email. Overall 30 responses were received from the respondents of which 29 responses were found valid – 27 responses were gotten via the online survey form, and two responses were obtained via the PDF fill-in form. The sample size for the validation questionnaire is adequate for further analysis when compared with previous studies such as Ameyaw (2014), Darko (2018), and Osei-Kyei (2018) where 7, 5, and 6 respondents participated in these studies' validation exercises. Table 9.2 shows the background information of the invited experts.

Table 9.2: Experts' demographics for validation survey

Description	Frequency	Percentage (%)	Description	Frequency	Percentage (%)
Major profession or occupation			**Years of working experience**		
Architect	2	6.9	Less than 5 years	15	51.7
Building Services Engineer	2	6.9	5 - 10 years	5	17.2
Civil Engineer	6	20.7	11 - 15 years	5	17.2
Electrical Engineer	1	3.4	16 - 20 years	1	3.4
Estate Manager	2	6.9	Above 20 years	3	10.3
Project Manager	6	20.7	**Total**	**29**	**100**
Quantity Surveyor	9	31.0			
Urban Planner	1	3.4			
Total	**29**	**100**			

From the analysis of the experts' demographics as presented in Table 9.2, the invited experts are from key professional groups in the built environment and possess adequate years of experience in the subject matter. About 50 percent of the respondents have more than five years of experience in sustainability implementation in building projects; this is due to the slow adoption of sustainability and green buildings in the sub-Saharan region of Africa (Jung & Lee, 2015; Olawumi & Chan, 2018a). The analysis of the invited experts' demographics lends further credence to the data collated from them for this validation exercise.

9.3.3.2 Validation survey results

The results of the analysis of the responses and level of agreement of the invited experts regarding the eight validation questions are presented in Table 9.3. The eight VQs relate to the BSAM scheme green rating system developed as part of same project and which has been integrated with the C-SDSS platform, while three validation statements (VQ4, VQ6, & VQ8) pertains to validating the C-SDSS platform itself. Seven of the validation statements have at least a mean score of 4.00 with only VQ4 with a mean score of 3.97. These mean scores fall within the "very important” classification of Li et al. (2013) mean classification scheme based on a 5-point Likert scale. Therefore, based on the results analysis of Table 9.3, it is seen that the four validation areas – external, internal, construct, and content validity – is adequate. VQ1 and VQ8 address external validity, while VQ7 relates to content validity. Meanwhile, VQ4 and VQ6 measure internal validity and VQ2, VQ3, and VQ5 refer to the construct validity (Table 9.3).

The two validation statements (VQ4 and VQ6) that address the internal validity as presented in Table 9.3 have an average mean score of 4.02. VQ4 with a mean score of 3.97 certified that the developed BSAM scheme as well the C-SDSS templates and platform are easily understandable to the users (or green building assessors), and it is easy to use and deploy in practice within the context of the sub-Saharan region. Meanwhile, the VQ6 with a mean index of 4.07, the experts confirm that the development of the C-SDSS platform and its integrated BSAM scheme sufficiently address the objectives of the study. As regards the external validity, its two validation statements (VQ1 and VQ8) have an average mean score of 4.14; and most notably, both validation statements have a mean index of 4.14 each. For VQ1, the experts affirm that the identified sustainability indicators (of the BSAM scheme) adopted to achieve a holistic evaluation of the sustainability performance of buildings within the context of sub-Saharan region, is very reasonable. Also, for VQ8, the experts adjudge the suitability and adequacy of the BSAM scheme and the C-SDSS platform to assess the sustainability performance of green buildings to be very high.

Table 9.3: Validation survey results of the C-SDSS platform and the BSAM scheme

Code	Validation statements/questions	Mean	BSAM scheme	C-SDSS platform
VQ1	The identified sustainability indicators (of the BSAM scheme) adopted to achieve a holistic evaluation of the sustainability performance of buildings is reasonable.	4.14	√	
VQ2	The identified sustainability attributes within each sustainability indicator (of the BSAM scheme) are adequate and appropriate.	4.31	√	
VQ3	The identified sustainability sub-attributes within each sustainability attribute are adequate and appropriate.	4.17	√	
VQ4	The developed BSAM scheme and the C-SDSS templates are easily understandable and easy to use in practice.	3.97	√	√
VQ5	The BSAM scheme is inclusive, comprehensive, and of a logical structure.	4.03	√	
VQ6	The BSAM scheme and the C-SDSS platform sufficiently address the objectives of the study.	4.07	√	√
VQ7	The appropriate use of the BSAM scheme would lead to a successful implementation of sustainability in buildings.	4.21	√	
VQ8	The BSAM scheme and the C-SDSS platform are suitable and adequate to assess holistic sustainability of buildings.	4.14	√	√

Note: √ – implies the validation statement applies to either the BSAM scheme and/or the C-SDSS platform.

Meanwhile, three validation questions (VQ2, VQ3, and VQ5) relating to the construct validity were asked the experts, which resulted in an average mean score of 4.17. VQ2, with a mean value of 4.31, affirmed the appropriateness and adequacy of the identified sustainability attributes within each sustainability indicator of the BSAM scheme. More so, VQ3 has a mean index of 4.17, which certifies that the identified sustainability sub-attributes within each sustainability attribute are very adequate and appropriate within the context of sub-Saharan region. Meanwhile, the VQ5 with a mean score of 4.03, which implies the experts affirms and adjudges the BSAM scheme to be inclusive, very comprehensive, and of a very good logical structure.

Furthermore, VQ7 was asked to address the content validity for the BSAM scheme, which was integrated within the C-SDSS platform and has a mean score of 4.21. The high mean index of VQ7 indicated that there is a good tendency of successful implementation of sustainability in buildings when there are appropriate use and deployment of the integrated BSAM scheme within the C-SDSS platform. Conclusively, the high mean indexes achieved by the four validation aspects of the validation exercise shows the C-SDSS platform and its integrated BSAM scheme are comprehensive, inclusive, reliable, appropriate, suitable, and applicable for the sustainability assessment of green buildings and to enhance the implementation of sustainability practices in the built environment within the context of the sub-Saharan region of Africa.

9.4 Research implications

The current study has developed and demonstrated the deployment and implementation of the C-SDSS platform for the assessment of the sustainability performance of green buildings and to promote the implementation of sustainability practices in building and real estate. The various programming codes, design, and interfaces of the C-SDSS platform have been verified as well as validated using real-life case study building projects and experts' validation exercises. The developed C-SDSS platform has also been implemented in practice in the built environment. The research findings and the deliverables of this study have several beneficial contributions to knowledge and practice as discussed in this section.

A key deliverable and contribution of this study are that – the C-SDSS platform and its integrated BSAM scheme green rating system developed in this study provided an automated and dynamic system for decision-makers, assessors, and other relevant stakeholders in the built environment to evaluate the sustainability performance of green buildings. Meanwhile, the C-SDSS platform has illustrated and demonstrated in this study also provides avenues for its users to compare their building designs or models as well as completed building projects for their sustainability potential or performance, respectively. On the C-SDSS platform, the weighting of the buildings' sustainability indicators and attributes can be compared. Hence, in a scenario where the client or their consultants favor a sustainability criterion, say energy or indoor environmental quality, in their building project; using the “Compare Projects” functionality of the C-SDSS platform – the user or assessor can identify among a set of building designs – the design that best aligns to the intended sustainability criteria targets.

More so, the C-SDSS platform when used for the sustainability assessment of green building projects – can help pinpoint areas of the sustainability assessment of a building project or design that needs enhancement in order to meet the client or developers’ pre-set sustainability certification grade or objectives, especially when the calculated BSAR value of the building is below the targeted certification grade level. Besides, the C-SDSS platform is an open-source project (free-to-use) to assess a building project, hence providing a solution to one of the key barriers to the implementation of sustainability and sustainability assessment in the construction industry (Olawumi et al., 2018; Olawumi & Chan, 2020b). Also, the BSAM scheme green rating system which is integrated with the C-SDSS platform provides a suitable regional context rating tool to assess the greenness of buildings within the sub-Saharan region. According to Todd and Geissler (1999) and Banani et al. (2013) the regional or local context has a significant effect on the importance given to sustainability criteria. More so, the C-SDSS platform and its integrated BSAM scheme can serve as a consultative policy toolkit for relevant government departments, national and international organizations, towards enhancing the implementation of green buildings. It also provides for the integration of the United Nations Sustainable Development Goals (SDGs) in the planning and design of buildings and neighborhood developments.

The findings and deliverables of this study, as highlighted above have significant benefits to all strata of the society – government, real estate developers and end-users, etc. even the ecosystem – apart from expanding the current body of knowledge. It is expected to improve the quality of life, wellbeing, and the sustainability profile of people, buildings, and the environment within the context of the sub-Saharan region. Also, the findings will be shared and discussed with government agencies, developers, corporate bodies with a view to instigating the formulation of new policies or amendment of the existing ones to that which is more robust and include the three pillars of sustainable development.

These deliverables of this study as well as its contributions to knowledge and practice will be measured by keeping track of the users of the C-SDSS platform by getting regular feedback from them as regards various quantifiable and qualitative variables such as user-friendliness, ease of use; and whether the BSAM scheme and C-SDSS platform meet their needs, facilitate or improve their implementation of green building practices among others.

9.5. Conclusions

The use of digital technology tools to aid the adoption of green buildings and the sustainability assessment of building projects is essential. More so, for the assessment metric or system to bear significant benefit to its users and the built environment at large, it must embed the three pillars of sustainable development. That is, enhancing social and economic impacts while minimizing environmental impacts. The current study builds on the existing knowledge and bridges the gaps in practice by developing a dynamic cloud-based decision support system (C-SDSS) platform which integrates the BSAM scheme as its primary green building rating system. The BSAM scheme is a recently developed green rating system suited for the sub-Saharan region of Africa and holistically considers the three pillars of sustainable development in its sustainability assessment of buildings.

The study utilized high-level programming languages such as PHP, Jscript, etc. as well as relational databases such as the MySQL to develop the C-SDSS platform which is developed with the intent to facilitate the assessment of the sustainability performance of green buildings and infrastructures as well as to promote the implementation of sustainability practices within the context of sub-Saharan region of Africa. More so, the current study improved the sustainability assessment algorithm of the BSAM scheme through the use of the GCFI technique during the coding of the green building sustainability assessment GUI of the C-SDSS platform. The developed C-SDSS platform includes among others, various interfaces for the registration of new green projects on the platform, evaluation of the sustainability performance of buildings, displaying the infographic results of the sustainability assessment, comparing the sustainability credentials of green buildings on a three-tier basis. The C-SDSS platform is hosted on a local cloud-based server.

The developed C-SDSS platform was validated using four case study building projects – two new building projects and two existing building projects, as well via experts' opinions. More so, the verification of the C-SDSS platform's programming codes, design, and interfaces was also undertaken. The verification and validation exercises shield more information and details on the capacity of the C-SDSS platform as discussed in Section 9.3. Meanwhile, the significant benefits, contributions, and implications of the developed C-SDSS platform and research findings to knowledge, practice, and the built environment at large were expatiated upon in Section 9.4.

The study recommends the development of digital cloud-based tools such as the C-SDSS platform for the other existing green building rating tools such as LEED, BREEAM, BEAM Plus, etc. The study also suggests improvement to these existing rating tools, that is, the inclusion of social and economic sustainability criteria into these rating systems to ensure they wholly consider the three pillars of sustainable development. An apparent limitation of the developed C-SDSS platform is that it is not currently applicable to some regions of the world, other than the sub-Saharan region of Africa, due to its use of the BSAM scheme as its primary green rating system. Future studies can consider integrating more green building rating systems as 'secondary' green rating tools within the C-SDSS platform, in addition, to its current primary green building rating tool – the BSAM scheme. More so, further research in this area may consider upgrading the existing C-SDSS platform to automatically process and analyze BIM models to deduce relevant sustainability modelling results such as energy simulations, daylighting consumptions, etc.

9.6 Chapter Summary

Digital technological systems are regarded as enablers of the adoption of green buildings and the sustainability assessment of building projects. However, there is currently a dearth of technological tools that can aid the sustainability assessment of buildings. Hence, this study set out to develop a Cloud-based Sustainability Decision Support System (C-SDSS) to facilitate the assessment of the sustainability performance of green buildings. The C-SDSS platform was developed using various high-level programming languages and relational databases. The primary green building rating system used on the C-SDSS platform is the Building Sustainability Assessment Method (BSAM) scheme – which was designed specifically for the sub-Saharan region of Africa and holistically considered the social, economic, and environmental sustainability criteria. The assessment algorithm of the BSAM scheme was enhanced using an efficient Multi-criteria Decision Making (MCDM) technique before its integration to the C-SDSS. The developed C-SDSS was validated using four real-life building case study projects and via experts' opinions. The outcomes of the validation exercise show the efficiency of the C-SDSS platform to enable its users to adequately measure and assess the sustainability performance of green buildings. Also, the established C-SDSS platform allows for two or more building projects to be compared to each other based on their sustainability credentials. The study's findings generate salient benefits and profound impacts to all strata of the society, the ecosystem, and the built environment. The following chapter combines the various deliverables and findings from the previous chapters to develop a holistic Green-BIM Assessment Framework for green building projects in Sub-Saharan Region of Africa.

CHAPTER 10: GREEN-BIM ASSESSMENT FRAMEWORK FOR EVALUATING SUSTAINABILITY PERFORMANCE OF BUILDING PROJECTS[10]

10.1 Chapter Overview

The previous chapter developed a C-SDSS platform to facilitate the assessment of the sustainability performance of green buildings. The current chapter combines the various deliverables and findings from the previous chapters to develop a holistic Green-BIM assessment (GBA) framework for green building projects in the Sub-Saharan Region of Africa. A conceptual research framework approach based on a consolidated desktop literature review form part of the basis of the GBA framework development. The GBA framework is expected to serve as an automated and dynamic digital tool for the evaluation of the sustainability performance of green building projects for comparison and benchmarking purposes. Three of the six components of the GBA framework are based on the deliverables of chapters 7, 8, and 9; hence developed beyond the 'conceptual' level.

10.2 Methodology

This section discusses the mixed research method employed for the development of the GBA framework.

10.2.1 Conceptual Framework Development

The development of research frameworks is essential in the creation of new knowledge (Agherdien, 2007). In the development of research frameworks from the existing literature, there are mainly five steps or algorithms towards it. Although the steps listed below are not the standard linguistic terms, it expresses the purpose or aim of each framework or model development stages. The essential steps of research framework development include:

i. The description of the statement of facts, phenomenon, or purpose of the study.

[10] This chapter is fully reported in this working paper:
Olawumi, T.O., & Chan, D.W.M. Green-BIM Assessment Framework for Evaluating Sustainability Performance of Building Projects: A Case of Nigeria.

ii. The search for and specifications of the latent concepts, theories, or even existing frameworks that have some connections with the proposed research framework.
iii. Review of the underlying concepts and theories; and discussion of the different components or variables of the proposed framework with regard to its positive attributes (*e.g., benefits, strengths, drivers, etc.*) or negative attributes (*e.g., barriers, threats, weaknesses, etc.*).
iv. The aggregation of the components or variables (*main and its sub-components*) of the proposed framework and/or with the underlying theories or concepts that explain each component of the proposed research framework.
v. The creation of a diagram or map to interconnect the main components to illustrate how the framework best explains the facts and purpose of the research framework development.

There are two types of research frameworks, which are theoretical frameworks and conceptual frameworks (Zack, 2019) and are regarded as paths towards a research inquiry (Dickson et al., 2018). According to Zack (2019), a theoretical framework is a "*structure that can hold or support a theory of a research work*"; or can be regarded as a research guide or blueprint (Osanloo & Grant, 2016). Fulton and Krainovich-Miller (2010) in describing the usefulness of a theoretical framework; compared its roles in a research inquiry to that of a geographical map to a traveler. Meanwhile, Ravitch and Carl (2015) reported that theoretical frameworks help the users to integrate and contextualize latent and formal theories in their research as a guide. It also affects the adopted research design, data collection, and analysis process for such studies (Dickson et al., 2018; Lester, 2005). In summary, a theoretical framework is made of principles, concepts, and constructs that define a theory (Osanloo & Grant, 2016).

Moreover, Zack (2019) defined a conceptual framework as "the researcher's own position on the problem," and such frameworks might be an adaptation from previous models or frameworks with significant modifications to suit the current inquiry. It is referred to as a structure which presents a natural explanation to a phenomenon being studied (Camp, 2001) and outlined an integrated way and explanation on how best to explore the research problem (Dickson et al., 2018; Liehr & Smith, 1999). It eases the definition and specification of concepts within the research problem (Luse et al., 2012) and shows the series of steps towards achieving the research purpose (Dixon et al., 2001), and the presentation of the key framework variables or constructs in graphical and logical structure to illustrate the relationships between the constructs (Dickson et al., 2018; Miles & Huberman, 1994).

The theoretical framework is based entirely on existing theory, while the conceptual framework is the operationalization of such theory. Despite the differences in the concepts and roles of these research framework types in research inquiry, they make research findings relevant, useful, acceptable to the underlying theory or concepts, and allows for the generalizability of the research findings and contributions (Akintoye, 2015; Dickson et al., 2018). Nevertheless, the chosen research framework should resonate with the aim and purpose of the research (Osanloo & Grant, 2016).

10.2.1.1 Why conceptual framework for GBA framework development?

The conceptual framework approach was employed to contextualize the proposed GBA framework. The adoption of the conceptual framework development approach was necessitated in this study because: *firstly*, there are no previous theoretical frameworks or studies which have conceptualized the information exchange workflows of the GBA framework. That is, the *extraction* of relevant data and statistics from BIM models and simulation software, GBRS, regulatory and policy documents, and other documentary evidence *into* a relational database; and the *use* of such building data on a C-SDSS *to* assess its sustainability performance. Akintoye (2015) argued that when existing theories, concepts, or frameworks are not sufficient or applicable in creating a structure that fulfills the purpose of a study, then it is advisable to utilize the conceptual framework route.

More so, *secondly*, the key variables and concepts of the proposed GBA framework have been will be outlined. *Thirdly*, these concepts are interconnected to explain their relationships and how they fulfilled the research objective. L*astly*, the study aims at the development of a new green-BIM assessment system, which will be useful for organizational firms, government authorities, and other key stakeholders in the built environment. These four reasons corroborated the assertions of Dickson et al. (2018) and Akintoye (2015) and made the conceptual framework approach best suited for the development of the GBA framework in this paper.

More so, Akintoye (2015), and Liehr and Smith (1999) posited that a conceptual framework provides the best way that a researcher can generate useful solutions and remedies to his or her defined research problems. It also provides an avenue for the development of a new theoretical construct (Osanloo & Grant, 2016). Fisher (2007) noted that for the development of a 'good' conceptual framework, its structure should be illustrated graphically as well as outlining the relations between the constructs.

10.2.2 Experts' consultation and validation

Validation exercise is fundamental to every research study (Lucko & Rojas, 2010), and it is regarded as the significant last lap of the research cycle (Hu et al., 2016a). Validation serves several purposes, such as- (i) ensures the research methodology, and each stage of the research process adheres to the highest quality standard (Lucko & Rojas, 2010). (ii) test whether a developed model achieved an acceptable quality and met defined requirements (Hu et al., 2016a). (iii) ensures the new knowledge emanating from the research meet acceptable credibility from the academic and industry practitioners, government agencies, and other relevant stakeholders; and (iv) enhance the credibility of the research outputs.

Moreover, there exists no single definition of validation or concept of validity in the extant literature (El-Diraby & O'Connor, 2004; Kamat & Martínez, 2003). Also, Lucko and Rojas (2010) and Sargent (1991) reported there are no procedures or algorithms to deduce the type of validation technique or statistical method to be employed during a validation exercise; and this poses a lot of challenges to scientists and researchers. Moreover, Law (2007) defined validation as a process to determine whether a proposed model is an accurate and real-world representation of the system towards fulfilling the objective of the study. Yang et al. (2011) stressed further that validation attempts to assess whether the proposed model or framework can predict the performance of the real-life system that it represents.

Several approaches to validation have been adopted in the extant literature which include questionnaire surveys, case studies, experiments, modeling and simulation exercises among others (Hu et al., 2016a; Kihn & Ihantola, 2015; Lucko & Rojas, 2010; Pyett, 2003; Sousa, 2014; Taherdoost, 2016). More so, other validation approaches used in the literature include the Delphi survey technique (Olawumi et al., 2018; Olawumi & Chan, 2018d; Rajendran & Gambatese, 2009) and observational studies (Leicht et al., 2010). Some studies have adopted a combination of two or more of the highlighted validation methods. However, the validation approach adopted must be suited to the research subject and its knowledge domain – including its research methodology and its results being examined; and according to Fellows and Liu (2008), it should consider the scope and depth of research. Law (2007) argued further that validation and the approaches adopted depends on the objective of the research study. Meanwhile, there are distinctions between validation and verification – while validation deals with "doing the right things," verification deals with "doing things right" (Lucko & Rojas, 2010; Yang et al., 2011).

More so, Yang et al. (2011) attempt to classify the validation techniques into qualitative and quantitative methods. Qualitative validation techniques make use of hypothesis testing of numerical data to examine the relationships among variables (Yang et al., 2011), while the qualitative method involved the use of research techniques that deduce meaning and interpretation of data which are in a construct of words and ideas rather than numerical data (Tuuli, 2009). Validation in quantitative research has to do with the accuracy and reliability of the measurement data, but in qualitative research, the focus is on understanding, explaining, or representing a complex phenomenon (Pyett, 2003). A qualitative validation technique was used in validating the GBA framework using questionnaire surveys. As argued by Yang et al. (2011), a qualitative approach such as the use of surveys provides "valuable, complementary empirical experience, credibility assessment, and improvement recommendations quickly and at low cost." The feedback from such a survey can also help improve and enhance the research process, including the proposed model, such as the proposed GBA framework.

The process of validation is divided into six main areas (Lucko & Rojas, 2010): such as internal validity, external validity, content validity, face validity, construct validity, and criterion validity. Due to the nature of the proposed framework, a qualitative validation approach will be suited in the validation of the proposed green-BIM assessment framework. More so, in designing the validation questionnaire survey, as explained in the subsequent section, four types of validation were found appropriate such as internal, external, construct, and content validity. Internal validity deals with causality, that is, the relations within the data (Leedy & Ormrod, 2001; Lucko & Rojas, 2010). The internal validity of the GBA framework examines whether the proposed framework is easily understandable and easy to use in practice. External validity assesses whether the research results or models are generalizable for prediction purposes (Lucko & Rojas, 2010). For the GBA tool, external validity examines whether the proposed tool is applicable in developing countries within the sub-Saharan region of Africa.

Construct validity evaluates whether the theoretical and conceptual constructs of a study or model are appropriate for operationalization. It examines whether the research method, process, and outputs observe and measure what it ought to measure according to the defined objectives (Field, 2009; Leedy & Ormrod, 2001; Lucko & Rojas, 2010). Specifically, it evaluates the comprehensiveness, inclusivity, and appropriateness of the GBA framework; and checks whether the GBA framework is of a logical structure and addresses the research objective. The content validity evaluates whether the content of the study represents a real-world situation or system (Lucko & Rojas, 2010; Taherdoost, 2016). The content validity examines whether the proposed GBA framework is suitable and adequate as a tool for the evaluation of sustainability performance of buildings, and its appropriate use would lead to a successful adoption of BIM and sustainability practices in the built environment.

10.3 Green-BIM Assessment framework: Development and Process Maps

This section discusses the development of the various components that made up the proposed GBA system. The proposed GBA framework was developed to serve as an automated and dynamic digital system to aid the sustainability performance of buildings with the support of a cloud-based decision support system. The proposed GBA system (Figure 10.1) has six main components, such as BIM, regulatory documents, data and evidence, the BSAM scheme (a green building rating system), relational databases, and the C-SDSS platform.

The proposed GBA system is applicable to building projects and construction organizations where BIM infrastructure is employed, and sustainability practices implemented. More so, the GBA framework is primarily suited to the local context of countries within the sub-Saharan region of Africa. Three of the GBA framework's components have been fully developed in previous chapters. Hence, this chapter focus on conceptualizing and integrating the other key components (BIM, regulatory documents, data & evidence) towards facilitating the evaluation of the sustainability performance of green buildings.

10.3.1 GBA Framework and its information exchange workflow

The development of the GBA framework emanates from the aggregation of its components' process maps. The GBA framework involves partly the information exchange workflows between its six components and the i/o of data by the system users. Hence, it is necessary to address the "*what*," "*who*," "*when*," and "*to whom*" of the information workflows to aid the effective adoption and implementation of the GBA framework by project decision-makers and other users of the proposed tool.

Table 10.1 presents the "what" aspect of the information exchange workflow of the GBA framework, that is, *what needs to be provided in terms of data to be analyzed.* Also, Figure 10.2 illustrates the various building development stages of a building project and the various data required. Thus, illustrating the "when" aspect of the information exchange workflow. More so, the "to whom" aspect of the GBA framework's information exchange workflow defines the expected users of the proposed GBA framework. These include various stakeholders in the built environment such as construction firms, consultants, government agencies, clients, and property developers, professional bodies, among others.

Meanwhile, the "who" aspect of the information exchange workflow of the GBA framework refers to practitioners and stakeholders with the required competency to provide the necessary data highlighted in Table 10.1. The "who" aspect has been highlighted within the BSAM scheme documentation (Olawumi & Chan, 2019c) and will not be further discussed in this chapter.

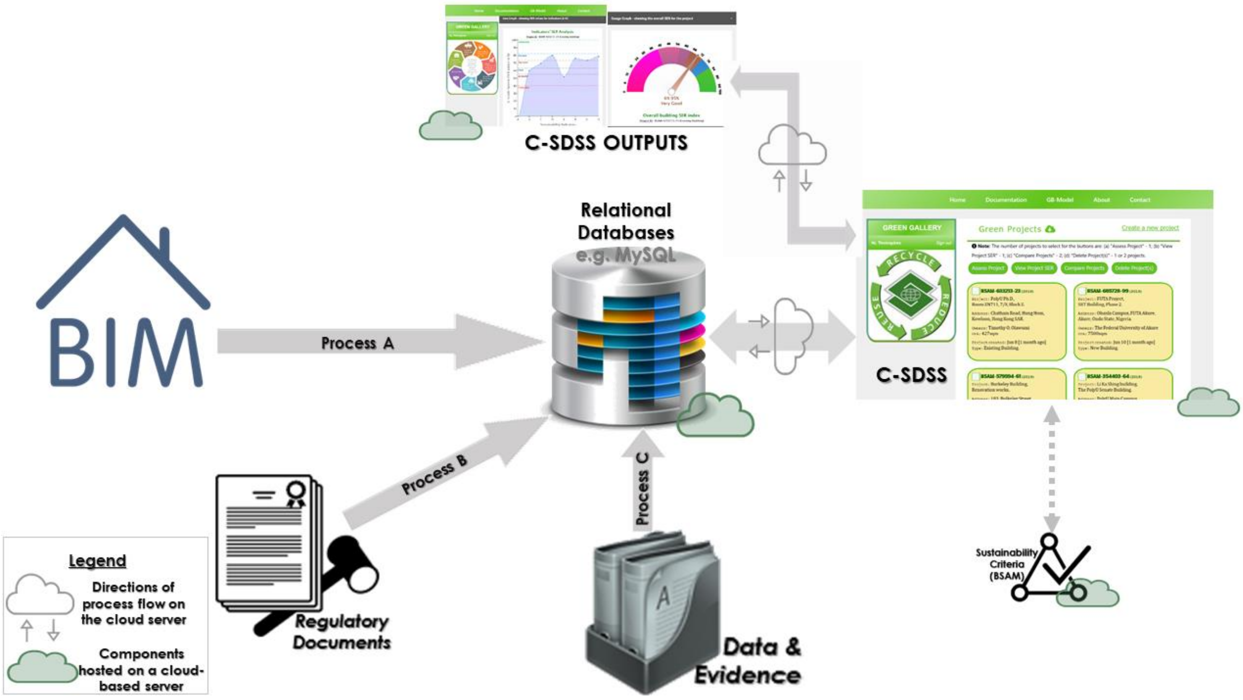


Figure 10.1: Components of the proposed GBA tool

Note: The thick arrows, such as the arrows indicating the process flow from BIM, regulatory documents, and data & evidence components to the relational databases, and represents the process maps A, B, and C, respectively.

Table 10.1: Descriptions of the data/information required for the GBA tool

GBA framework's component	Data required	Description
BIM system	BM	BIM model (contains a coordinated architectural, structural, and building services design, drainage designs).
	CS	Specification for the building projects.
	MR	Modeling results and outputs, e.g., energy simulation, lifecycle assessment, ventilation modeling, flooding & hazard assessment, thermal modeling results, etc.
Regulatory Documents	BC	Building contracts (or excerpts from the BC) between the client and contractor, and/or other stakeholders. BC should detail the relationship between the client and parties involved, and their roles in the project.
	PP	Project plan schedule for the design and construction stages. It should detail the responsibility matrix, that is, who is responsible for each aspect of the design and construction stages.
	TPC	Third-party assessment standards and codes (safety, labor, environmental & energy standards, etc.).
Data & Evidence	FS	Feasibility study report. It should consider site-wide issues to be addressed during project development.
	PE	Photographic evidence of the buildings' components, parts, systems, spaces, etc. as required in the C-SDSS documentation.
	RDI	Relevant records, data, and information as it might be required for each stage of assessment, e.g., utility records (logs of energy usage, water, waste, and other utilities), maintenance records, purchase records, surveys, and feedback, and commissioning records, etc.
	SR	Surveys and reports from specialists' consultants and subcontractors (land surveyors, geologists, ecologists, etc.), test results such as site

GBA framework's component	Data required	Description
		investigation, IAQ plan, acoustics, water run-off, flood risk assessment, ecology, heat island effect, risk assessment study reports, etc.
	TPAR	Third-party assessor reports of the building projects and site to confirm its compliance with the sustainability criteria.
	TPCC	Third-party compliance certificates (e.g., from ISO, environmental organizations, government agencies, or other designated and accreditation bodies).
	TPI	Third-party data and information such as public transportation routes map and timetables, manufacturer and technical manuals, maps, etc.
Sustainability Assessment Criteria (BSAM)	A – H	A- Sustainable Construction Practices; B- Site and Ecology; C- Energy. D- Water; E- Material and Waste; F- Transportation; G- Indoor; Environmental Quality; H- Building Management.
C-SDSS	IR	Interim review of the sustainability performance of the building design (*assess project, view project SER, compare projects* [AVC]).
	IR & C	Interim review of the sustainability performance of the building design and certification (*AVC*).
	IA	An interim assessment of the sustainability performance of the building project and certification (*AVC*).
	FA & C	A final assessment of the sustainability performance of the building project and certification (*AVC*).

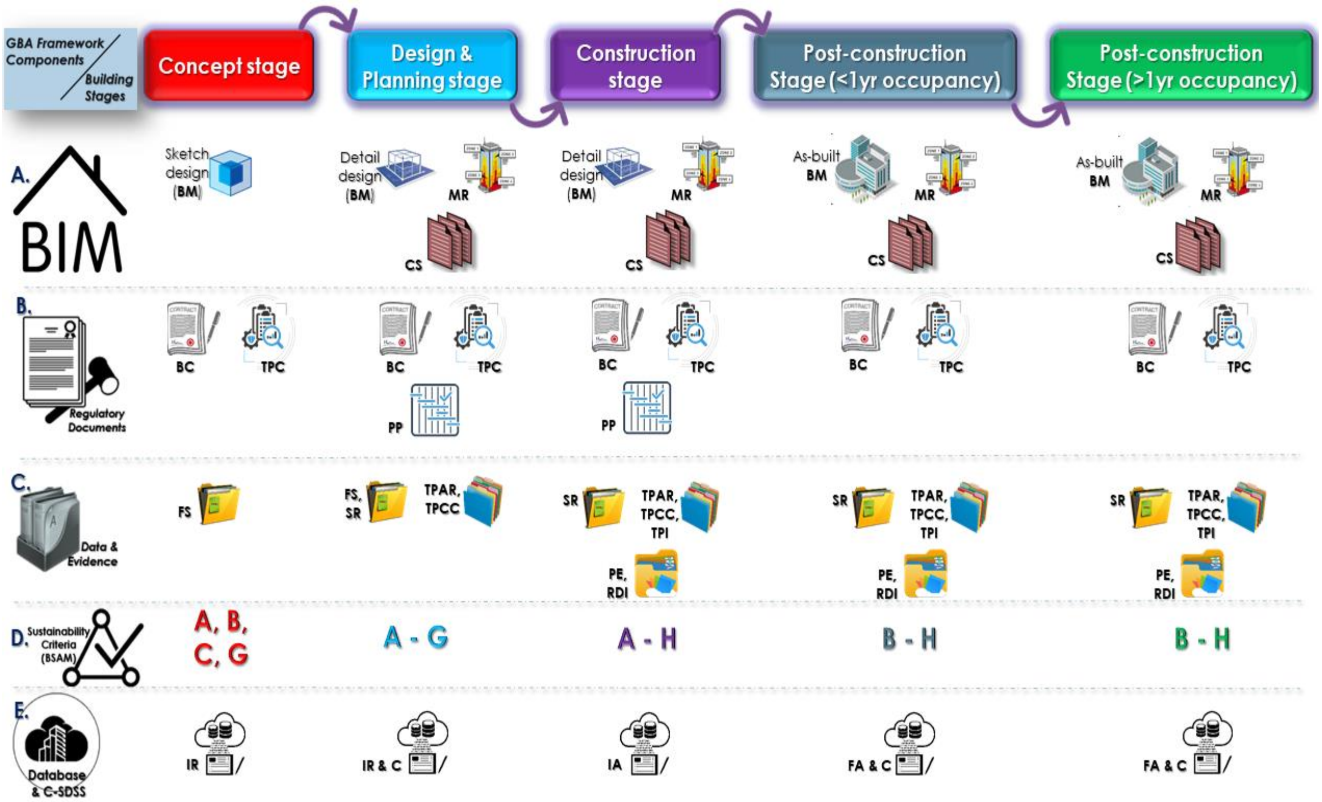


Figure 10.2: Data required by each GBA framework's component at the building development stages

As shown in Figure 10.2, the level of data required by each GBA framework's component varies from the concept stage to the post-construction stages of a typical building project.

10.3.1.1 BIM system

The information, data, and specification of buildings are represented in forms of information models throughout the project development stage (Olawumi et al., 2017; Philipp, 2013). BIM software is a revolutionary information technology (IT) tool used in the design and creation of building models (Ma et al., 2018; Olawumi & Chan, 2019b). Each BIM model (BM) is a structured database containing necessary information about the building elements and parameters (attributes) required at each stage of the building lifecycle. According to Ignatova et al. (2018), the information in the BIM model is provided in the form of either a specification or graphical form. Each specification (CS) in the BIM model contains details such as a "name" and the "technical characteristics" of the element (Ignatova et al., 2018).

Each BIM software has two main data transmission formats (Ignatova et al., 2018): the graphical information (using formats such as dxf, dwg, SAT); and the complete set of data- *both graphical and numerical* (using formats such as RVT, PLA, IFC). Most BIM software programs use the IFC format, and Ignatova et al. (2018) highlighted some problematic issues with the use of the IFC data schema. Moreover, at each stage of the building development and post-occupancy stages, the data stored in the BIM model can be extracted using data schemas such as IFC, gbXML, etc. The extracted data undergoes the required analysis, processing, or simulation; the resultant simulation or modeling result (MR) or output is communicated to the relevant project stakeholders, which forms the basis of a reliable and informed decision making for the building project.

As shown in Figure 10.2 and Table 10.1, three kinds of BIM documents may be required from the concept stage of a building project to the post-construction stages. More so, the level of detail (LoD) of the BIM model required for the sustainability assessment of a building varies from a sketch design (BM) during the concept stage to a detail BM at the construction stage, and to as-built BM for the post-construction stages. Also, only the BM is required for the concept stage, while the BM, MR, and the CS is required from the design and planning stage upward; although, the LoD increases as the building project stages progress.

Meanwhile, as shown in Figure 10.3, relevant data from the BIM model, such as the BM, MR, and the CS will be extracted and linked with the corresponding sustainability criteria of the BSAM scheme (using programming scripts) that they intend to fulfill. For instance, an energy MR will be linked with indicator C of the BSAM scheme green building rating system (Olawumi & Chan, 2019c) and uploaded to the relational databases of the developed C-SDSS platform to aid the assessment of the sustainability performance of the building.

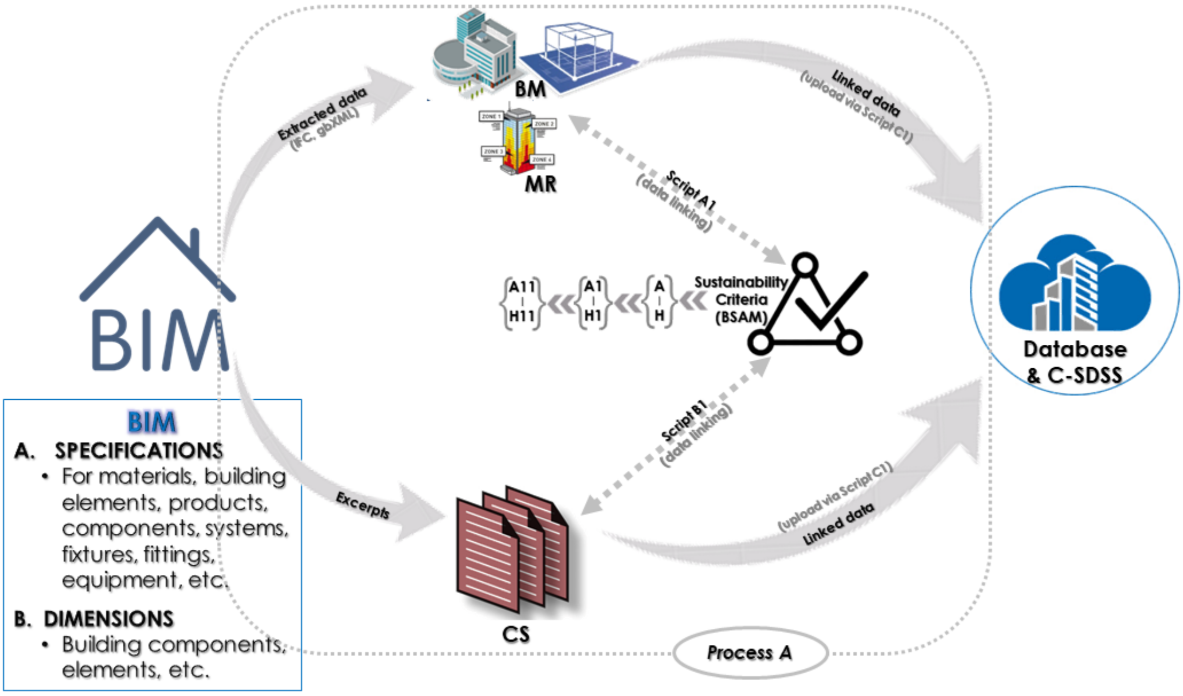


Figure 10.3: Process map for the BIM system of the GBA framework

Practitioners can use the GBA system to access the stored BIM model data in the relational database during the process of evaluating the building sustainability performance. Meanwhile, high-level programming languages such as Python, PHP, Jscript, etc. would be suitable to code the scripts required to extract and upload the data.

10.3.1.2 Regulatory Documents

The required data that constitute the regulatory documents have been highlighted in Table 10.1 and outlined in the BSAM scheme documentation (Olawumi & Chan, 2019c). As shown in Figure 10.2, three kinds of regulatory documents may be required from the concept stage to the post-construction stages. Also, only the BC and TPC documents are necessary for the concept stage and the post-construction stages, while the BC, TPC, and PP documents are required for only the design and planning stage and construction stage.

More so, to allow the various regulatory documents (BC, TPC, and the PP documents) to be adequately considered when evaluating the sustainability performance of building projects using the GBA framework. The three regulatory documents must be available in either hardcopy or softcopy document format (*preferable*). As shown in Figure 10.4, excerpts from these documents are extracted and linked with the BSAM scheme using a script. The resultant linked data are uploaded to the relational database of the GBA system using another script.

The uploaded data in the relational database (say, MySQL database) is then accessible to the relevant green building assessors using the C-SDSS platform to assess the sustainability performance of green buildings.

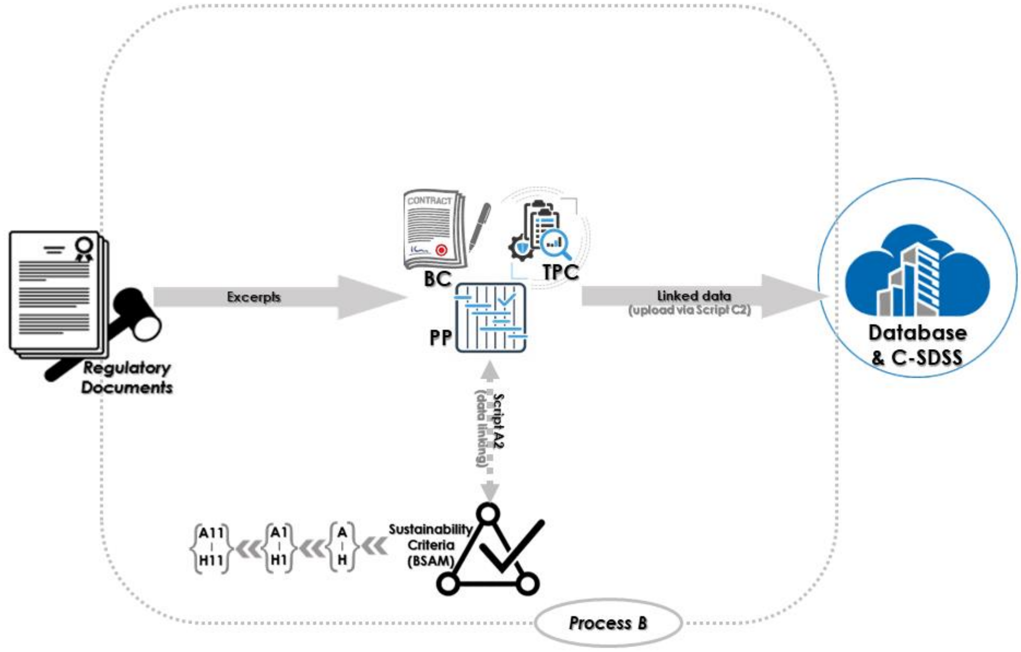


Figure 10.4: Process map for the Regulatory documents of the GBA framework

10.3.1.3 Data and Evidence

The required information that embodies the data and evidence component has been highlighted in Table 10.1. As shown in Figure 10.2, seven kinds of data and evidence documents may be required from the concept stage to the post-construction stages. More so, the LoD of the SR data needed for the assessment of the sustainability performance of the building project varies from a partial SR during the design and planning stage to a detailed SR from the construction stage upward. At the concept stage, only the FS data is needed. In contrast, at the design and planning stage, in addition to the FS data, the SR, TPAR, TPCC data are required for the evaluation of the sustainability performance of buildings. Meanwhile, from the construction stage upwards, the SR, TPAR, TPCC, TPI, PE, and RDI data are required for similar assessments.

More so, to allow for the various data and evidence documents to be considered when evaluating the sustainability performance of green building projects using the GBA framework; some of the data and evidence documents (such as the FS, RDI, SR, and the TPAR) must be available in either hardcopy or softcopy document format (*preferable*). The other three sets of data and evidence documents (TPI, TPCC, and the PE) should be made available in softcopy format – either in an image file format such as JPEG, TIFF, PNG, or as a PDF document.

As illustrated in Figure 10.5, excerpts from these documents are extracted and linked with the BSAM scheme using programming scripts – establishing a link between the regulatory documents and the BSAM scheme green rating system. The resultant linked data are uploaded to the relational database of the GBA tool using another script. The data in the relational database is then accessible for the relevant assessor via the C-SDSS platform during the evaluation of the sustainability performance of the green building projects.

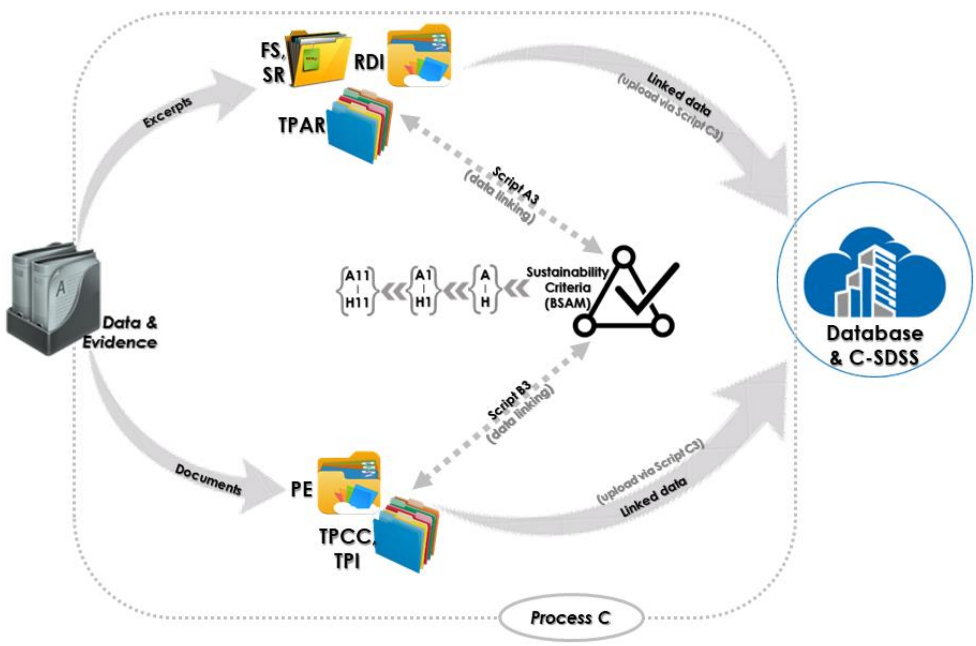


Figure 10.5: Process map for the Data and Evidence component

10.3.1.4 BSAM scheme green building rating system

The BSAM scheme developed for the sub-Saharan region is well outlined in the BSAM scheme documentation (Olawumi & Chan, 2019c). The BSAM scheme was integrated with the GBA framework, as its primary green building rating system. The BSAM scheme comprises of three hierarchical levels of sustainability criteria – indicators, attributes, and sub-attributes – which can be linked with the GBA framework's components A, B, and C to aid the sustainability assessment of green buildings. As shown in Table 10.1, the BSAM scheme green building rating system comprises of eight sustainability indicators (criteria) (Olawumi & Chan, 2019c).

As shown in Figure 10.2, the sustainability criteria which are assessed in green buildings vary from the concept stage of such buildings to the post-construction stages. For instance, during the concept stage, only sustainability criteria A, B, C, and G of the BSAM scheme are assessed during the evaluation of the sustainability performance of the building project. Others include, for the design and planning stage (criteria A – G), post-construction stages (criteria B – H), sustainability criteria A – H are assessed at the construction stage.

10.3.1.5 Relational databases and C-SDSS platform

The C-SDSS is a cloud-based digital system that functions as a decision support system for the GBA framework, where relevant stakeholders and green building assessors can assess the sustainability performance of green building projects. The relational databases and the developed C-SDSS system are hosted on a cloud-based server and are designed to operate together seamlessly. The C-SDSS platform was developed mainly using the PHP high-level programming language as well as Jscript, while an open-source relational database management system – MySQL was used to manage the data on the GBA system.

The C-SDSS platform has several vital interfaces such as – (i) two interfaces to register the details of the green building assessor and the building projects; (ii) the green building project assessment interface (see Figure 10.6); (iii) an interface to view each project assessment scores; (iv) an interface to compare the sustainability assessment scores of building projects; and (v) an interface to view all building projects registered by the assessor on the C-SDSS platform.

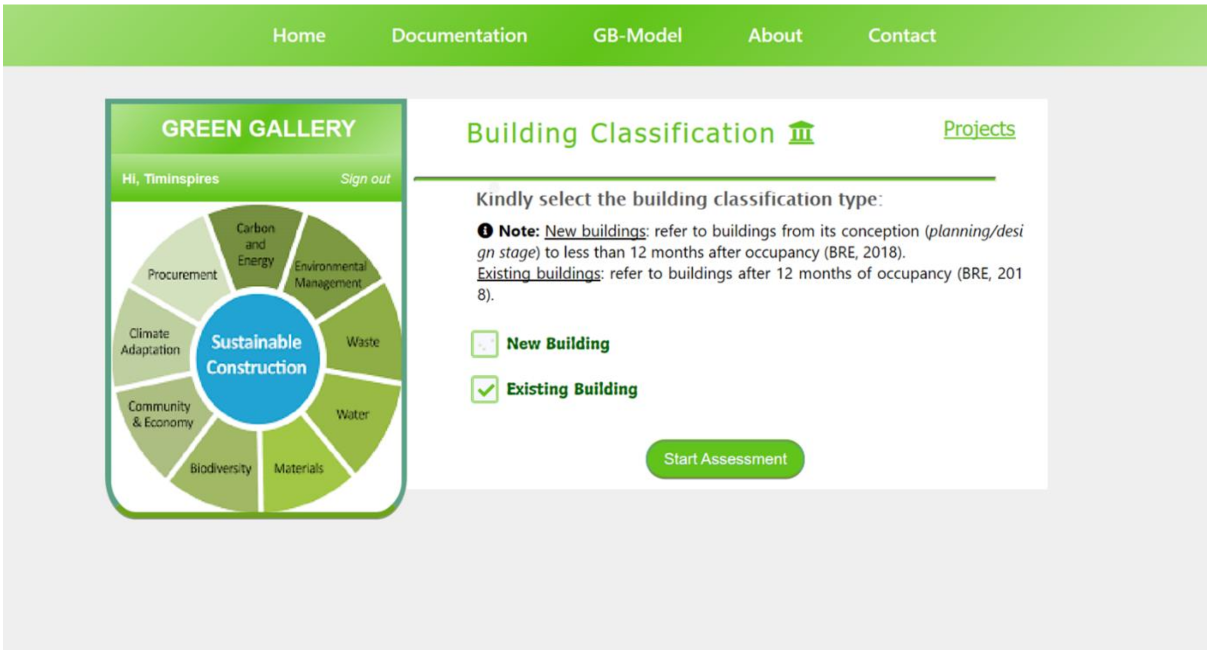


Figure 10.6: The C-SDSS Project Assessment Interface

As shown in Figure 10.2, the type of sustainability assessment for green building projects (and the certification regimes) that can be undertaken on the GBA system varies across the building development stages. At the concept stage, an interim review of the sustainability performance of the building project is carried out since only the sketch design of the BIM model is available, while the IR and certification are deferred to the design and planning stage when the detailed BM design is available. An interim assessment is undertaken at the construction stage, while the final assessment and certification are undertaken at the post-construction stages.

10.4 Experts' validation surveys

This section presents the results of the expert validation surveys carried out to validate the suitability, credibility, and quality of the proposed GBA framework as a tool to aid the assessment of the sustainability performance of green buildings, as well as promote the implementation of green-BIM in the built environment. Two modes of survey distributions were adopted – the fill-in PDF survey forms; and online survey forms (Olawumi & Chan, 2019a). The fill-in PDF survey form was sent as an email attachment to the targeted respondents, along with the link to the online survey form. Andrews et al. (2003) and Olawumi and Chan (2019a) highlighted some benefits these distribution modes to include time and cost savings as well as the ease to communicate and get feedback from the survey participants.

The validation exercise comprises of four sections. The first section of the survey form solicited relevant background information from the respondents, while the second section presented the process maps of the six GBA framework's components and how it relates to the building lifecycle stages. The third section presented the proposed GBA framework, while the fourth section presented the eight validation questions which relate to the four validity types – internal, external, construct, and content validity; and solicited for the perception and opinions of the survey participants. The experts were requested to rate their level of agreement on each of the eight validation questions using a 5-point Likert scale (1 = strongly disagree; 3 = Neutral, and 5 = strongly agree) (Olawumi & Chan, 2019d).

10.4.1 Experts' demographics

The selection criteria used to invite the survey respondents include those with adequate experience in BIM and green building adoption implementation in Nigeria as well those with requisite expertise in the built environment. Purposive sampling technique was used to for the survey form distributions. Based on the above, potential experts were identified and sent emails with links to the online survey and the PDF fill-in survey. Overall, 25 responses were received, of which 20 responses were valid for further analysis. Of the 20 valid responses, 19 responses were collated via the online survey form, and only one response was collected via the PDF fill-in survey form. The sample size for this study is adequate for the validation questionnaire survey when compared with previous studies such as Darko (2018), Osei-Kyei (2018), and Ameyaw (2014), which utilized 5, 6, and 7 respondents respectively to validate the proposed models/tools. Table 10.2 shows the demographics of the invited experts. The experts were asked to indicate their position within their organizations, and they were divided into the three major levels of management – top-level, middle-level, and first-level management (Jones & George, 2006).

Table 10.2: Demographics of the experts involved in the validation process

Description	Frequency	Percentage (%)	Description	Frequency	[a]Average years
Major profession or occupation			**Positions**		
Architects	4	20	Top-level managers	9	15
Civil Engineers	1	5	Middle-level staff	8	5
Project Managers	2	10	First-level staff	3	2.5
Quantity Surveyors	7	35	**Total**	**20**	
Estate valuers	2	10			
Builders	1	5			
Academics	3	15			
Total	**20**	**100**			

Note: [a]Average years – The average years of experience (of the respective expert's management level) in the construction industry.

The analysis of expert demographics reveals the experts are from diverse groups of key stakeholders involved in the construction industry and possess adequate years of experience in the subject matter. More so, more than two-thirds of the experts are either in a top-level managerial position or in middle-level roles, which shows the invited experts have the requisite experience in the built environment. The analysis of the demographics of the invited experts further lends credence and reliability to the data collected.

10.4.2 Validation survey results

Table 10.3 shows the analysis of the level of agreement of the invited experts to the eight validity statements. It is worthy to note that some of the experts were consulted during the development of the GBA framework, who proffered modifications to some aspects of the proposed GBA framework before its eventual development. Five of the validity statements (VS) have a mean value of at least 4.00 and the remaining three statements – VS3, VS4, and VS8 have mean values of 3.85, 3.90, and 3.95 respectively which is classified as "very important" based on Li et al. (2013) factors' classification scheme. Hence, the analysis of the experts' perception implies that the four validation aspects – internal, external, construct, and content validity – for the GBA framework is adequate. The validity statements relating to external validity are VS1 and VS8, while VS4 and VS6 addressed the internal validity. Moreover, VS2, VS3, and VS5 measure the construct validity, and VS7 relates to content validity.

The two validation statements (VS1 and VS 8) that relate to external validity have an average mean of 4.05. VS1 obtained a mean index of 4.15, which implies the proposed GBA framework's components and its process maps adopted to achieve a holistic evaluation of the sustainability performance of buildings, within the context of sub-Saharan Africa, is very reasonable. Besides, VS6, with a mean score of 3.95, confirms the suitability and adequacy of the GBA framework to act as a tool for the assessment of the sustainability performance of buildings is high. As regards the internal validation statements (VS4 and VS6), the average mean score is 4.03. VS4 has a mean index of 3.90, which indicated the proposed GBA tool and the process maps of its components are easily understandable to its users and can be effectively deployed for use in the built environment for green building assessment. Besides, VS6, with a mean score of 4.15, confirms that the development of the proposed GBA framework has sufficiently addressed the objective of this study.

In evaluating the construct validity of the GBA framework, three validation questions (VS2, VS3, and VS5) were asked and resulted in an average mean of 3.983. VS2, with a mean score of 4.05, affirmed that the required documents outlined for each component of the GBA framework and its associated process map are very adequate and appropriate. Also, VS3 with a mean index of 3.85, certified that the information required from each of the GBA framework's component to assess the building sustainability performance at each building lifecycle stage are very adequate and appropriate within the context of sub-Saharan Africa. More so, VS5 had a mean score of 4.05, which signifies and adjudges the proposed GBA framework to be inclusive, very comprehensive, and of a very good logical structure.

Meanwhile, the content validity for the proposed GBA framework development was measured using VS7 and had a mean index of 4.25. The mean value for the VS7 indicated that there is a very high tendency of a successful implementation of smart and sustainability practices in buildings, when and if, relevant stakeholders in the built environment adequately adoption, deploy, and make use of the proposed GBA framework. In summary, the high mean scores attained by the four validation facets of the GBA framework show that it is credible, reliable, replicable, comprehensive, appropriate, inclusive, and suitable for the promotion of smart sustainable practices in the built environment as well as the assessment of the sustainability performance of green buildings within the context of the sub-Saharan region of Africa.

Table 10.3: Validation results of the GBA framework

Code	Validation statement/questions	Level of agreement (%)					Mean
		Strongly agree	*Agree*	*Neutral*	*Disagree*	*Strongly disagree*	
VS1	The identified GBA framework's components and its process maps adopted to achieve a holistic evaluation of the sustainability performance of buildings in reasonable.	20	75	5	-	-	4.15
VS2	The required documents within each GBA framework's component and its process map are adequate and appropriate.	15	75	10	-	-	4.05
VS3	The information required from each GBA framework's component is sufficient to assess a building sustainability performance at each building lifecycle stage are adequate and appropriate.	10	65	25	-	-	3.85
VS4	The developed GBA framework and its components' process maps are easily understandable and easy to use in practice.	25	50	15	10	-	3.90
VS5	The developed GBA framework is inclusive, comprehensive, and of a logical structure.	15	75	10	-	-	4.05
VS6	The development of the GBA framework sufficiently addresses the objective of the study.	20	75	5	-	-	4.15
VS7	The appropriate adoption and use of the GBA framework as a tool would lead to a successful implementation of smart and sustainability practices in buildings.	35	55	10	-	-	4.25
VS8	The GBA framework as a tool is suitable and adequate to assess the sustainability performance of buildings.	15	65	20	-	-	3.95

Note: VS – Validation statement

10.5 Research implications and recommendations

The GBA framework and its associated process maps will enhance the capacity of stakeholders to support the implementation of smart sustainable practices in the Nigeria construction sector. Also, industry practitioners can deploy the GBA system to assist in the evaluation of the sustainability performance of green buildings in Nigeria. Its implementation by relevant stakeholders will also enhance the adoption of the green-BIM initiatives in Nigeria. The GBA system can also be used to compare the sustainability performance of different construction projects and building for benchmarking purposes.

As argued by Yuan et al. (2019), project owners and other associated project team members are vital to the adoption and implementation of BIM and sustainability in the construction industry and play salient roles in its diffusion within the built environment. Hence, it is recommended for stakeholders within the sub-Saharan region to embrace and adopt the GBA framework. More so, Martin et al. (2018) and Lim et al. (2018) argued for the government and private sectors to get involved in advocacy roles to drive the digitalization of the built environment and enhance the implementation of smart and sustainability initiatives. Within the context of the sub-Saharan region where there is a low-level adoption of green-BIM initiative and practices (Jung & Lee, 2015; Olawumi et al., 2017; Olawumi & Chan, 2017, 2018a), such advocacy is needed from every stakeholder involved in the built environment.

Necessary strategies are recommended for implementation by construction stakeholders to ensure the GBA framework adequately facilitates the adoption and implementation of green-BIM initiatives. These strategies are dissemination, development, and advancement. Firstly, by dissemination – the study findings, as well as its key deliverables – such as the developed GBA framework and its process maps should be shared via various forums and conferences where relevant stakeholders in the built environment are involved. Also, local meetings organized by industry practitioners, professional institutions, and green building councils, among others – such as the West Africa Built Environment Research (WABER) Conference, is another avenue of demonstrating the GBA system and usefulness to evaluate the sustainability performance of buildings.

More so, by development, further practical and real-life case study validation of the developed GBA framework should be undertaken by conducting real-life sustainability assessment of green building projects for comparison and benchmarking purposes. More so, top management of construction firms should be encouraged and supported to create their in-house customized versions of the GBA system. Lastly, by advancement – comprehensive guidelines and practice notes for implementing smart sustainable practices should be formulated for reference purposes. It will provide practitioners with the necessary best practices and guidelines for deploying the GBA framework in the construction industry. Overall, the implementation of the GBA framework will help increase the capacity of construction professionals and organizations to enhance the sustainability potential of their green building projects in the future.

10.6 Conclusions

The interest in sustainable buildings and cities as well as smart buildings as gained traction in recent years due to the various socio-economic benefits derivable from its adoption. Recently, there have been calls to consolidate the initiatives of green and smart buildings for implementation within the construction industry. However, a plethora of barriers had hindered these initiatives. Hence, this study proposed and developed a GBA framework that integrates green and smart components such as BIM, BSAM scheme green building rating system, regulatory documents, data and evidence, relational databases, and the C-SDSS digital platform. The established GBA framework provides a cloud-based automated system for the holistic assessment of the sustainability performance of green buildings.

The developed GBA tool comprises six distinct components and builds on the previous research, which are products of larger project work. This study outlined the 4Ws of the information exchange workflows that can help practitioners to understand the operationalization of the GBA framework towards facilitating its implementation within the sub-Saharan region. The study discussed the components of the GBA framework and how it functions to aid the assessment of the sustainability performance of buildings.

More so, the developed GBA framework was validated by experts, and the analysis of the validation results provided credence to the applicability of the GBA framework to help in the digitalizing the sustainability assessment of green buildings and enhance the implementation of smart sustainable buildings in the region. The practical implication of the adoption of the GBA framework in the construction industry was highlighted, as well as recommendations and strategies to enhance its implementation.

A limitation of the study is that the GBA framework development focused on the context of the Nigeria construction industry, although it could be applied to other countries in sub-Saharan Africa. Future research studies can focus on validating the GBA framework in real-world building projects. More so, further researches can work on embedding more technological tools along with BIM within the GBA framework. Meanwhile, to allow for the applicability and generalizability of the proposed GBA framework beyond Nigeria and the sub-Saharan region, future studies can extend the GBA framework to incorporate other GBRS such as LEED, BREEAM, and CASBEE, among others.

10.7 Chapter Summary

The advantages of the use of technology-enhanced tools to aid the sustainability assessment of green buildings is well established in the literature, and this informs the development of the green-BIM assessment (GBA) framework in this chapter. Hence, a mixed research design was adopted to formulate and establish the different components of the GBA framework. The GBA framework incorporates the BSAM scheme as the primary green building rating system in the proposed framework. The various components of the GBA framework were discussed and how its components' functionalities aggregate to aid the assessment of the sustainability performance of buildings. Practitioners adopting the developed GBA system – an automated and dynamic digital tool – will assist them to facilitate the implementation of smart sustainable practices in building projects. Also, the proposed GBA framework was validated which highlights its suitability and applicability in the construction industry. The GBA framework will also enable practitioners to compare the sustainability performance of building projects for benchmarking purposes. The next chapter of this thesis concludes the research.

CHAPTER 11: CONCLUSIONS AND RECOMMENDATIONS

11.1 Chapter Overview

The previous chapters have provided an overview of the study and employed several research methodologies to provide answers to the research objectives towards achieving the study's aim. The current chapter concludes the research study. The research aims and objectives are reviewed; and its conclusions highlighted. The significance, value, and contributions of the study to knowledge and practice are buttressed. More so, the limitations of the study are outlined with relevant recommendations for future studies. The conclusions, significance and contribution of the research findings, limitations of the study, and recommendations for future studies highlighted in this Chapter 11 have already been thoroughly discussed in the previous chapters. Hence, a summary of these are presented here.

11.2 Review of the Research Objectives and Conclusions

This study aims to develop a green-BIM assessment model and cloud-based sustainability decision support system for evaluating buildings' compliance to sustainability principles with a view to integrating smart sustainable practices in building construction and management, improving operational efficiency, and enhancing the overall implementation of sustainable development in the built environment. The scope of study mainly focuses on those developing countries located in the sub-Saharan region of Africa with practical applications to other regions.

The following research objectives were pursued and established to achieve the study's aim:

1. To identify and assess the inherent benefits, barriers and critical success factors (drivers) associated with integrating BIM and sustainability principles in building projects.

2. To establish the relative weightings of the key sustainability indicators, sustainability attributes and sub-attributes for buildings.

3. To develop a sustainability evaluation index for buildings using the Generalized Choquet Fuzzy Integral method.

4. To develop a cloud-based sustainability decision support system (C-SDSS) for buildings.

5. To develop a conceptual Green-BIM assessment framework as a tool for the evaluation of sustainability performance of buildings.

A range of research approaches were adopted towards achieving the above objectives as discussed in Chapters #1, #4 – #10. More so, the principal findings and implications of the study as well as the conclusions which have been discussed and presented in previous chapters (Chapter #4 – #10), are summarized in this section through the review of each of the objectives.

11.2.1 To identify and assess the inherent benefits, barriers, and critical success factors (drivers) associated with integrating BIM and sustainability principles in building projects.

A review of the extant literature and practice formed the bedrock for gathering the 36 benefits, 38 barriers, and 30 drivers' factors of the implementation of BIM and sustainability (smart sustainable practices) in the built environment. The factors formed the questionnaire items sent to the survey participants. A total of 220 respondents from 21 countries participated in the empirical questionnaire survey, which constitutes professionals of varied backgrounds and from different organization setups; and have direct and extensive experience in smart sustainable practices. The study meanwhile conducted a comparative assessment of the perceptions of the study participants based on their professional disciplines and organizational backgrounds towards establishing patterns of difference. The diversity of the respondents, their levels of experience, and the sample size lend further credence to the data collected. The review of extant literature also revealed the deep-seated variance in the adoption, trend, and application of BIM and sustainability practices; and noted the shortcoming of the existing green rating tools that place more consideration on environmental sustainability.

Firstly, for the benefit of BIM and sustainability implementation. Most of the respondents' groups agreed on the benefit factor "*enhance overall project quality, productivity, and efficiency*" as the most significant benefit of BIM and sustainability practices implementation in construction projects. Other key factors are (1) real-time sustainable design and analysis early in the design phase. (2) facilitate sharing, exchange, and management of project information and data. (3) Better design products and facilitate multi-design alternatives; and (4) prevent and reduce materials wastage through reuse and recycling and ensure materials efficiency. A factor analysis of the thirty-six benefit factors using the PCA method resulted in five underlying clusters.

Secondly, for the barriers to the implementation of BIM and sustainability in the built environment; a significant finding of this study is that there is a relative level of agreement among most of the groups of respondents on the barrier factor "*inadequacy of requisite experience, knowledge, and skills from the workforce*" as a critical impediment to the implementation of smart sustainable practices in the built environment. The other critical barriers or impediments to smart sustainable practices implementation are (1) Industry's resistance to change from traditional working practices. (2) Longer time in adapting to new technologies (steep learning curve). (3) Lack of understanding of the processes and workflows for BIM and sustainability; and (4) The high initial investment in staff training costs. Another profound research finding is the classification of the critical barriers or impediments via factor analysis of the 38 barrier factors yielded 7 clusters.

Thirdly, for the drivers of BIM and sustainability implementation. There was a consensus among the various respondents' groups on the need to organize training programs and workshops for the training of cross-field specialists who are skilled and knowledgeable about smart technologies and sustainability issues. Other significant drivers are the (1) Technical competence of staff. (2) Early involvement of project teams. (3) Greater awareness and experience level within the firm; and (4) Effective collaboration and coordination among project participants. A factor analysis of the perceived individual drivers of smart sustainable practices yielded five-factor clusters.

Based on the review of extant literature and the perceptions of the respondents, it is revealed that the construction industry still lags in the adoption and implementation of smart and sustainable practices in the construction industry. It is evident from these significant research findings and collective perspectives that the implementation of BIM and sustainability practices have an essential role to play as well as exerts profound impacts on construction projects and the built environment. Also, there must be synergy among all relevant construction stakeholders, firms, and government agencies towards achieving smart sustainable practices in the built environment. Collaborative efforts from policymakers, local authorities, practitioners, academics, and other key stakeholders can help to combat these challenges. It is envisaged that the research findings have stimulated multitudinous open debate for reference to the underlying problems besetting the built environment in each local context and internationally.

11.2.2 To establish the relative weightings of the key sustainability indicators, sustainability attributes and sub-attributes for buildings.

A review of the extant literature, existing green rating systems, green building technical notes, and guidelines using the content analysis approach as well as experts' consultation helped in identifying the sustainability criteria – environmental, social, and economic sustainability criteria – of the BSAM scheme. The need for green building rating systems to focus on the three pillars was also emphasized. Eight (8) key sustainability criteria were identified for inclusion in the BSAM scheme. The link to the publicly available repository of the 77-page BSAM scheme documentation was provided in Chapter 7 (section 7.3.2). In determining the credit weighting of each of the BSAM scheme sustainability criteria – experts consultation exercises were conducted – via the use of questionnaire survey forms, informal discussions, and interviews – of which well experienced and diverse set of experts participated in the development of the BSAM scheme.

The weights and the significance of each sustainability sub-attributes were established; also, the criteria-based ranking of the BSAM scheme based on its attributes and sub-attributes was generated. The BSAM scheme certification grading system scales were established which are outstanding, excellent, very good, good, acceptable, and unclassified, which are on the scale of 0-100%. Two case studies of building projects (residential and commercial buildings) were employed to validate the BSAM scheme. Further validation exercise was done by means of a comparative analysis of the BSAM scheme with six selected common green rating tools – LEED, BEAM Plus, BREEAM, IGBC, Green Mark, and Green Star, as discussed in Chapter 7. Based on the comparison of these green rating tools, several conclusions were reached, as highlighted in Chapter 7. The conventional "*aggregation of points*" technique used in Chapter 7 limits the expressions of the key criteria and fails to address the complex relationship among the key sustainability criteria of the BSAM scheme. These two limitations are addressed in chapter 8 (Objective #3).

11.2.3 To develop a sustainability evaluation index for buildings using the Generalized Choquet Fuzzy Integral method.

The current study used an MCDM technique, the generalized Choquet fuzzy integral (GCFI) method using the TFN to develop a building sustainability evaluation index (BSEI) for the BSAM scheme. The GCFI method adopted in Chapter 8 helped addressed the limitations of the conventional "*aggregation of points*" technique used in Chapter 7. The data collected from the 189 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. Also, the advantages and superiority of the GCFI over other weighting techniques were discussed in the study. The use of the GCFI also helped addressed the shortcomings in these existing green rating tools, which only utilize points aggregation which have been reported in the literature and discussed in Chapter 8 to be an insufficient metric.

As it is revealed in the weighting calculation for the respective eight sustainability criteria of the BSAM scheme, significant priority was given to criteria such as sustainable construction practices, transportation, and energy with normalized weights of 0.1346, 0.1286, and 0.1271 respectively. More so, 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. The practical contributions of Objective #3 from the industry and theoretical standpoints are also discussed in Chapter 8. The BSAM scheme can assess the sustainability performance of both new and existing buildings.

11.2.4 To develop a cloud-based sustainability decision support system (C-SDSS) for buildings.

The current study builds on the existing knowledge and bridges the gaps in practice by developing a dynamic cloud-based decision support system (C-SDSS) platform which integrates the BSAM scheme developed in Chapters 7 and 8 as its primary green building rating system. The study utilized high-level programming languages such as PHP, Jscript, etc. as well as relational databases such as MySQL to develop the C-SDSS platform. The C-SDSS platform was developed with the intent to facilitate the assessment of the sustainability performance of green buildings and infrastructures within the context of the sub-Saharan region of Africa. The developed C-SDSS platform includes, among others, various interfaces for the registration of new green projects on the platform, evaluation of the sustainability performance of buildings, displaying the infographic results of the sustainability assessment, comparing the sustainability credentials of green buildings on a three-tier basis. The C-SDSS platform is hosted on a local cloud-based server.

The developed C-SDSS platform was validated using four case study buildings as well via experts' opinions. More so, the verification of the C-SDSS platform's programming codes, design, and interfaces was also undertaken. The verification and validation exercises shield more information and details on the capacity of the C-SDSS platform as discussed in Chapter 9 (section 9.3). Meanwhile, the significant benefits, contributions, and implications of the developed C-SDSS platform and research findings to knowledge, practice, and the built environment at large were expatiated upon in Chapter 9. The study recommends the development of digital cloud-based tools such as the C-SDSS platform for the other existing green building rating tools such as LEED, BREEAM, BEAM Plus, etc. The study also suggests improvement to these existing rating tools, that is, the inclusion of social and economic sustainability criteria into these rating systems to ensure they wholly consider the three pillars of sustainable development.

11.2.5 To develop a conceptual Green-BIM assessment framework as a tool for the evaluation of sustainability performance of buildings.

Objective #5 developed a conceptual green-BIM assessment (GBA) framework which integrates a few green and smart components. These components include BIM, a regional-based green building rating system (BSAM scheme), regulatory documents, data and evidence, relational databases, and a C-SDSS digital platform. The GBA framework has provided a cloud-based automated system for the holistic assessment of the sustainability performance of green building and infrastructure projects. Before the development of the conceptual GBA framework, an extensive review of the extant literature led to the formulation of five critical steps essential for the development of any research frameworks – whether it is a theoretical or conceptual framework. The developed GBA framework consists of six main components as mentioned earlier, and three critical process maps, namely BIM, regulatory documents, and data and evidence process maps.

Moreover, the study provided detailed descriptions of the key components of the GBA framework and how they are to be used to achieve a smart sustainable building as well as the associated assessment of green buildings. The level of detail (LOD) required for each set of documents in each GBA framework's component was illustrated. It is worthy of note that three of the six GBA framework have been developed, as discussed in Chapters 7, 8, and 9. Furthermore, the developed GBA framework was validated. The invited experts graded the proposed GBA framework based on eight validation statements or questions which covered content, construct, internal, and external validations. The proposed GBA framework will provide a sound platform for evaluating the sustainability performance of green building projects towards as well as aiding effective smart sustainable decision-making process in building projects with a broad range of benefits towards promoting sustainable development in the built environment.

11.3 Significance and Contributions of the Study

The research study contributes to existing knowledge and practice by providing the salient and key factors – benefits, barriers, and drivers – that influence and facilitates the implementation of BIM and sustainability practices in the built environment. Also, the ranking of these key factors can form a sound basis for the development of an efficient and well-informed decision-making process by government departments, agencies, and other key construction stakeholders. The findings from the surveys of Objective #1 can also be adopted as a policy instrument and useful guidelines for government agencies, stakeholders, and others towards ensuring BIM can be used to deliver the full potential of sustainability practices in the construction industry.

More so, it provides effective strategies and recommendations towards increasing the uptake of BIM and sustainability practices and enhancing the full implementation of smart sustainable practices in the construction industry. A summary of these recommendations includes that – (1) Local authorities and government departments should liaise with relevant built environment professional bodies to set-up 'green-BIM compliance' incentives to motivate construction firms and clients to implement the concepts in their projects. They should also work synchronously towards developing relevant policies and standards to aid the adoption of these concepts within the local context. (2) Key stakeholders in the construction industry are encouraged to prioritize early collaboration and coordination of their activities at the early stages of project development. (3) For countries that are yet to develop their BIM and sustainability assessment standards, the establishment of such standards is advocated, as this will provide both qualitative and quantitative guidelines to assess the impact of green BIM on the built environment.

Other recommendations include (4) Construction projects are encouraged to develop green BIM execution plan for use in construction projects as well as pursue the early adoption of green BIM initiatives at the planning stage of project development. (5) Professional bodies and construction firms should engage more in the training of their members and staff through the mediums of training workshops and knowledge seminars; (6) Increase in funding support (both in research and practice) from the government and corporate bodies to aid the adoption of smart sustainable practices. (7) Provision of government subsidy to ease the ‘financial stress’ of small and medium scale construction firms. (8) It advised that colleges and universities enrich their curriculum based on the recent trends in BIM and sustainability practices. (9) The need for construction firms and stakeholders to be proactive in adopting new and innovative concepts. (10) The development of open-source or affordable cloud-based technologies should be accelerated to mitigate against the potential barrier posed by the cost of purchasing the commercial desktop-based software.

More so, the development of the Building Sustainability Assessment Method (BSAM) scheme to suit the regional context of the sub-Saharan region of Africa is a significant contribution to knowledge and practice. It is the first attempt at developing a holistic green building rating system for countries within Africa in a local context. The BSAM scheme encompasses the necessary sustainability criteria as well as an improvement on the existing green rating tools. The study also utilized a robust MCDM technique – the GCFI method to determine the weightings of the BSAM scheme to evaluate the sustainability performance of building projects. The BSAM scheme is available to assess both new and existing buildings.

The proposed BSAM scheme also provided practical guidelines towards evaluating green buildings as well as the documentary evidence to be assessed and verified to ascertain the fulfillment of the sustainability criteria. It also covers the maintenance and improvement of the sustainability performance of the buildings throughout their lifecycles. Moreover, implementing the proposed BSAM scheme can promote greener buildings and sustainable development and guide the design team as well as the construction team to employ greener technologies to achieved priority sustainability criteria. It also helps fulfills the need for a technical scheme through the experience-based ranking of the key criteria.

The BSAM scheme also enables the comparative assessment of buildings using unified sustainability criteria and evaluation model based on the BSAM scheme. It helps pinpoint aspects in the sustainability performance of buildings that need more improvement based on project' objectives. It is recommended for each developing country in the sub-Saharan region to establish its green building councils towards joining the global body. Also, stakeholders in the built environment are encouraged to adopt and test the proposed BSAM scheme in evaluating their building projects to accelerate the implementation of this green rating tool.

A key deliverable and contribution of the development of the C-SDSS platform and its deployment in this research study is that – the C-SDSS platform and its integrated BSAM scheme green rating system provided an automated and dynamic system for decision-makers, assessors, and other relevant stakeholders in the built environment to evaluate the sustainability performance of green buildings. It also provides a digital avenue for users to compare their building designs or models for their sustainability potential or performance respectively. Besides, the C-SDSS platform being an open-source project (free-to-use), provides a cost-effective tool and solution in the assessment of building sustainability performance.

More so, the C-SDSS platform and its integrated BSAM scheme can serve as a consultative policy toolkit for relevant government departments, national and international organizations, towards enhancing the implementation of green buildings. It also provides for the integration of the United Nations Sustainable Development Goals (SDGs) in the planning and design of buildings and neighborhood developments. It is expected to have significant benefits to all strata of the society – government, real estate developers and end-users, etc. even the ecosystem – apart from expanding the current body of knowledge. It is expected to improve the quality of life, wellbeing, and the sustainability profile of people, buildings, and the environment within the context of the sub-Saharan region.

Moreover, the developed GBA framework provides a cloud-based automated system for the holistic assessment of the sustainability performance of green building and infrastructure projects. The developed GBA framework is also able to enhance the implementation of smart sustainable practices and enable practitioners to compare the sustainability performance of building projects for benchmarking purposes.

11.4 Limitations and Recommendations for Future Research Study

In achieving Objective #1 using empirical questionnaire surveys to collate data from international experts, there is a limitation in the relatively small sample size for regions such as Europe (30) and America (12), both in the number of respondents and countries. However, the level of experience of the respondents from these two regions helps to minimize this limitation. Future studies can conduct in-depth surveys on these regions as well as projects in these countries for comparisons. Also, an obvious limitation of this study is that only BIM out of the several smart technological tools was examined as it influenced sustainability practices. The justification for this has been provided in Chapter 1, sections 1.3.2 and 1.3.6.

It is recommended that future research studies should explore and conduct a quantitative cost-benefit analysis of the gains of green-BIM implementation in the construction industry to provide a sound basis for project comparison and benchmarking. It is also recommended for future studies to examine the key benefits, barriers and drivers highlighted in this study based on an in-depth case study of construction projects, organizations, and countries and ways of maximizing each stakeholder input towards extending the scope of the current research and substantiating the critical findings derived in the study. This kind of future studies can help verify and evaluate the feasibility and effectiveness of those identified key factors in promoting and achieving smart sustainable practices in the built environment

Future research studies can focus on expanding the scope of the key sustainability criteria of the BSAM scheme and adding more variables at each sub-level – attributes, and sub-attributes. A limitation of this study is that the developed BSER value and the sustainability evaluation model are based on the BSAM scheme, which is region-specific. However, the GCFI algorithm can be applied to the other green rating tools to develop their BSER – although these tools focused heavily on only the environmental sustainability construct. For this reason, it is recommended for the future development of these existing green rating tools and other regional tools to incorporate the social and economic aspects of sustainable development.

For future studies, the GCFI can be applied to other green tools or to evaluate various sustainability issues in the built environment. More so, countries using the existing green rating systems such as LEED, BREEAM, BEAM Plus, etc. which emphasizes the environmental sustainability are implored to examine the social and economic sustainability criteria in the BSAM scheme with a view to including in their country or region customizable green rating system towards improving it.

An apparent limitation of the developed C-SDSS platform is that it is not currently applicable to some regions of the world, other than the sub-Saharan region of Africa, due to its use of the BSAM scheme as its primary green rating system. Future studies can consider integrating more green building rating systems as 'secondary' green rating tools within the C-SDSS platform. More so, further research in this area may consider upgrading the existing C-SDSS platform to automatically process and analyze BIM models to deduce relevant sustainability modeling results such as energy simulations, daylighting consumptions, etc.

A limitation of the development of the GBA framework is the integration of only BIM and the native C-SDSS digital platform as the smart tools in the GBA framework. However, it should be noted that of the several smart tools currently being adopted in the construction industry, BIM is the most prominent and widely used based on the extant literature. Further research studies can focus on coding the three GBA framework's process maps as well as conducting real-life assessments of the developed GBA framework on some selected green building projects to confirm its applicability and usefulness.

11.5 Chapter Summary

This chapter have presented the major conclusions and recommendations of this study. Similarly, the significance and contributions of the study was outlined as well as its limitations. It also provides recommendations for future research study.

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APPENDICES

Appendix A: The Documentation for the Building Sustainability Assessment Method (BSAM) Scheme

The composition and full documentation for the BSAM scheme as developed in the course of this research can be accessed via – http://dx.doi.org/10.17632/jvjm5h8md3.1. The BSAM scheme is a 77-page documentation.

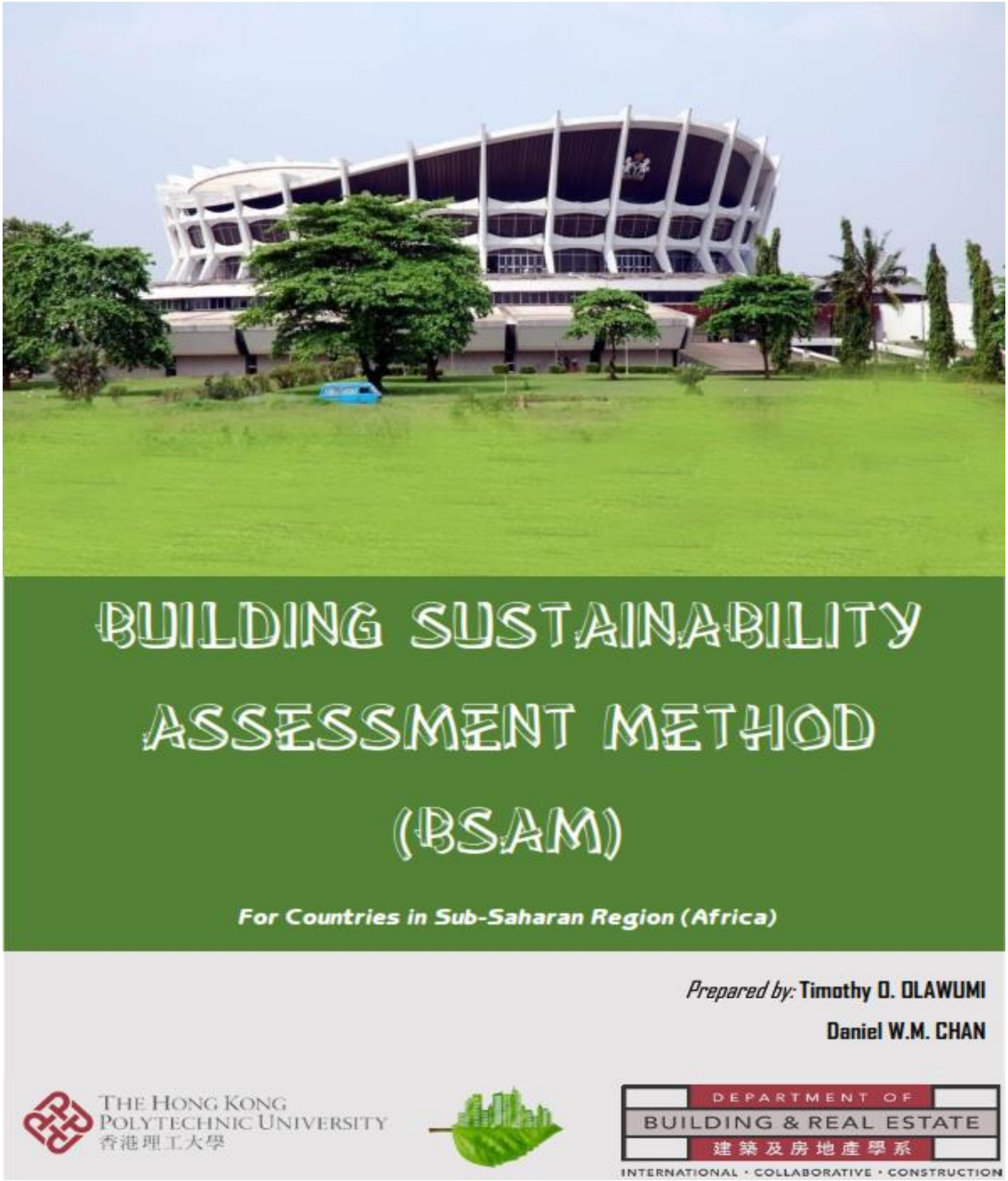

Figure A1: Cover page of the BSAM scheme documentation

Appendix B: Questionnaire Survey Template (International Survey)

PolyU THE HONG KONG POLYTECHNIC UNIVERSITY 香港理工大學

DEPARTMENT OF BUILDING & REAL ESTATE 建築及房地產學系

INTERNATIONAL • COLLABORATIVE • CONSTRUCTION

(31469)

LINK ONLINE SURVEY (scan to read)

December 2017

Dear Sir/Madam

<u>Invitation for Participation in a Research Survey</u>

Building Information Modelling (BIM) has observed a dramatic increase in use in both the design and construction industry over the last few years worldwide due to its ability to foster collaborations among many disciplines. Also, the need for sustainability measures to be embedded in the early stage of project development is of paramount importance.

This questionnaire survey forms part of a funded research project entitled: "***<u>An Exploratory Study of the Application of Building Information Modelling (BIM) to the Sustainability of the Built Environment</u>***"; under the supervision of Dr. Daniel W.M. Chan at the Department of Building and Real Estate, The Hong Kong Polytechnic University, Hong Kong.

It aims at soliciting international experts' views on issues regarding the integration of Building Information Modelling (BIM) and Sustainability measures to enhance construction projects' compliance with sustainability principles to improve the implementation of sustainable development.

This questionnaire survey aims to draw on your knowledge and experience in construction management practices to help evaluate the identified **benefits, barriers** and **critical success factors** (CSF) of integrating BIM and sustainability principles in construction projects **at the design stage.** Please, complete the questionnaire by 'ticking' ☑ or selecting from the given options.

It is expected to take about 15 minutes of your valuable time. Kindly return the completed questionnaire (saved as PDF file) within **TWO WEEKS** to the emails stated below. All the information and data you provide will be kept in strict confidence and used solely for research purposes. If you prefer online questionnaire survey, click this web link: https://goo.gl/forms/HggKafNuHchgtR5A2 or scan the barcode above using QR code.

Should you have any further enquiries about this research study, please feel free to contact me (Timothy) by office phone at +852-2766- or via email timothy.o.olawumi@ Thank you in anticipation for your generous assistance with this research. We are looking forward to receiving your early response.

Yours sincerely,	**Endorsed by:**
Mr. Timothy O. Olawumi,	**Associate Prof. (Dr.) Daniel W.M. Chan**
Full-time Ph.D. Candidate	Chief Supervisor and Associate Head (Teaching)
Department of Building and Real Estate	Department of Building and Real Estate
Faculty of Construction and Environment	Faculty of Construction and Environment
The Hong Kong Polytechnic University	The Hong Kong Polytechnic University

Kind request: You may also forward this survey questionnaire to other colleagues or platforms that could contribute to the success of this research. Thank you in anticipation of your kind assistance.

© Department of Building and Real Estate, The Hong Kong Polytechnic University, 2017

SURVEY QUESTIONNAIRE
Project Title: An Exploratory Study of the Application of Building Information Modelling (BIM) to the Sustainability of the Built Environment.

A. BACKGROUND OF RESPONDENT

1. Please indicate your major profession:

☐ Architect ☐ Civil Engineer ☐ Project Manager ☐ Quantity Surveyor

☐ BIM Manager ☐ Structural Engineer ☐ Building Services Engineer

☐ Other (pls specify)

2. Type of organization in which you are engaged:

☐ Public client ☐ Private client ☐ Project consultant ☐ Trade subcontractor

☐ Main contractor ☐ Property management company

☐ Academic/research institution ☐ Other (pls specify)

3. Years of professional working experience in the construction industry:

☐ < 5 years ☐ 5-10 years ☐ 11-15 years ☐ 16-20 years ☐ > 20 years

4. Please indicate your level of awareness of BIM process in the Construction Industry:

☐ Very High ☐ High ☐ Average ☐ Low ☐ Very Low

5. Please indicate your level of awareness of Sustainability practices in the Construction Industry:

☐ Very High ☐ High ☐ Average ☐ Low ☐ Very Low

6. At what stage of project development would you advise the implementation of both BIM and sustainable practices?

☐ Planning stage ☐ Design stage ☐ Construction stage

☐ Facility management stage

7. Please indicate the present country that you are working in (kindly type in the drop-down box, if country not available in the drop-down menu):

Australia

B. Benefits Of Integrating Building Information Modelling (BIM) And Sustainability Principles In Construction Projects.

8. Please rate the level of agreement on the following factors as ***benefits of integrating BIM and sustainability principles*** in construction projects at the design stage based on your general experience using a 5-point Likert scale. (**1 = Strongly Disagree**; **2 = Disagree; 3 = Neutral**; **4 = Agree**; and **5 = Strongly agree)**. Please, you may also check the option "**N/A**" (under the last column to the right) if the factor is not applicable in your opinion.

S/N	Benefits of Integrating of BIM and Sustainability Principles in Construction Projects at the Design Stage	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	N/A
A	**Efficiency & Productivity**						
1	Enhance overall project quality, productivity, and efficiency	☐	☐	☐	☐	☐	☐
2	Schedule compliance in the delivery of construction projects	☐	☐	☐	☐	☐	☐
3	Predictive analysis of performance (energy analysis, code analysis)	☐	☐	☐	☐	☐	☐
4	Improve the operations and maintenance (facility management) of project infrastructure	☐	☐	☐	☐	☐	☐
B	**Financial Issues**						
5	Reduction in cost of construction works and improvement in project's cost performance	☐	☐	☐	☐	☐	☐
6	Improve financial and investment opportunities	☐	☐	☐	☐	☐	☐
7	Reduction in the cost of as-built drawings	☐	☐	☐	☐	☐	☐
C	**Information & Process-related Issues**						
8	Facilitate sharing, exchange, and management of project information and data	☐	☐	☐	☐	☐	☐
9	Facilitates resource planning and allocation	☐	☐	☐	☐	☐	☐
10	Reduction in site-based conflicts	☐	☐	☐	☐	☐	☐
D	**Legal Issues**						
11	Ease the process to obtain building plan approvals and construction permits	☐	☐	☐	☐	☐	☐
12	Support collaboration and ease procurement relationships	☐	☐	☐	☐	☐	☐
13	Reduced claims or litigation risks	☐	☐	☐	☐	☐	☐
14	Increase firms' capability to comply with prevailing statutory regulations.	☐	☐	☐	☐	☐	☐
E	**Planning & Design**						
15	Better design products and facilitate multi-design alternatives	☐	☐	☐	☐	☐	☐
16	Facilitate building layout flexibility and retrofitting	☐	☐	☐	☐	☐	☐
17	Real-time sustainable design and analysis early in the design phase	☐	☐	☐	☐	☐	☐
F	**Practice & Education**						
18	Facilitate, support and improve project-related decision-making	☐	☐	☐	☐	☐	☐

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S/N	Benefits of Integrating of BIM and Sustainability Principles in Construction Projects at the Design Stage	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	N/A
19	Improved organization brand image and competitive advantage	☐	☐	☐	☐	☐	☐
20	Enhance business performance and technical competence of professional practice	☐	☐	☐	☐	☐	☐
21	Enhance innovation capabilities and encourage the use of new construction methods	☐	☐	☐	☐	☐	☐
G	**Sustainability Issues**						
22	Prevent and reduce materials wastage through reuse & recycling and ensure materials efficiency	☐	☐	☐	☐	☐	☐
23	Reduce safety risks and enhance project safety & health performance	☐	☐	☐	☐	☐	☐
24	Control of lifecycle costs and environmental data	☐	☐	☐	☐	☐	☐
25	Facilitate the implementation of green building principles and practices	☐	☐	☐	☐	☐	☐
26	Ease the integration of sustainability strategies with business planning	☐	☐	☐	☐	☐	☐
27	Minimize carbon risk and improve energy efficiency	☐	☐	☐	☐	☐	☐
28	Improve resource management and reduce environmental impact across the value chain	☐	☐	☐	☐	☐	☐
29	Facilitate the selection of sustainable materials, components, and systems for projects	☐	☐	☐	☐	☐	☐
30	Higher capacity for accommodating the three pillars of sustainability (*social, economic & environmental sustainability*)	☐	☐	☐	☐	☐	☐
H	**Technology-related Issues**						
31	Enhance the accuracy of as-built drawings	☐	☐	☐	☐	☐	☐
32	Facilitate integration with domain knowledge areas such as project management, safety, and sustainability	☐	☐	☐	☐	☐	☐
33	Allow the checking of architectural design of buildings from the sustainability point of view	☐	☐	☐	☐	☐	☐
34	Facilitate accurate geometrical representations of a building in an integrated data environment	☐	☐	☐	☐	☐	☐
35	Ability to simulate building performances and energy usage	☐	☐	☐	☐	☐	☐
36	Encourage the implementation of clean technologies that require less energy consumption	☐	☐	☐	☐	☐	☐
37	*Others:*	☐	☐	☐	☐	☐	☐
38		☐	☐	☐	☐	☐	☐
39		☐	☐	☐	☐	☐	☐
40		☐	☐	☐	☐	☐	☐

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C. Barriers To Integration Of Building Information Modelling (BIM) And Sustainability Principles In Construction Projects.

9. Please rate the level of agreement on the following factors as ***barriers to the integration of BIM and sustainability principles*** in construction projects at the design stage based on your general experience using a 5-point Likert scale. (**1 = Strongly Disagree**; **2 = Disagree; 3 = Neutral**; **4 = Agree**; and **5 = Strongly agree)**.
Please, you may also check the option "**N/A**" (under the last column to the right) if the factor is not applicable in your opinion.

S/N	Barriers to Integration of BIM and Sustainability Principles in Construction Projects at the Design Stage	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	N/A
A	**Attitude & Market**						
1	Varied market readiness across organizations and geographic locations	☐	☐	☐	☐	☐	☐
2	Industry's resistance to change from traditional working practices	☐	☐	☐	☐	☐	☐
3	Lack of client demand and top management commitment	☐	☐	☐	☐	☐	☐
4	Lack of support and involvement of the government	☐	☐	☐	☐	☐	☐
5	Low level of involvement of BIM users in green projects	☐	☐	☐	☐	☐	☐
6	Societal reluctance to change from traditional values or culture	☐	☐	☐	☐	☐	☐
7	The lack of awareness and collaboration among project stakeholders	☐	☐	☐	☐	☐	☐
B	**Education, Knowledge & Learning**						
8	Inadequacy of requisite experience, knowledge, and skills from the workforce	☐	☐	☐	☐	☐	☐
9	Longer time in adapting to new technologies (*steep learning curve*)	☐	☐	☐	☐	☐	☐
10	Lack of understanding of the processes and workflows required for BIM and sustainability	☐	☐	☐	☐	☐	☐
11	Low level of research in the industry and academia	☐	☐	☐	☐	☐	☐
12	Inadequate in-depth expertise and know-how to operate sustainability-related analysis software programs	☐	☐	☐	☐	☐	☐
13	Shortage of cross-field specialists in BIM and sustainability	☐	☐	☐	☐	☐	☐
C	**Financial Issues**						
14	High cost of BIM software, license, and associated applications	☐	☐	☐	☐	☐	☐
15	High initial investment on staff training costs	☐	☐	☐	☐	☐	☐
16	Recurring need for additional and associated resources and high economic expenses	☐	☐	☐	☐	☐	☐
D	**Organizational & Project-related**						
17	Lack of initiative and hesitance on future investments	☐	☐	☐	☐	☐	☐
18	Fragmented nature of the construction industry	☐	☐	☐	☐	☐	☐

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S/N	Barriers to Integration of BIM and Sustainability Principles in Construction Projects at the Design Stage	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	N/A
19	Organizational challenges, policy, and project strategy	☐	☐	☐	☐	☐	☐
E	**Information & Data**						
20	Difficulty in assessing environmental parameters of building properties	☐	☐	☐	☐	☐	☐
21	Difficulty in accessing sustainability-related data (*such as safety, health, and pollution index, etc.*)	☐	☐	☐	☐	☐	☐
F	**Legal Issues**						
22	The risk of losing intellectual property and rights	☐	☐	☐	☐	☐	☐
23	Difficulty in allocating and sharing BIM-related risks	☐	☐	☐	☐	☐	☐
24	Lack of legal framework and contract uncertainties	☐	☐	☐	☐	☐	☐
25	Increased risk and liability	☐	☐	☐	☐	☐	☐
26	Lack of suitable procurement policy and contractual agreements	☐	☐	☐	☐	☐	☐
G	**Sustainability Issues**						
27	Non-uniformity of sustainability evaluation criteria and measures	☐	☐	☐	☐	☐	☐
28	Lack of comprehensive framework and implementation plan for sustainability	☐	☐	☐	☐	☐	☐
29	Absence or non-uniformity of industry standards for sustainability	☐	☐	☐	☐	☐	☐
30	Inaccuracy and uncertainty in sustainability assessments for projects	☐	☐	☐	☐	☐	☐
H	**Technology-related Issues**						
31	Incompatibility issues with different software packages	☐	☐	☐	☐	☐	☐
32	Absence of industry standards for BIM	☐	☐	☐	☐	☐	☐
33	Insufficient level of support from the BIM software developers	☐	☐	☐	☐	☐	☐
34	Inadequacy of BIM data schemas to semantically represent sustainability-based knowledge	☐	☐	☐	☐	☐	☐
35	Lack of supporting sustainability analysis tools	☐	☐	☐	☐	☐	☐
36	Non-implementation of open source principles for software development	☐	☐	☐	☐	☐	☐
37	Domination of the market by commercial assessment tools	☐	☐	☐	☐	☐	☐
38	User-unfriendliness of BIM analysis software programs	☐	☐	☐	☐	☐	☐
39	*Others:*	☐	☐	☐	☐	☐	☐
40		☐	☐	☐	☐	☐	☐
41		☐	☐	☐	☐	☐	☐
42		☐	☐	☐	☐	☐	☐

D. CRITICAL SUCCESS FACTORS (CSFs) THAT INFLUENCE THE INTEGRATION OF BUILDING INFORMATION MODELLING (BIM) AND SUSTAINABILITY PRINCIPLES IN CONSTRUCTION PROJECTS.

10. Please rate the level of agreement on the following factors as ***critical success factors (CSFs) that influence the integration of BIM and sustainability principles*** in construction projects at the design stage based on your general experience using a 5-point Likert scale. (**1 = Strongly Disagree**; **2 = Disagree; 3 = Neutral**; **4 = Agree**; and **5 = Strongly agree)**. Please, you may also check the option "**N/A**" (under the last column to the right) if the factor is not applicable in your opinion.

S/N	Critical Success Factors that Influence the Integration of BIM and Sustainability Principles in Construction Projects at the Design Stage.	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	N/A
A	**Education, Knowledge & Learning**						
1	Technical competence of staff	☐	☐	☐	☐	☐	☐
2	Greater awareness and experience level within the firm	☐	☐	☐	☐	☐	☐
3	More training programs for cross-field specialists in BIM and Sustainability	☐	☐	☐	☐	☐	☐
4	Increased research in the industry and academia	☐	☐	☐	☐	☐	☐
B	**Financial Issues**						
5	Government establishment of start-up funding for construction firms to kick-start BIM initiatives	☐	☐	☐	☐	☐	☐
6	Adequate construction cost allocated to BIM	☐	☐	☐	☐	☐	☐
7	Availability of financial resources for BIM software, licenses, and its regular upgrades	☐	☐	☐	☐	☐	☐
C	**Industry Culture**						
8	Information and knowledge-sharing within the industry	☐	☐	☐	☐	☐	☐
9	Effective collaboration and coordination among project participants	☐	☐	☐	☐	☐	☐
10	Establishment of a model of good practice for BIM and sustainability implementation	☐	☐	☐	☐	☐	☐
11	Availability and a well-managed in-house database of information on similar projects	☐	☐	☐	☐	☐	☐
D	**Legal Issues**						
12	Development of appropriate legal framework for BIM use and deployment in projects	☐	☐	☐	☐	☐	☐
13	Security of intellectual property and rights	☐	☐	☐	☐	☐	☐
14	Shared risks, liability, and rewards among project stakeholders	☐	☐	☐	☐	☐	☐
15	Establishment of BIM standards, codes, rules, and regulations	☐	☐	☐	☐	☐	☐
16	Appropriate legislation and governmental enforcement & credit for innovative performance	☐	☐	☐	☐	☐	☐

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S/N	Critical Success Factors that Influences the Integration of BIM and Sustainability Principles in Construction Projects at the Design Stage	Strongly Agree	Agree	Neutral	Disagree	Strongly Disagree	N/A
E	**Organization & Project-related Issues**						
17	Increased involvement of project stakeholders in green projects	☐	☐	☐	☐	☐	☐
18	Clarity in requirements and measures for achieving sustainable projects	☐	☐	☐	☐	☐	☐
19	Number of subcontractors experienced with BIM projects	☐	☐	☐	☐	☐	☐
20	Client requirement and ownership	☐	☐	☐	☐	☐	☐
21	Early involvement of project teams	☐	☐	☐	☐	☐	☐
22	Client satisfaction level on BIM projects	☐	☐	☐	☐	☐	☐
23	Supportive organizational culture and effective leadership	☐	☐	☐	☐	☐	☐
24	Project complexity (regarding building shape or building systems)	☐	☐	☐	☐	☐	☐
F	**Technology-related Issues**						
25	Availability and affordability of cloud-based technology	☐	☐	☐	☐	☐	☐
26	Interoperability and data compatibility	☐	☐	☐	☐	☐	☐
27	Standardization & simplicity of BIM and sustainability assessment software	☐	☐	☐	☐	☐	☐
28	Technical support from software vendors	☐	☐	☐	☐	☐	☐
29	Availability of BIM and sustainability databases	☐	☐	☐	☐	☐	☐
30	Open-source software development	☐	☐	☐	☐	☐	☐
31	*Others:*	☐	☐	☐	☐	☐	☐
32		☐	☐	☐	☐	☐	☐
33		☐	☐	☐	☐	☐	☐
34		☐	☐	☐	☐	☐	☐

***Any other valuable contributions, suggestions, etc. (*optional*):**

*If you wish to receive a copy of the summary of the research findings for reference, please provide your contact details below (*optional*):

Name: **Email Address:**

Organization:

End of the questionnaire ***Thank you for your valuable contribution***

Please kindly return the completed questionnaire to timothy.o.olawumi

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Appendix C: Questionnaire Survey Template (Research Objectives #2 – #5)

The full sets of the **questionnaire survey forms** for Objectives #1 (Delphi survey), #2 – #4 as well as the **Validation questionnaire surveys** for Objectives #3 – #5 can be accessed via – http://bit.ly/2RD2Nlb

APPENDIX C1

In respect of the rating scales (*Outstanding, Excellent, ... etc.*). Kindly **allocate** a **range of values** (*minimum, median, and maximum values*) for each "**Degree of Importance**". Recall that the "**Degree of Importance**" scale ('*Very low*' to '*Very High*') was used in evaluating the *sustainability indicators* and its respective *sustainability attributes* in the main questionnaire survey. **The range must be between 0 and 100**.

- For example, you may allocate for "**Very High**" scale a value of 83, 87, 92, 100 (*min, median-a, median-b, and max*) values respectively. Also, you may give "**High**" scale a value of 65, 70, 76, 82 (*min, median-a, median-b, and max*) values. *Use the same approach for the other 'Degree of Importance' scales.*

S/N	'Degree of Importance' Scales (Qualitative description)	Range (0 - 100)			
		Minimum	Median-A	Median-B	Maximum
1	Very High				
2	High				
3	Medium				
4	Low				
5	Very Low				

APPENDIX C2

Please rate the degree of importance of the respective ***sustainability attributes*** in respect of each ***sustainability indicators*** (**A - H**). Check the last column (F.I.) for more information.

- **For example**, "**D- Water**" is a sustainability indicator with three (3) sustainability attributes (**D1**- *Water Efficiency*, **D2**- *Water Management*, **D3**- *Water Efficient Systems & Equipment*). If you consider **D1** to be of **very high** *degree of* **importance** in respect of "**D- Water**", please tick (√) "Very High". Similarly, if you consider **D2** to be of **medium** *degree of* **importance** in respect of "**D- Water**", please tick (√) "Medium".

S/N	Sustainability Attributes	Degree of Importance					F.I.
		Very High	High	Medium	Low	Very Low	
A	**Sustainable Construction Practices**						
A1	Project Site and Design	☐	☐	☐	☐	☐	Consider the importance of **A1-A6** in respect of **A**– "***Sustainable Construction Practices***"
A2	Societal Engagement	☐	☐	☐	☐	☐	
A3	Safety & Health	☐	☐	☐	☐	☐	
A4	Ethics & Equity	☐	☐	☐	☐	☐	
A5	Construction Material & Waste	☐	☐	☐	☐	☐	
A6	Project Management	☐	☐	☐	☐	☐	
B	**Site and Ecology**						
B1	Site Selection	☐	☐	☐	☐	☐	Consider the importance of **B1-B3** in respect of **B**– "***Site & Ecology***"
B2	Site Management	☐	☐	☐	☐	☐	
B3	Reduction of Heat Island Effect	☐	☐	☐	☐	☐	
C	**Energy**						
C1	Energy Performance	☐	☐	☐	☐	☐	Consider the importance of **C1-C3** in respect of **C**– "***Energy***"
C2	Energy Management	☐	☐	☐	☐	☐	
C3	Energy Efficient Systems & Equipment	☐	☐	☐	☐	☐	
D	**Water**						
D1	Water Efficiency	☐	☐	☐	☐	☐	Consider the importance of **D1-D3** in respect of **D**– "***Water***"
D2	Water Management	☐	☐	☐	☐	☐	
D3	Water Efficient Systems & Equipment	☐	☐	☐	☐	☐	

APPENDIX C3

Please rate the level of significance of the ***sustainability sub-attributes*** in respect of each ***sustainability attributes***. Check the last column (F.I.) for more information.

- **For example**, "**A2- Societal engagement**" is a sustainability parameter with four (4) sustainability sub-attributes (**A21**- *Engage local firms*, **A22**- *Local employment opportunities*, **A23**- *Enhance local economy,* **A24**- *Public participation*).

- If you consider **A21** as **required or a pre-requisite** in order for a building to properly achieve "**A2- Societal engagement**", please tick (√) "Required". Similarly, if you consider **A22** to be of **optional** for a building in order to achieve "**A2- Societal engagement**, please tick (√) "Optional".

- Use these instructions for the tables (**Table A** – **Table H**). Unless otherwise stated, the sustainability attributes and indicators should be applied to both '*New Buildings*' and '*Existing Buildings*'.

Table A: Sustainable Construction Practices ***(Applied to 'New Buildings' only)***

S/N	Sustainability Sub-Attributes	Level of Significance: Required	Level of Significance: Optional	Level of Significance: Negligible	F.I.
A1	**Project Site and Design**				
A11	Land Use	☐	☐	☐	Consider the significance of **A11-A16** in respect of **A1**
A12	Integration of cultural heritage in design	☐	☐	☐	
A13	Construction method	☐	☐	☐	
A14	Buildability (ease of construction)	☐	☐	☐	
A15	Enhanced watershed features	☐	☐	☐	
A16	Reduction of ecological impacts	☐	☐	☐	
A2	**Societal Engagement**				
A21	Engagement of local firms	☐	☐	☐	Consider the significance of **A21-A24** in respect of **A2**
A22	Local employment opportunities	☐	☐	☐	
A23	Enhanced local economy	☐	☐	☐	
A24	Public participation	☐	☐	☐	

APPENDIX C4

Kindly provide a **range of values** (*minimum and maximum values*) for the proposed **rating scales** of the study's building rating system. **The range must be between 0 and 100**. For example: for "**Outstanding**" scale, you can give its *range* as **85** (*min*) to **100** (*max*). For "Excellent" scale, you can give its *range* as **70** (*min*) to **84** (*max*). *Do likewise for every underlisted rating scales*.

S/N	Rating Scales (Qualitative description)	Range (0 - 100)	
		Minimum value	Maximum value
1	Outstanding		
2	Excellent		
3	Very Good		
4	Good		
5	Acceptable		
6	Unclassified/Fail		

Appendix D: Credit points and Significance value of BSAM scheme criteria

Appendix D1: Determination of credit points (score-weights) for the BSAM scheme sustainability criteria

Sustainability Indicators	Attributes & sub-attribute code	Attributes & Sub-attributes	Credit Points (CP)	Sustainability Indicators	Attributes & sub-attribute code	Attributes & Sub-attributes	Credit Points (CP)
W_z(A) = **11.5**	**A1**	**Project Site and Design**	**17**	W_z(E) = **5.75**	**E1**	**Sustainable Purchasing Practice**	**5**
	A11	Land Use	3		E11	Sustainable purchasing plan	1
	A12	Integration of cultural heritage in design	3		E12	Ongoing consumables & durable goods	1
	A13	Construction method	4		E13	Facility alterations and additions & reuse *(applied to 'Existing Buildings' only)*	2
	A14	Buildability (ease of construction)	3		E14	Reduced mercury in Lamps	1
	A15	Enhanced watershed features	2		**E2**	**Efficient Use & Selection of Materials**	**4**
	A16	Reduction of ecological impacts	2		E21	Modular and standardized design	2
	A2	**Societal Engagement**	**8**		E22	Using non-ozone depleting substances (non-CFC, non-HCFC)	1
	A21	Engagement of local firms	2		E23	Enhanced refrigerants management	1
	A22	Local employment opportunities	2		**E3**	**Waste Management Practice**	**9**
	A23	Enhanced local economy	2		E31	Solid waste management policy	1
	A24	Public participation	2		E32	Hazardous waste management	1
	A3	**Safety & Health**	**7**		E33	Waste stream audit	2
	A31	Operational safety and wellbeing	2		E34	Ongoing consumables & durable goods waste	1
	A32	Reduction of site disturbance	2		E35	Facility alterations and demolition waste *(applied to 'Existing Buildings' only)*	1
	A33	Safe neighborhood	1		E36	Collection, storage, and disposal of recyclables	2
	A34	Space accessibility & availability	1		E37	Waste equipment installation	1
	A35	Reduction of site pollution	1		**E4**	**Ease of Conversion of Building Functions**	**5**
	A4	**Ethics & Equity**	**14**		E41	Functional adaptation	1
	A41	Compliance with labor standards	2		E42	Ease of disassembly (deconstruction)	1
	A42	Compliance with social standards	3		E43	Designing for robustness for asset and landscape	2
	A43	Education & skills development	2		E44	Building adaptation strategy plans	1
	A44	Compliance with safety standards	2	W_z(F) = **5.333**	**F1**	**Alternative Means of Transport**	**7**
	A45	Compliance with client requirements	2		F11	Pedestrian & cyclist facilities	2
	A46	Environmental statutory requirements	3		F12	Reduction of conventional commuting trips	4
	A5	**Construction Material & Waste**	**11**		F13	Carpooling & vanpooling	1
	A51	Locally sourced materials	2		**F2**	**Community Accessibility**	**7**

Sustainability Indicators	Attributes & sub-attribute code	Attributes & Sub-attributes	Credit Points (CP)
	A52	Construction site waste management	2
	A53	Proper material handling	2
	A54	Reuse of construction materials	3
	A55	Storage facilities & space	2
	A6	**Project Management**	**12**
	A61	Project brief & design	3
	A62	Engagement of sustainability-conscious contractors & suppliers	3
	A63	Site emergency plan	2
	A64	Engagement of sustainability-conscious project management team	2
	A65	Site management plan	1
	A66	Commissioning & handover	1
W_z(B) = **5.0**	**B1**	**Site Selection**	**3**
	B11	Prior green certification *(applied to 'Existing Buildings' only)*	1
	B12	Adaptive reuse and preservation of historic landmarks	1
	B13	Regional priority	1
	B2	**Site Management**	**7**
	B21	Environmental policy and purchasing plan	3
	B22	Environmentally purchasing practices	1
	B23	Building exterior and hardscape management plan	2
	B24	Landscape management plan	1
	B3	**Reduction of Heat Island Effect**	**5**
	B31	Heat Island reduction in non-roofed areas	1
	B32	Heat Island reduction in roof areas	1
	B33	Exterior walls finishing materials	1
	B34	Consideration of wind movement and building movement and building	1

Sustainability Indicators	Attributes & sub-attribute code	Attributes & Sub-attributes	Credit Points (CP)
	F21	Public transport accessibility	4
	F22	Proximity to amenities	3
	F3	**Transport Management**	**2**
	F31	Car parking capacity	1
	F32	Provision of low emitting & fuel-efficient vehicles	1
W_z(G) = **7.0**	**G1**	**Visual Comfort**	**8**
	G11	Daylighting and external views	2
	G12	Glare control	1
	G13	Interior lighting distribution	2
	G14	High-frequency ballasts	1
	G15	Automatic lighting controls	2
	G2	**Indoor Air Quality**	**8**
	G21	Minimum IAQ performance	1
	G22	Environmental tobacco smoke control	1
	G23	Adequate cross-ventilation	1
	G24	Indoor air quality management	2
	G25	Control of greenhouse gases (GHS) emission sources	2
	G26	Reduction of light pollution	1
	G3	**Thermal Comfort**	**5**
	G31	Design and verification	2
	G32	Controllability of temperature	1
	G33	Thermal comfort in AC & non-AC premises	2
	G4	**Acoustic Performance**	**4**
	G41	Room acoustics	1
	G42	Noise isolation and control	2

Sustainability Indicators	Attributes & sub-attribute code	Attributes & Sub-attributes	Credit Points (CP)	Sustainability Indicators	Attributes & sub-attribute code	Attributes & Sub-attributes	Credit Points (CP)
		exterior design					
	B35	Greening & ecological enhancement	1		G43	HVAC background noise	1
W_z(C) = **10.67**	**C1**	**Energy Performance**	**10**		**G5**	**Hygiene**	**9**
	C11	Energy performance targets *(applied to 'Existing Buildings' only)*	2		G51	Plumbing and drainage system & liquid separators	3
	C12	Energy modeling & reporting *(applied to 'New Buildings' only)*	1		G52	Chemical leak prevention & storage	2
	C13	Energy conservation measures	2		G53	Integrated pest management	1
	C14	Thermal performance of building envelope	3		G54	Waste disposal facilities de-odorizing system	1
	C15	Compliance with local energy standards	2		G55	Occupancy comfort survey & feedback *(applied to 'Existing Buildings' only)*	2
	C2	**Energy Management**	**10**		**G6**	**Building Amenities**	**8**
	C21	Energy operating plan	2		G61	Access for persons with disability	3
	C22	Energy monitoring and metering	2		G62	Amenity features	2
	C23	Auditing, commissioning, and testing of energy systems	3		G63	Efficiency of use	1
	C24	Energy management systems	1		G64	Low-impact systems and materials	2
	C25	Sustainable maintenance	2	W_z(H) = **6.5**	**H1**	**Operation & Maintenance**	**13**
	C3	**Energy-Efficient Systems**	**12**		H11	Condition survey	3
	C31	Interior lighting efficiency and zoning control	2		H12	Staffing quality and resources	1
	C32	Renewable energy systems	3		H13	Building user manual and information	1
	C33	Energy-efficient circulation systems (lifts, moving walkways, and escalators)	2		H14	Operation & maintenance policy	3
	C34	Asset's energy savings *(applied to 'Existing Buildings' only)*	1		H15	Operation and maintenance procedures and manuals	3
	C35	Energy efficient appliances and laundry facilities	2		H16	Green lease	2
	C36	Energy-efficient HVAC equipment	1		**H2**	**Security**	**3**
	C37	Efficient hot water systems	1		H21	Security measures	2
W_z(D) = **6.0**	**D1**	**Water Efficiency**	**6**		H22	Intruder alarm system	1
	D11	Water recycling & rainwater harvesting	2		**H3**	**Risk Management**	**7**

Sustainability Indicators	Attributes & sub-attribute code	Attributes & Sub-attributes	Credit Points (CP)	Sustainability Indicators	Attributes & sub-attribute code	Attributes & Sub-attributes	Credit Points (CP)
	D12	Water-efficient landscaping and irrigation	3		H31	Fire risk assessment	2
	D13	Outdoor water use efficiency	1		H32	Fire risk manager	1
	D2	**Water Management**	**6**		H33	Natural hazards assessment	2
	D21	Water conservation plan	1		H34	Emergency strategy	2
	D22	Water performance monitoring	2		**H4**	**Green Innovations**	**3**
	D23	Cooling tower water management	1		H41	Innovations in techniques	2
	D24	Flood and surface management	2		H42	Performance enhancement	1
	D3	**Water Efficient Systems & Equipment**	**6**				
	D31	Efficient indoor plumbing fixtures & fittings	3				
	D32	Leak detection system	2				
	D33	Effluent discharge in foul sewer	1				

Appendix D2: Classification of the significance of each sustainability sub-attribute of the BSAM scheme

Sub-attribute code	Required (%)	Optional (%)	Negligible (%)	Inference	Sub-attribute code	Required (%)	Optional (%)	Negligible (%)	Inference
A1					**E1**				
A11	82.4	17.6	0	R	E11	74.1	24.9	1.1	R
A12	34.2	60.4	5.3	O	E12	49.2	47.6	3.2	O
A13	63.8	35.7	0.5	R	E13	43.9	49.7	6.3	O
A14	70.1	25.7	4.3	R	E14	34	56.4	9.6	O
A15	52.4	43.9	3.9	O	**E2**				
A16	55.6	40.6	3.7	O	E21	67.7	32.3	0	R
A2					E22	46	48.1	5.8	O
A21	53.5	44.4	2.1	O	E23	49.2	43.9	6.9	O
A22	46.5	48.7	4.8	O	**E3**				
A23	59.4	36.4	4.3	R	E31	67.7	28.6	3.7	R
A24	45.5	47.6	7	O	E32	61.9	34.4	3.7	R
A3					E33	46.6	46.6	6.9	O
A31	86.2	13.8	0	R	E34	51.3	42.9	5.8	O
A32	57.4	39.9	2.7	R	E35	49.7	45	5.3	O
A33	70.2	27.7	2.1	R	E36	54.5	40.2	5.3	O
A34	68.6	26.6	4.8	R	E37	49.7	42.9	7.4	O
A35	64.9	27.1	8	R	**E4**				
A4					E41	66.7	30.7	2.6	R
A41	78.7	17.6	3.7	R	E42	46.6	47.6	5.8	O
A42	61.2	36.7	2.1	R	E43	55.6	42.3	2.1	O
A43	60.1	38.8	1.1	R	E44	56.6	38.6	4.8	R
A44	65.8	33.7	0.5	R	**F1**				
A45	69.7	27.1	3.2	R	F11	67.2	30.7	2.1	R
A46	69.1	27.7	3.2	R	F12	41.5	56.9	1.6	O
A5					F13	42.3	50.3	7.4	O
A51	54.3	45.2	0.5	O	**F2**				
A52	56.4	41.5	2.1	O	F21	70.4	27	2.6	R
A53	69.1	28.7	2.1	R	F22	56.6	39.7	3.7	R
A54	46.8	49.5	3.7	O	**F3**				
A55	62.2	33.5	4.3	R	F31	72.3	25	2.7	R
A6					F32	46.5	45.5	8	O
A61	79.3	20.2	0.5	R	**G1**				
A62	58	40.4	1.6	O	G11	81	18	1	R

Sub-attribute code	Required (%)	Optional (%)	Negligible (%)	Inference	Sub-attribute code	Required (%)	Optional (%)	Negligible (%)	Inference
A63	59	37.2	3.7	R	G12	47.6	50.3	2.1	O
A64	58	39.9	2.1	R	G13	66	30.9	3.2	R
A65	66.8	30.5	2.7	R	G14	45.2	46.3	8.5	O
A66	59	36.2	4.8	R	G15	51.3	44.4	4.2	O
B1					**G2**				
B11	62.4	31.7	5.8	R	G21	71.1	23.5	5.3	R
B12	38.6	56.6	4.8	O	G22	42.3	49.2	8.5	O
B13	44.4	48.1	7.4	O	G23	68.3	30.7	1.1	R
B2					G24	65.1	32.8	2.1	R
B21	68.8	28	3.2	R	G25	53.4	43.4	3.2	O
B22	51.9	47.1	1.1	O	G26	54.5	39.7	5.8	R
B23	48.1	48.7	3.2	O	**G3**				
B24	51.6	45.2	3.2	O	G31	66.1	30.7	3.2	R
B3					G32	54.5	40.7	4.8	O
B31	62.8	31.9	5.3	R	G33	52.9	39.7	7.4	R
B32	48.7	46.5	4.8	O	**G4**				
B33	60.6	37.8	1.6	R	G41	64.4	31.9	3.7	R
B34	65.4	31.4	3.2	R	G42	50.8	45	4.2	O
B35	51.1	46.8	2.1	O	G43	50.8	44.4	22.8	O
C1					**G5**				
C11	67.7	30.2	2.1	R	G51	76.7	22.8	0.5	R
C12	41.3	55	3.7	O	G52	56.6	40.7	2.6	O
C13	55.6	41.3	3.2	O	G53	52.4	43.9	3.7	O
C14	50.3	45.5	4.2	O	G54	63.5	31.2	5.3	R
C15	63	31.2	5.8	R	G55	48.1	43.4	8.5	O
C2					**G6**				
C21	64	32.8	3.2	R	G61	69.3	27	3.7	R
C22	54	40.2	5.8	O	G62	56.6	41.8	1.6	O
C23	55.6	39.7	4.8	R	G63	66.1	31.7	2.1	R
C24	57.1	38.6	4.2	R	G64	51.9	46	2.1	O
C25	64	32.8	3.2	R	**H1**				
C3					H11	78.3	20.6	1.1	R
C31	70.4	26.5	3.2	R	H12	60.3	39.2	0.5	R
C32	54.5	42.9	2.6	O	H13	51.3	42.9	5.8	O
C33	55	41.3	3.7	O	H14	61.4	32.8	5.8	R
C34	44.4	49.7	5.8	O	H15	57.7	37	5.3	R

Sub-attribute code	Required (%)	Optional (%)	Negligible (%)	Inference
C35	47.6	47.6	4.8	O
C36	44.4	50.3	5.3	O
C37	44.4	45.5	10.1	O
D1				
D11	64	32.8	3.2	R
D12	46	51.3	2.6	O
D13	47.1	43.9	9	O
D2				
D21	67.7	30.7	1.6	R
D22	56.6	40.2	3.2	O
D23	42.3	51.3	6.3	O
D24	66.5	27.1	6.4	R
D3				
D31	76.6	21.3	21.1	R
D32	55.9	39.4	4.8	R
D33	62.8	34	3.2	R
H16	41.3	51.3	7.4	O
H2				
H21	83.6	15.3	1.1	R
H22	46	49.7	4.2	O
H3				
H31	76.2	21.7	2.1	R
H32	51.9	41.8	6.3	O
H33	58.7	34.9	6.3	R
H34	64.6	31.2	4.2	R
H4				
H41	67.2	29.1	3.7	R
H42	58.2	38.6	3.2	R

Note: For column "inference" – R = *required attribute*; O = *optional attribute*; N = *Negligible attribute.*

Appendix D3: Weight average for the sustainability attributes for the case study projects

Attributes codes	**Weighting average (Project A)**	**Weighting average (Project B)**
A1	15.5	14
A2	6	5
A3	4	6.5
A4	5	13
A5	3.5	5
A6	3.5	7
B1	1.5	2
B2	4	4.5
B3	2.5	1
C1	6.5	6.5
C2	9	10
C3	4.5	5.5
D1	3	4
D2	5	5.5
D3	2.5	3
E1	5	3
E2	3	1.5
E3	6.5	9
E4	5	4
F1	5	3
F2	7	4
F3	2	1.5
G1	3	7
G2	6.5	8
G3	2.5	4
G4	2.75	2.5
G5	8	9
G6	6	5
H1	6	10
H2	1	3
H3	3	4
H4	1	2

Appendix E: Cloud-based Sustainability Decision Support System (Graphical User Interfaces - GUI)

APPENDIX E1: Data entry and storage management GUIs

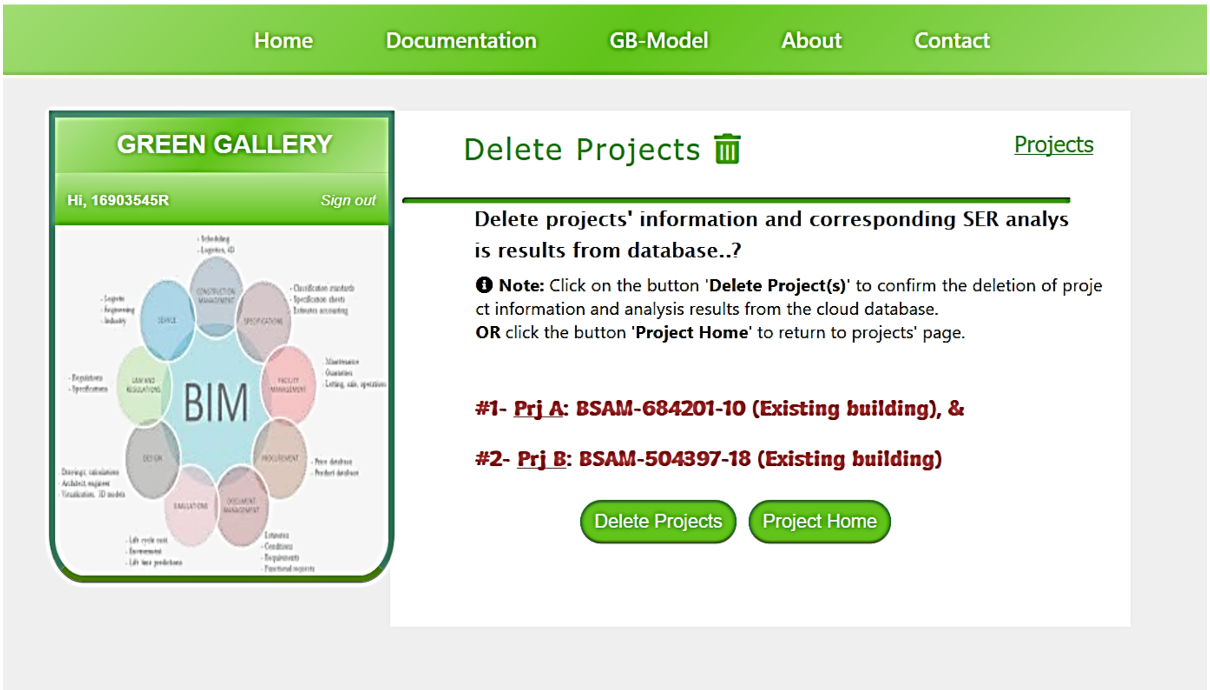

Figure E11: "Delete Projects" GUI

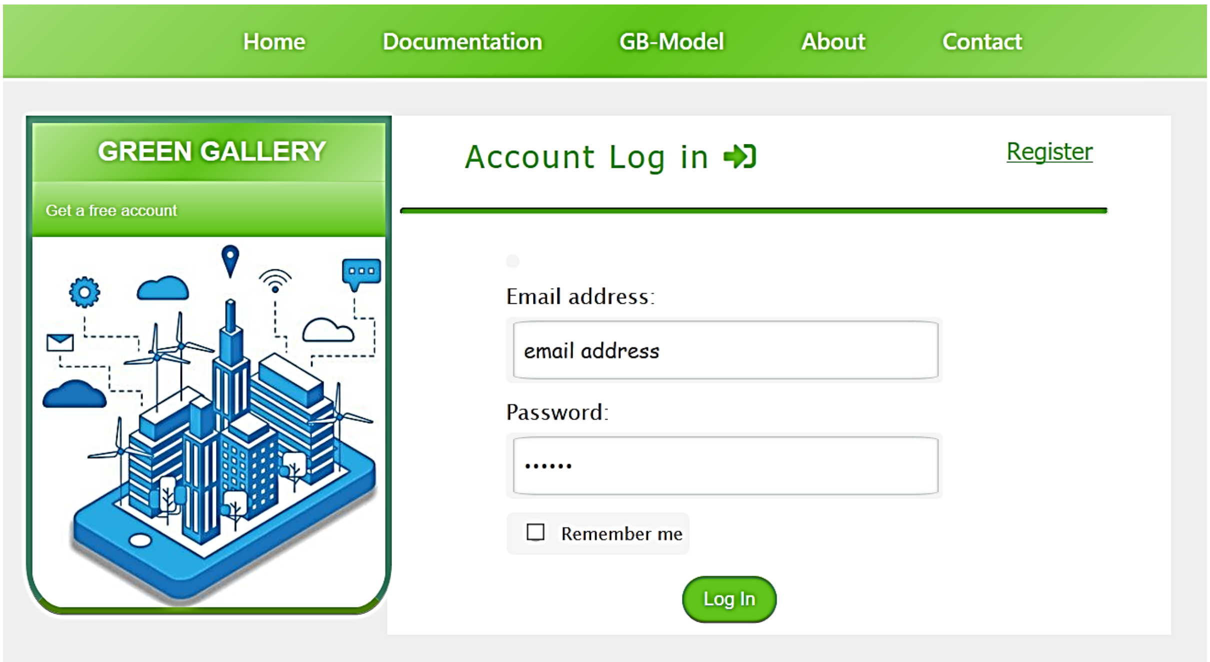

Figure E12: Sign-in GUI

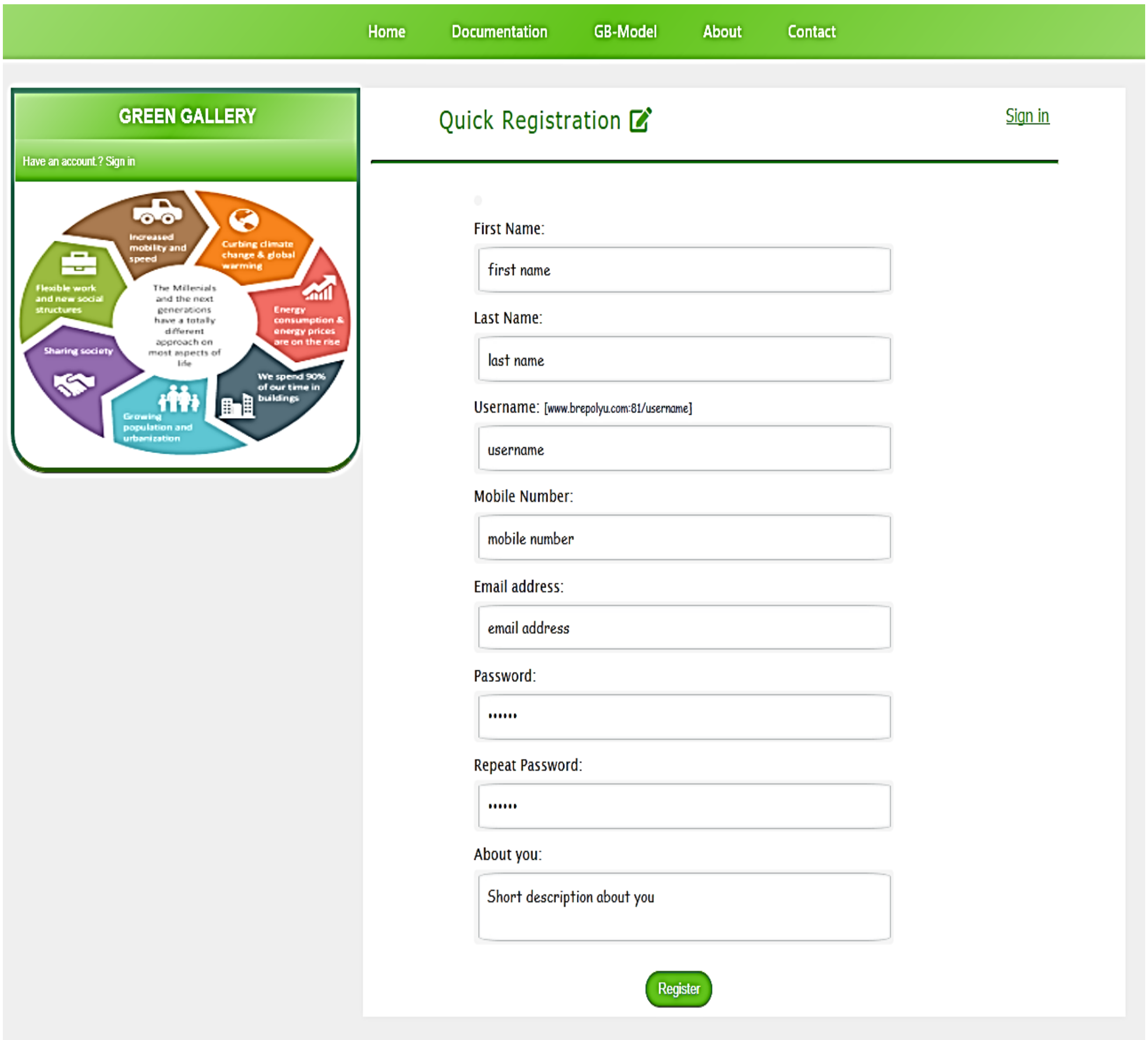

Figure E13: User registration GUI

APPENDIX E2: Coding and optimization process GUI

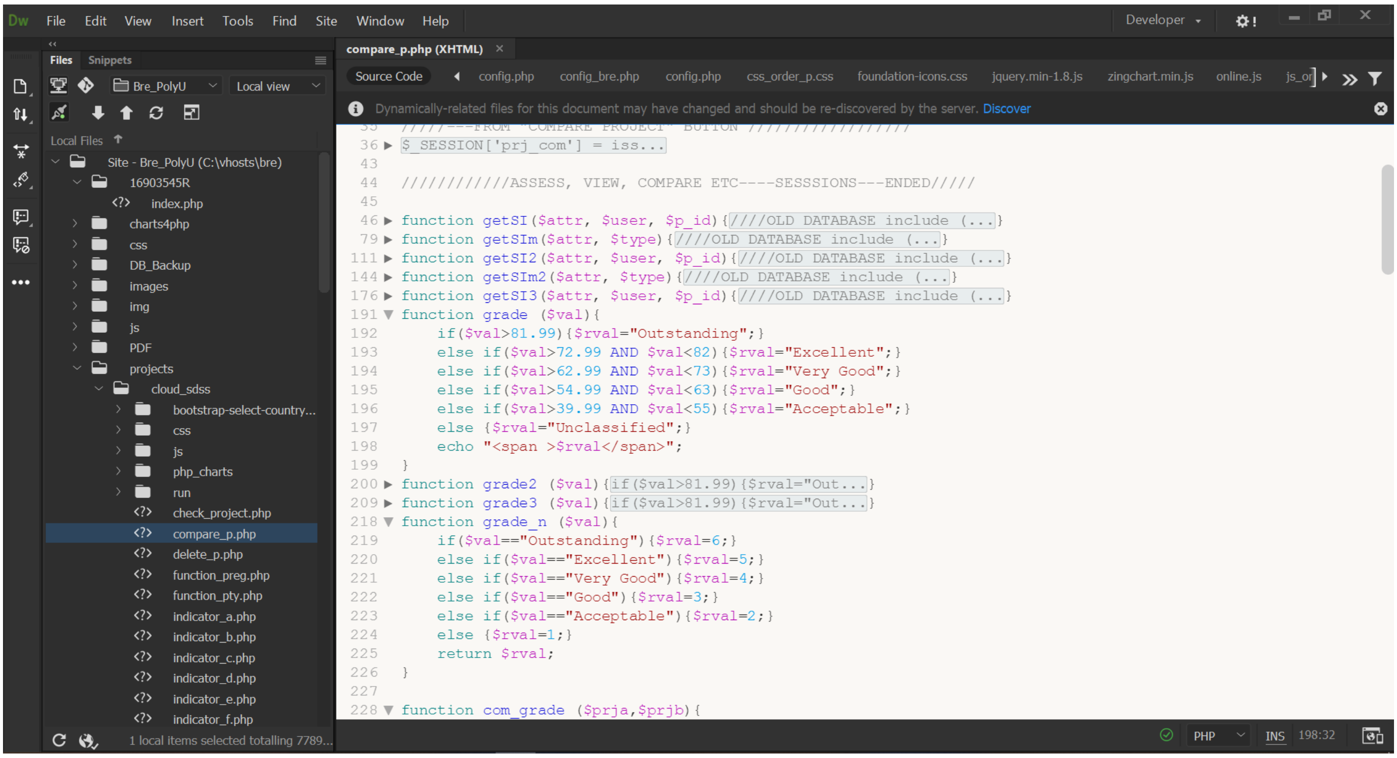

Figure E21: Programming codes for the "Compare Projects" GUI

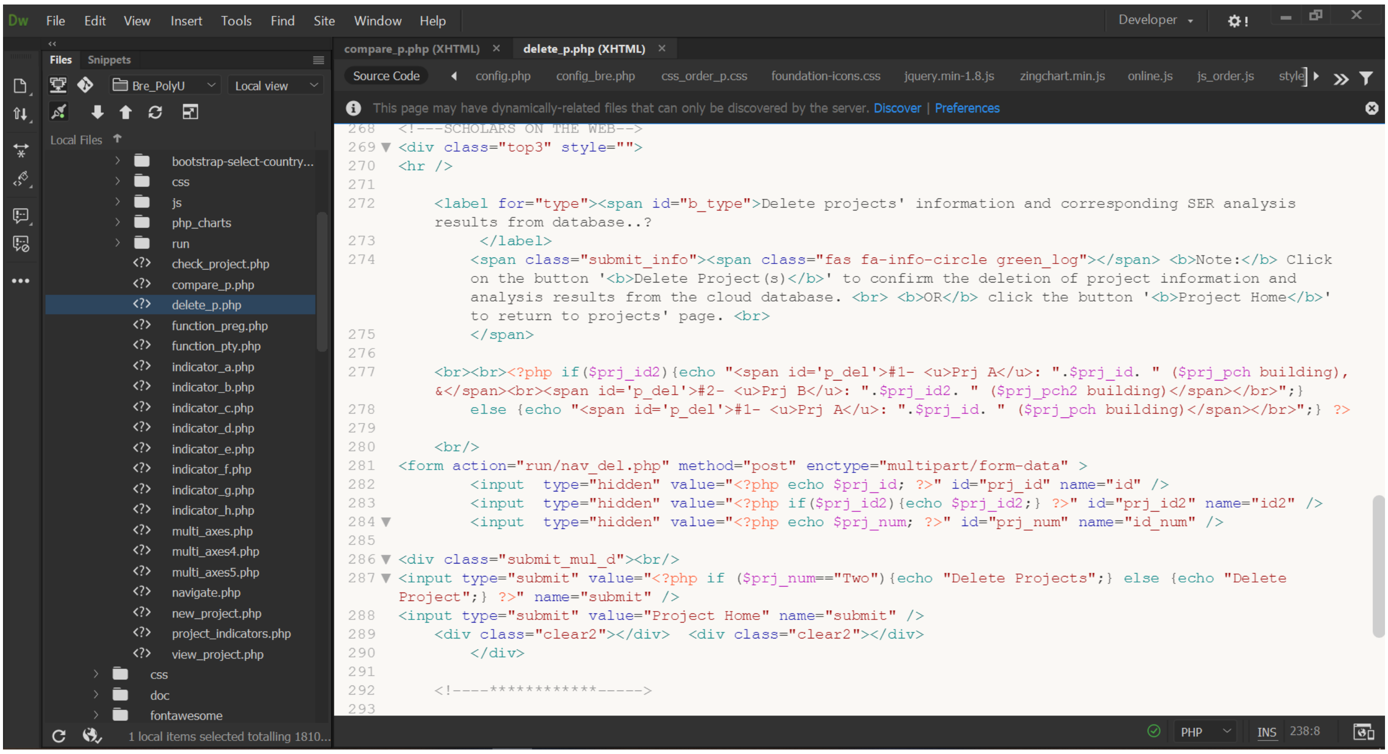

Figure E22: HTML codes for the "Delete Project(s)" GUI

APPENDIX E3: Coding and optimization process GUI

Projects' SI values comparison- based on attributes (A1-H4)

ATTRIBUTES	SI (Prj A)	SI (Prj B)	INF
A1- Project Site and Design	0.33183	0.29972	+ **Prj A**
A2- Societal Engagement	0.12316	0.10263	+ **Prj A**
A3- Safety & Health	0.09093	0.14776	+ **Prj B**
A4- Ethics & Equity	0.13103	0.34067	+ **Prj B**
A5- Construction Material & Waste	0.07275	0.10392	+ **Prj B**
A6- Project Management	0.08012	0.16023	+ **Prj B**
B1- Site Selection	0.05887	0.07850	+ **Prj B**
B2- Site Management	0.17012	0.19138	+ **Prj B**
B3- Reduction of Heat Island Effect	0.10509	0.04204	+ **Prj A**
C1- Energy Performance	0.26766	0.26766	*equal*
C2- Energy Management	0.39165	0.43517	+ **Prj B**
C3- Energy Efficient Systems & Equipment	0.19082	0.23322	+ **Prj B**
D1- Water Efficiency	0.12708	0.16944	+ **Prj B**
D2- Water Management	0.20314	0.22346	+ **Prj B**
D3- Water Efficient Systems & Equipment	0.07771	0.09325	+ **Prj B**
E1- Sustainable Purchasing Practice	0.16288	0.09773	+ **Prj A**
E2- Efficient Use & Selection of Materials	0.09720	0.04860	+ **Prj A**
E3- Waste Management Practice	0.20622	0.28554	+ **Prj B**
E4- Ease of Conversion of Building Functions	0.14974	0.11979	+ **Prj A**
F1- Alternative Means of Transport	0.21710	0.13026	+ **Prj A**
F2- Community Accessibility	0.28091	0.16052	+ **Prj A**
F3- Transport Management	0.09013	0.06759	+ **Prj A**
G1- Visual Comfort	0.06121	0.14282	+ **Prj B**
G2- Indoor Air Quality	0.13336	0.16414	+ **Prj B**
G3- Thermal Comfort	0.04700	0.07520	+ **Prj B**
G4- Acoustic Performance	0.05760	0.05236	+ **Prj A**
G5- Hygiene	0.16322	0.18362	+ **Prj B**
G6- Building Amenities	0.13339	0.11116	+ **Prj A**
H1- Operation & Maintenance	0.18377	0.30628	+ **Prj B**
H2- Security	0.02783	0.08350	+ **Prj B**
H3- Risk Management	0.09731	0.12974	+ **Prj B**
H4- Green Innovations	0.03101	0.06201	+ **Prj B**

Summary of inference (INF):
Prj A have **11** attributes with greater SI values than *Prj B*.
while **Prj B** have **20** attributes with greater SI values than *Prj A*.
Also, Prj A and Prj B have **1** attribute with the same SI values.

Note: CE duplex (*Prj A*) and RA labs (*Prj B*)

Figure E31: Comparative assessment of the NB projects respectively on the C-SDSS platform – based on the sustainability attributes

Projects' SI values comparison- based on attributes (A1-H4)

ATTRIBUTES	SI (Prj A)	SI (Prj B)	INF
A1- Project Site and Design			*equal*
A2- Societal Engagement			*equal*
A3- Safety & Health			*equal*
A4- Ethics & Equity			*equal*
A5- Construction Material & Waste			*equal*
A6- Project Management			*equal*
B1- Site Selection	0.09070	0.09070	*equal*
B2- Site Management	0.27028	0.22114	+ **Prj A**
B3- Reduction of Heat Island Effect	0.04857	0.12143	+ **Prj B**
C1- Energy Performance	0.30928	0.35686	+ **Prj B**
C2- Energy Management	0.50282	0.50282	*equal*
C3- Energy Efficient Systems & Equipme nt	0.31847	0.26948	+ **Prj A**
D1- Water Efficiency	0.29367	0.17131	+ **Prj A**
D2- Water Management	0.25819	0.23472	+ **Prj A**
D3- Water Efficient Systems & Equipmen t	0.19753	0.17957	+ **Prj A**
E1- Sustainable Purchasing Practice	0.15056	0.18820	+ **Prj B**
E2- Efficient Use & Selection of Materials	0.09360	0.11231	+ **Prj B**
E3- Waste Management Practice	0.23829	0.31160	+ **Prj B**
E4- Ease of Conversion of Building Funct ions	0.17301	0.17301	*equal*
F1- Alternative Means of Transport	0.25085	0.20068	+ **Prj A**
F2- Community Accessibility	0.32459	0.11592	+ **Prj A**
F3- Transport Management	0.05207	0.03905	+ **Prj A**
G1- Visual Comfort	0.16502	0.17681	+ **Prj B**
G2- Indoor Air Quality	0.14817	0.15409	+ **Prj B**
G3- Thermal Comfort	0.07603	0.07603	*equal*
G4- Acoustic Performance	0.05445	0.06655	+ **Prj B**
G5- Hygiene	0.17681	0.18860	+ **Prj B**
G6- Building Amenities	0.12844	0.15413	+ **Prj B**
H1- Operation & Maintenance	0.35390	0.30081	+ **Prj A**
H2- Security	0.09648	0.03216	+ **Prj A**
H3- Risk Management	0.14991	0.14991	*equal*
H4- Green Innovations	0.07165	0.07165	*equal*

Summary of inference (INF):
Prj A have **10** attributes with greater SI values than *Prj B*.
while **Prj B** have **10** attributes with greater SI values than *Prj A*.
Also, Prj A and Prj B have **12** attributes with the same SI values.

Figure E32: Comparative assessment of the EB projects respectively on the C-SDSS platform – based on the sustainability attributes

Note: SNN building (*Prj A*) and FT building (*Prj B*). Attributes A1 – A6 is not evaluated for existing buildings according to the BSAM scheme green rating system.