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Green-Building Information Modelling (Green-BIM) Assessment Framework for Evaluating Sustainability Performance of Building Projects: A Case of Nigeria

Abstract

There exists a research gap in the use of digital systems to aid the sustainability performance assessment of buildings, and this informs the development of the green-BIM assessment (GBA) framework in this paper. The study employed a conceptual framework design, expert surveys, and case studies to identify and establish the different components of the GBA framework. The developed GBA framework incorporates the BSAM scheme as its primary green building rating system and provides a cost-effective solution for sustainability appraisal. The findings revealed that the 4Ws of the information exchange workflows would facilitate the implementation of the GBA system and the expert validation confirmed its suitability for the Nigerian context. The C-SDSS served the digital component of the GBA system towards automating the sustainability performance assessment of buildings. The GBA system provides the construction industry with an effective tool that could ease of comparing two or more building projects or its designs for several uses – such as contract bidding, evaluating alternative designs, and the like. The application of the GBA system can be extended to facilitate its adoption in other regions or countries. The study's deliverables are expected to enhance the implementation of smart and eco-initiatives in Nigeria and sub-Saharan Africa.

Keywords: BIM; green buildings; green building rating system; sustainability; Nigeria

Abbreviations	
GBA framework	Green-BIM Assessment framework
Green-BIM	Green-Building Information Modelling
BIM	Building Information Modelling
i/o	Input and output
BSAM scheme	Building Sustainability Assessment Model scheme
C-SDSS	Cloud-based Sustainability Decision Support System
IoT	Internet of Things
GBRS	Green Building Rating System
LEED	Leadership in Energy and Environmental Design
BREEAM	Building Research Establishment Environmental Assessment Method
CASBEE	Comprehensive Assessment System for Built Environment Efficiency
GCFI Method	Generalized Choquet Fuzzy Integral Method
IEM	Information Exchange Workflows
BSER	Building Sustainability Evaluation Ratio

1. Introduction

In recent years, there has been an increase in the adoption of sustainability and digital tools such as BIM (Olawumi et al., 2020). These innovative developments have facilitated a paradigm shift which has enabled concepts such as smart buildings and cities, green buildings, among others (Lam & Yang, 2020). The Green-BIM concept as an emerging trend in the literature and practice involves the application of BIM to enhance sustainability implementation (Wu & Issa, 2014). Green-BIM is an innovative and emerging concept (Olawumi & Chan, 2019) with the potentiality to bridge and break the "aura of singularity" of the sole implementation of either smart initiative (with focus on BIM) and eco-initiatives in the built environment (Wu & Issa, 2014).

Several verifiable benefits of the adoption of BIM have been identified in the literature which includes enhanced collaboration, better design products, data exchange (Abdirad, 2016; Antón & Díaz, 2014; Cemesova et al., 2015) and the like. BIM applications also permit the integration of construction processes such as sustainability, scheduling, project management. For instance, Oti et al. (2016) and Tsai et al. (2014) demonstrated the capabilities of BIM to assess sustainability parameters of building models via the use of plugins. Yuan et al. (2019) pointed out the versatility of BIM across the building lifecycle.

1.1 Knowledge gaps, research objectives, and values

In practice, some buildings and cities have sprung up solely on either the concepts of "eco" – which incorporates mostly sustainability measures – or smart schemes (Cugurullo, 2017). However, project teams have been unable to implement both concepts (smart and sustainable practices - SSP) due to issues related to unclear standards (Lobos et al., 2019). A key limitation to implementing SSP is the interoperability issues of BIM software (Adamus, 2013). Other barriers associated with the joint implementation of smart and eco-initiatives in construction projects are highlighted in Olawumi et al. (2018). Conversely, there are practical benefits and positive effects of smart- and eco-initiatives, which include better occupants' comfort, less carbon footprint, better design of buildings, and the like (Ali & Al Nsairat, 2009; Lee et al., 2012).

However, Jung and Lee (2015) revealed a less than 10 per cent 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. Another study by Jung and Lee (2015) shows a low level of BIM adoption in Africa and a review of sustainable practices implementation across the globe, reveals that Africa as a region is a slow adopter (Olawumi & Chan, 2018). A key step in the Africa region to improve sustainability adoption was the recent development of a green building rating system (BSAM scheme) for sub-Saharan Africa (Olawumi et al., 2020). However, there is a need to integrate BIM as a digital tool to facilitate sustainability assessment (Saka & Chan, 2019) in the region. As reported by Olawumi and Chan (2019), the development of a digital and automated system can drive the implementation of green-BIM.

Given the above, the current study aims to develop a green-BIM assessment (GBA) framework to evaluate the sustainability performance of buildings and facilitate the implementation of smart, sustainable practices in Nigeria. Towards achieving the study's aim, firstly, the key components constituting the proposed GBA framework will be identified. Also, the data required for each GBA framework's component and at the different building development stages will be identified. An expert validation exercise and case studies will be undertaken to verify its suitability and applicability within the Nigeria built environment. Some parts of the GBA framework have been validated in real-life case study building projects (see Figure 1, step 3 – 5).

Scope. The scope of the application of the proposed GBA framework is delimited to Nigeria with applicability to other countries in sub-Saharan Africa because:

(i) One of the GBA components – the BSAM scheme – was designed to suit the local context of sub-Saharan Africa (Olawumi et al., 2020).

(ii) Nigeria has the largest economy and construction market in the sub-Saharan region and has always being a reference point to other countries in the region. Hence, the application of this Nigeria case study reference could easily be extended to the other countries in the region.

This study presents one of the key stages of concerted research works to digitalize sustainability assessment in sub-Saharan Africa. The research reported in this paper forms part of a larger project to develop a digitalized system to aid the sustainability assessment of green buildings in Nigeria and sub-Saharan Africa. The results of the previous stages of this project have been published in the extant literature (see Figure 1). The current study (Figure 1, stage 6) augments these earlier works by developing the GBA system to aid the implementation of SSP in the built environment.

Insert Figure 1

The study's deliverables are expected to enhance the implementation of SSP as well as aid clients, project teams, and other stakeholders assess the 'greenness' of building projects.

2. Research Methodology

The study employed a mixed research design, as outlined in Figure 2 to develop, and validate the proposed GBA framework. It involves the conceptualizing the GBA framework, case studies and expert survey validations of the GBA system.

2.1 Conceptual Framework Development

This section discusses the approach to utilizing the conceptual framework and why it is adopted in this study. 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.
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). Readers interested in the use of theoretical frameworks can consult previous studies (*see* Osanloo & Grant, 2016; Ravitch & Carl, 2015; Zack, 2019). 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 eases the presentation of the key framework constructs in graphical and logical structure to illustrate their interrelationships (Dickson et al., 2018).

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).

2.1.1 Why conceptual framework for GBA framework development?

The conceptual framework approach was employed to contextualize the proposed GBA framework. The suitability of the conceptual framework development approach was based on the fact that – *firstly*, there are no previous theoretical frameworks/studies (Akintoye, 2015) which have conceptualized GBA framework's IEM. That is the *extraction* of relevant data from BIM systems, a GBRS, regulatory documents, and other documentary evidence *into* a relational database; and the *use* of such building data on a C-SDSS *to* assess a building sustainability performance.

More so, *secondly*, the key constructs of the proposed GBA framework were identified and discussed. *Thirdly*, these constructs are interconnected to explain their relationships and how they fulfilled the research objective. L*astly*, the developed GBA system has potential impacts on the construction industry. 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.

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.

2.2 Case studies and experts' survey validations

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., 2016). Key reasons for a validation exercise are to test whether a developed model achieved an acceptable quality and requirements (Hu et al., 2016) as well as to enhance the credibility of the research outputs. Several approaches to validation have been adopted in the extant literature which include questionnaire surveys, case studies, experiments, modelling and simulation, etc. (Hu et al., 2016; Lucko & Rojas, 2010). Case studies and expert validations are adopted in this study.

Section 3 goes in-depth towards identifying and mapping the components of the GBA framework and illustrating its operationalization. Meanwhile, Section 4 discusses the validation of the GBA framework via expert validation and the case studies evaluation of the cloud-based sustainability assessment system.

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 evaluation of the sustainability performance of green buildings with the support of a cloud-based decision support system. The proposed GBA system (Figure 3) has six main components, such as the BIM system, regulatory documents, data and evidence, the BSAM scheme (a green building rating system), relational databases, and the C-SDSS platform.

The proposed GBA system applies to building projects and construction organizations where BIM infrastructure is employed, and sustainability practices implemented. More so, the GBA framework is primarily suited to Nigeria and could be extended to other countries within sub-Saharan Africa. Three of the GBA framework's components have been fully developed as part of a larger project, as illustrated in Figure 2. Hence, this paper focus on conceptualizing and integrating the other key components (BIM system, regulatory documents, data & evidence) towards facilitating the evaluation of the sustainability performance of green buildings.

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 framework.

Table 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 4 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 construction industry, such as construction firms, consultants, government agencies, clients, professional bodies, among others.

Meanwhile, the "who" aspect of the information exchange workflow of the GBA framework refers to the professionals with the required competency to provide the necessary data highlighted in Table 1. The "who" aspect has been highlighted within the BSAM scheme documentation (Olawumi et al., 2020) and will not be further discussed in this paper.

Insert Figure 3

Insert Table 1

Insert Figure 4

As shown in Figure 4, 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.

3.1.1 BIM system

The building data and specifications are represented in forms of information models in BIM system (Philipp, 2013). BIM software is a revolutionary information technology (IT) tool used in the design and creation of building models (Ma et al., 2018). 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: 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 processing or simulation; the resultant simulation or modelling 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 4, 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 5, 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 fulfil. For instance, an energy MR can be linked with sustainability criteria C of the BSAM scheme green building rating system (Olawumi et al., 2020) and uploaded to the relational databases of the C-SDSS system to aid the assessment of building sustainability performance.

Insert Figure 5

Practitioners can use the GBA system to access the stored BIM model data in the relational database during the process of evaluating 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.

3.1.2 Regulatory Documents

The required data that constitute the regulatory documents have been highlighted in Table 1 and outlined in the BSAM scheme documentation (Olawumi et al., 2020). As shown in Figure 4, 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/softcopy document format (*preferable*). As shown in Figure 6, 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.

Insert Figure 6

3.1.3 Data and Evidence

The required information that embodies the data and evidence component has been highlighted in Table 1. As shown in Figure 4, 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 7, 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 framework 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 green building projects.

Insert Figure 7

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 et al., 2020). 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 mapped to the respective data of the GBA framework's components A, B, and C to aid the sustainability assessment of buildings. As shown in Table 1, the BSAM scheme green building rating system comprises of eight sustainability indicators (criteria) (Olawumi et al., 2020).

As shown in Figure 4, the sustainability criteria which are assessed in green buildings vary from the concept stage 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. Readers could refer to (Olawumi et al., 2020) on how the BSAM scheme can be used to evaluate the building sustainability performance.

3.1.5 Relational databases and C-SDSS system

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 building projects. The relational databases and the 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 key 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 (Figure 8); (iii) an interface to view each project assessment index; (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.

Insert Figure 8

As shown in Figure 4, 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.

4. Validation of the GBA framework

This section presents the findings from the real-life case studies and expert validations of the GBA framework.

4.1 Case study analysis

Case studies validation of the developed cloud-based sustainability assessment system was carried out in real-life building projects in Nigeria. The C-SDSS component of the GBA framework was coded, designed, and developed using programming languages such as PHP, Jscript, etc. More so, the BSAM scheme was embedded, and the MySQL relational databases integrated respectively into the cloud-based system, as shown in Figure 2 and illustrated in Figure 3. Relevant data from GBA components A, B, and C as highlighted in the BSAM scheme documentation (Olawumi et al., 2020) and section 3 were collated for two new building projects. The building projects were classified based on (BRE, 2018) classification, which defined new buildings as those facilities within a year of occupancy.

The cloud-based system was tested on a residential and a commercial building, respectively because the BSAM scheme – which is the main GBRS of the GBA framework supports the sustainability assessment for both building types. Also, relevant BIM models and sustainability-related data (utility records – energy, water, and the like; specifications; transportation routes; etc.) for the two buildings were gotten to undertake the sustainability assessment process. Where the required data were not available, reasonable assumptions were made as advised by (Mahmoud et al., 2019).

The case study residential building is in south-east Nigeria and comprises of rooms of varying sizes, staircase, gatehouse, and other facilities covering a gross floor area (GFA) of about 460m^2. The green area is about 40% of the GFA of this building site and also included a paved area (about 142m^2). The case study commercial facility is located in Lagos, south-west Nigeria. The facility comprises of office areas, laboratories, stores, meeting rooms, and the like within its about 347m^2 GFA. It has no paved area, and its green area is about 10% of its GFA. Both case study projects are one storey buildings.

The results of the two case study building projects' sustainability assessment conducted on the cloud-based system show that the residential building is rated "Good" and the commercial building is rated "Very Good" based on the BSAM scheme grading system with a BSER value of 62.54% and 70.05%, respectively. Appendix A shows the output results of the two case studies as produced on the C-SDSS.

4.2 Experts' validation surveys

After the case-study building projects assessment, expert validation surveys were carried out to validate the suitability, credibility, and quality of the GBA framework as a tool to evaluate the sustainability performance of green buildings, as well as promote the implementation of smart technologies in building projects. Two modes of survey distributions were adopted – the fill-in PDF survey forms and online survey forms. 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) 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 the respondents' background information, while the second section presented the process maps of the GBA components and how it relates to the building lifecycle stages. The third and fourth sections presented the proposed GBA framework and the eight validation questions which relate to the four validity types – internal, external, construct, and content validity – respectively. 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).

4.2.1 Experts' demographics

Selection criteria and sampling. The selection criteria used to invite the survey respondents – includes those with extensive experience in BIM and green building implementation in Nigeria as well those with requisite expertise in the built environment. Purposive sampling technique was used 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 the other via the PDF fill-in survey form. The sample size for this study is adequate and larger 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. Table 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).

Insert Table 2

The analysis of expert demographics reveals the experts are from diverse groups of key stakeholders involved in the Nigeria 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.

4.2.2 Validation survey results

Table 3 shows the analysis of the experts' perceptions of the eight validity statements. 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. The Li et al. (2013) factors' classification scheme was also adopted by Zahoor et al. (2017), and it provides convenient scale intervals to categorize the significance of the variables. 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 in Nigeria, 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 framework 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 data 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 in the Nigeria construction industry. 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 construction industry as well as the assessment of the sustainability performance of green buildings in Nigeria.

Insert Table 3

5. Practical implications and recommendations

Practical implications. The developed GBA framework provides the first attempt in the literature and practice of the digitalization of the sustainability assessment process of green buildings. Prior to this study, assessing of the greenness of building and infrastructure as being via a manual and tedious process which resultant loss of man-hours and cost which will not appeal to clients and project teams – especially in Nigeria or other countries in sub-Saharan Africa. More so, the GBA system provides a cost-effective solution to the sustainability assessment process, thereby eliminating a key barrier to the adoption of sustainability and BIM in Nigeria and sub-Saharan Africa.

The illustrated 4Ws of the GBA information exchange workflows provide industry practitioners with an operationalization guideline towards deploying the GBA framework in construction projects. Thus, eliminating the limitation of usability and learning curves problems faced when new tools are introduced within the built environment. Moreover, the GBA framework extends the applicability of the BSAM scheme as a green building rating system for use within the sub-Saharan region, of which Nigeria is inclusive.

The GBA framework utilizes a cloud-based platform for its operation, eliminating the need for software installation and upgrades as well as improving the computational speed for sustainability assessment. Also, the GBA framework, via its embedded C-SDSS platform allows a user to register and assess an unlimited number and categories of buildings. Hence, this can facilitate the ease of comparing two or more building projects or its designs for several uses – such as contract bidding, evaluating alternative designs, and the like. The GBA framework also provides the results of building assessment and comparison in various forms – tables and graphs to ease the project decision-making process.

The study also extended the knowledge base of sustainability assessment in the built environment by highlighting the various data required for each GBA components while also providing a digital tool to facilitate green building assessment in practice. The GBA framework also allows for the future integration of other existing GBRS such as LEED, BREEAM, etc. to extend its application beyond Nigeria. 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. The study's deliverables are expected to improve the implementation of smart and eco- initiatives in Nigeria and sub-Saharan Africa.

Recommendations. The following strategies are recommended for implementation by relevant stakeholders to ensure the optimal implementation of the GBA framework and facilitate green-BIM initiatives in the built environment. These strategies are dissemination, development, and advancement. Firstly, by dissemination – stakeholders in the region are encouraged to facilitate the creation of workshops/seminars and conferences to increase the awareness and skillset of stakeholders on the green and smart initiatives. Also, exhibitions and science forums should be organized regularly to allow the showcase of digital systems such as the GBA framework to the industry as well as attract the wider interest of researchers and the government.

More so, by development, after these industry-organized workshops and exhibitions, the showcased digital systems and initiatives such as the developed GBA system must be further implemented in a real-life case study environment. For instance, the GBA framework can be used to assess the sustainability performance of ongoing/completed projects as well as for comparison and benchmarking purposes. More so, 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 in Nigeria (and in other sub-Saharan countries) should be formulated for reference purposes by amalgamated bodies of built environment professionals. Such guidelines will provide stakeholders with the best practices and guidelines for deploying the GBA framework and improving SSP in the built environment.

6. Conclusions

The increased interest in sustainable buildings and cities have led to calls to consolidate the smart- and eco- initiatives for implementation in the built environment. Hence, a GBA framework that integrates some 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) was developed in this paper. The established GBA framework provides a cloud-based automated system for the holistic assessment of the sustainability performance of green buildings.

This study expatiated on the 4Ws of the information exchange workflows and how it is designed to operate within the GBA framework. More so, the 4Ws is intended to assist construction stakeholders in understanding the operationalization of the GBA framework towards facilitating its use for sustainability assessment. The GBA framework components and their functionality were discussed and illustrated. More so, the developed GBA framework was validated by experts as well as using case studies to validate its cloud-based components. The analysis of the validation results provided credence to the applicability of the GBA framework to facilitate the sustainability assessment of green buildings using digital systems as well as enhance the implementation of smart sustainable buildings in Nigeria. The case studies assessment shows the capability of the cloud-based components of the GBA framework to automate the sustainability assessment of buildings in the built environment. The practical implications of the GBA framework in the built environment were highlighted, as well as necessary 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. However, it could be applied to other countries in sub-Saharan Africa. Future research studies can focus on further improvements on the GBA framework and its deployment in building projects in other contexts. More so, further studies could embed 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.

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Table 1: Descriptions of the data/information required for the GBA framework

Components of GBA framework	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 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*).

Table 2: Demographics of the experts involved in the validation process

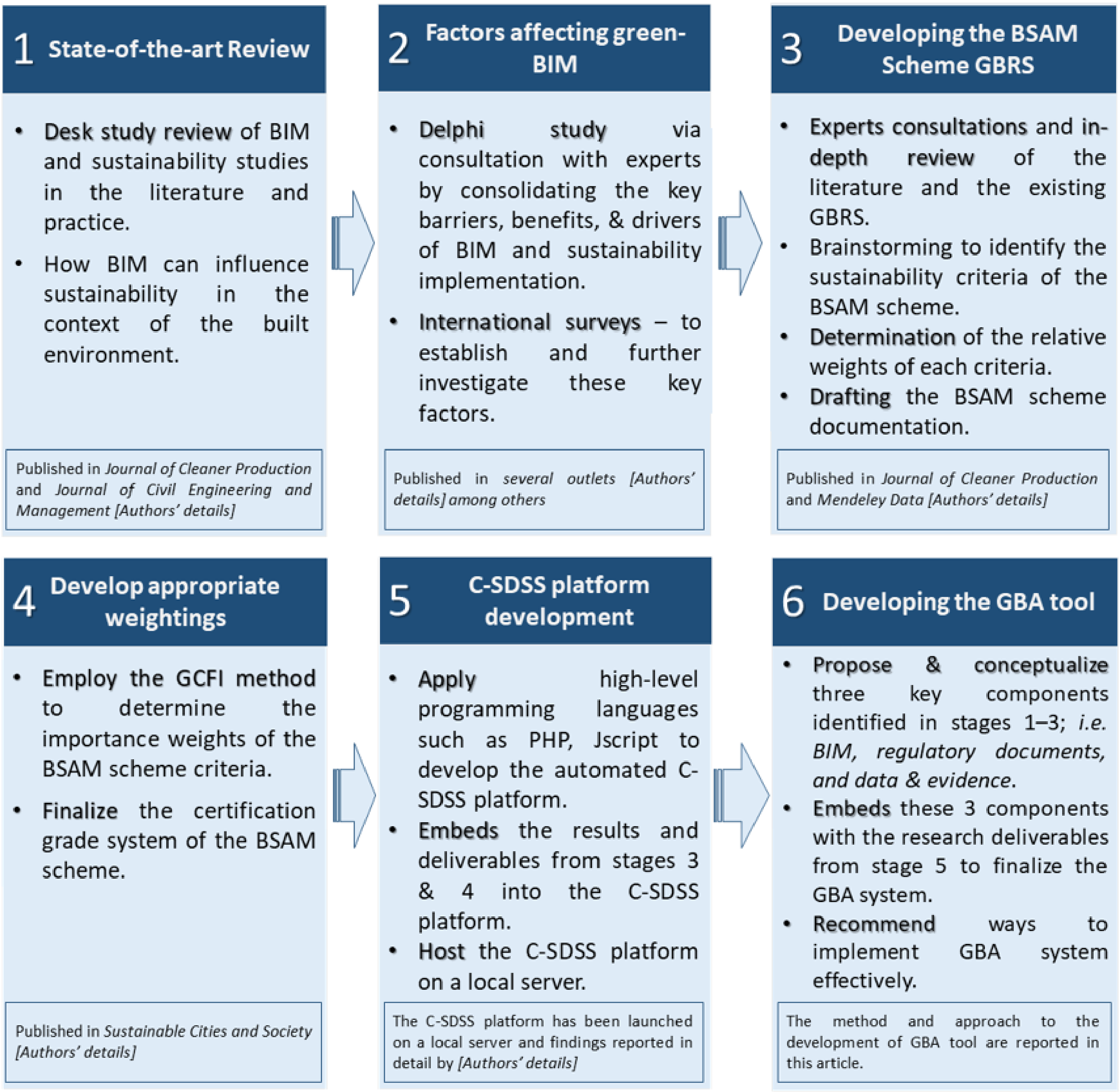
Description	Frequency	Percentage (%)	Description	Frequency	^{a}Average year
Major profession or occupation			**Positions**		
Architects	4	20	Top-level managers	9	15
Civil Engineers	1	5	Middle-level staff	8	5
Project Managers	2	10	First-level staff	3	2.5
Quantity Surveyors	7	35	**Total**	**20**	
Estate Valuers	2	10			
Builders	1	5			
Academics	3	15			
Total	**20**	**100**			

Note: ^{a}Average year – The average year of experience (of the respective expert's management level) in the construction industry.

Table 3: Validation survey 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 to assess a building sustainability performance at each building lifecycle stage is 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



1 State-of-the-art Review

- **Desk study review** of BIM and sustainability studies in the literature and practice.
- How BIM can influence sustainability in the context of the built environment.

Published in *Journal of Cleaner Production* and *Journal of Civil Engineering and Management [Authors' details]*

2 Factors affecting green-BIM

- **Delphi study** via consultation with experts by consolidating the key barriers, benefits, & drivers of BIM and sustainability implementation.
- **International surveys** – to establish and further investigate these key factors.

Published in *several outlets [Authors' details] among others*

3 Developing the BSAM Scheme GBRS

- **Experts consultations** and **in-depth review** of the literature and the existing GBRS.
- Brainstorming to identify the sustainability criteria of the BSAM scheme.
- **Determination** of the relative weights of each criteria.
- **Drafting** the BSAM scheme documentation.

Published in *Journal of Cleaner Production* and *Mendeley Data [Authors' details]*

4 Develop appropriate weightings

- **Employ the GCFI method** to determine the importance weights of the BSAM scheme criteria.
- **Finalize** the certification grade system of the BSAM scheme.

Published in *Sustainable Cities and Society [Authors' details]*

5 C-SDSS platform development

- **Apply** high-level programming languages such as PHP, Jscript to develop the automated C-SDSS platform.
- **Embeds** the results and deliverables from stages 3 & 4 into the C-SDSS platform.
- **Host** the C-SDSS platform on a local server.

The C-SDSS platform has been launched on a local server and findings reported in detail by *[Authors' details]*

6 Developing the GBA tool

- **Propose & conceptualize** three key components identified in stages 1–3; *i.e. BIM, regulatory documents, and data & evidence.*
- **Embeds** these 3 components with the research deliverables from stage 5 to finalize the GBA system.
- **Recommend** ways to implement GBA system effectively.

The method and approach to the development of GBA tool are reported in this article.

Figure 1: Stages of the development of the Green-BIM Assessment (GBA) framework

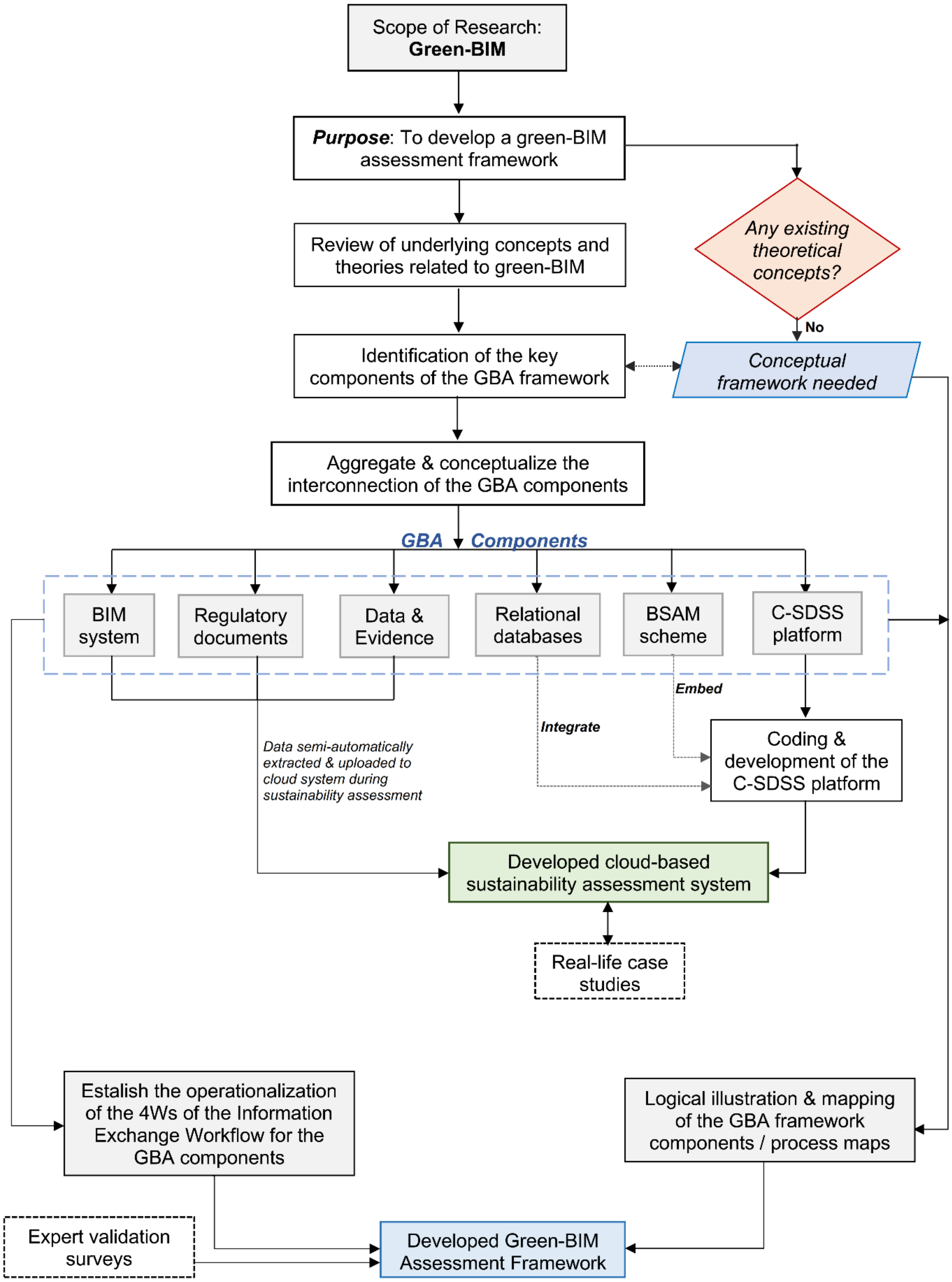


Figure 2: Outline of the research design

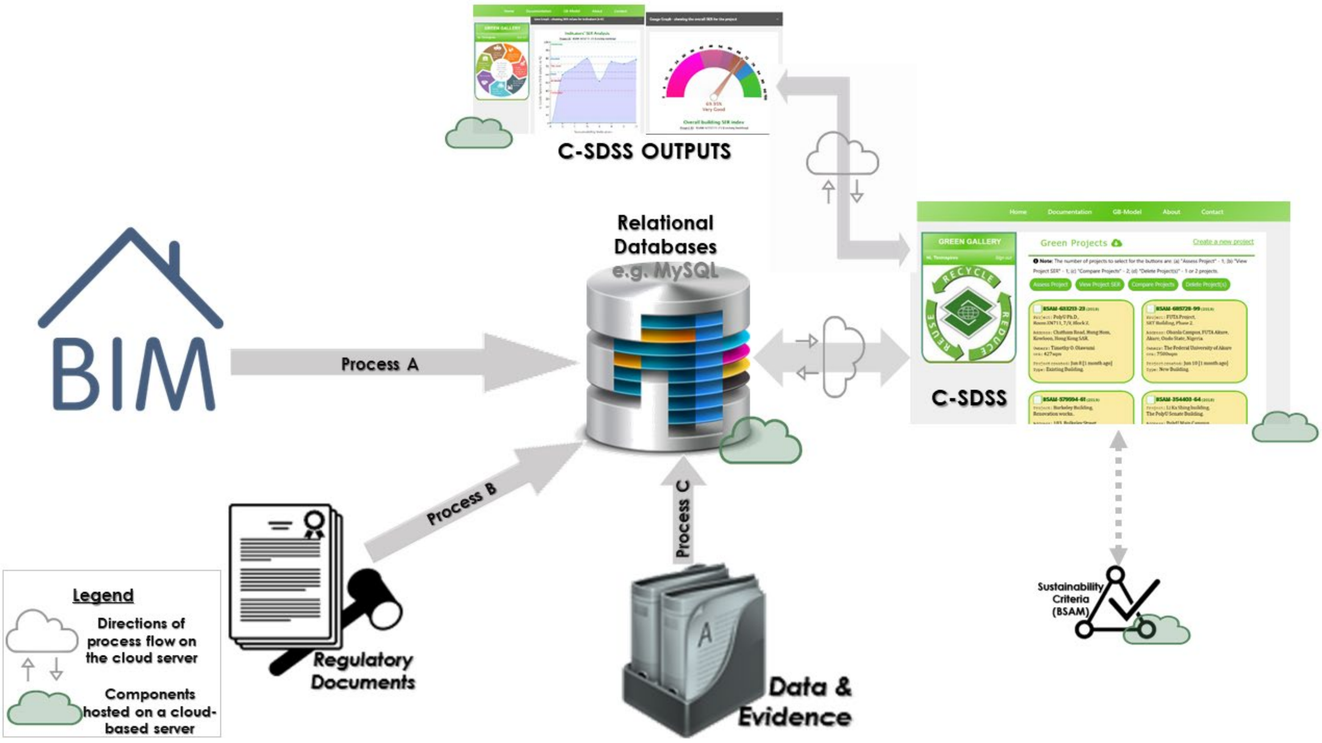


Figure 3: Components of the proposed GBA framework

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.

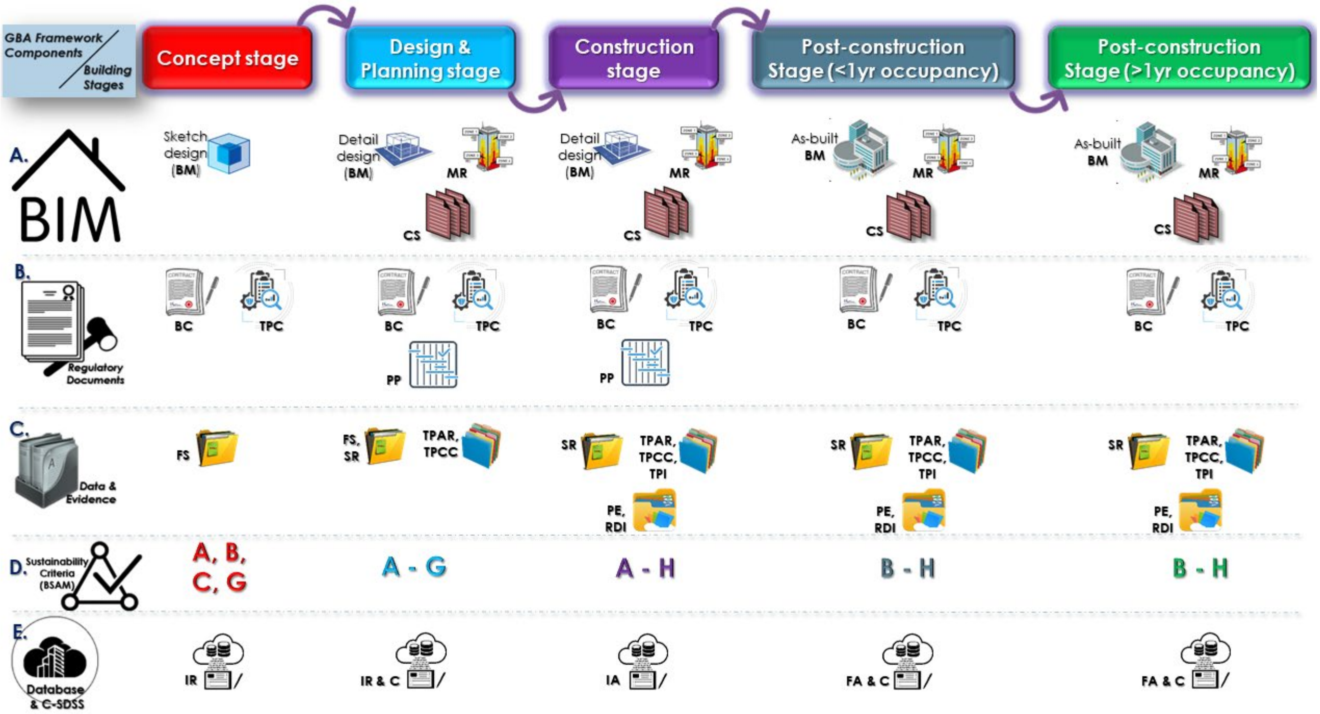


Figure 4: Data required by each component of the GBA framework at the various stages of building development

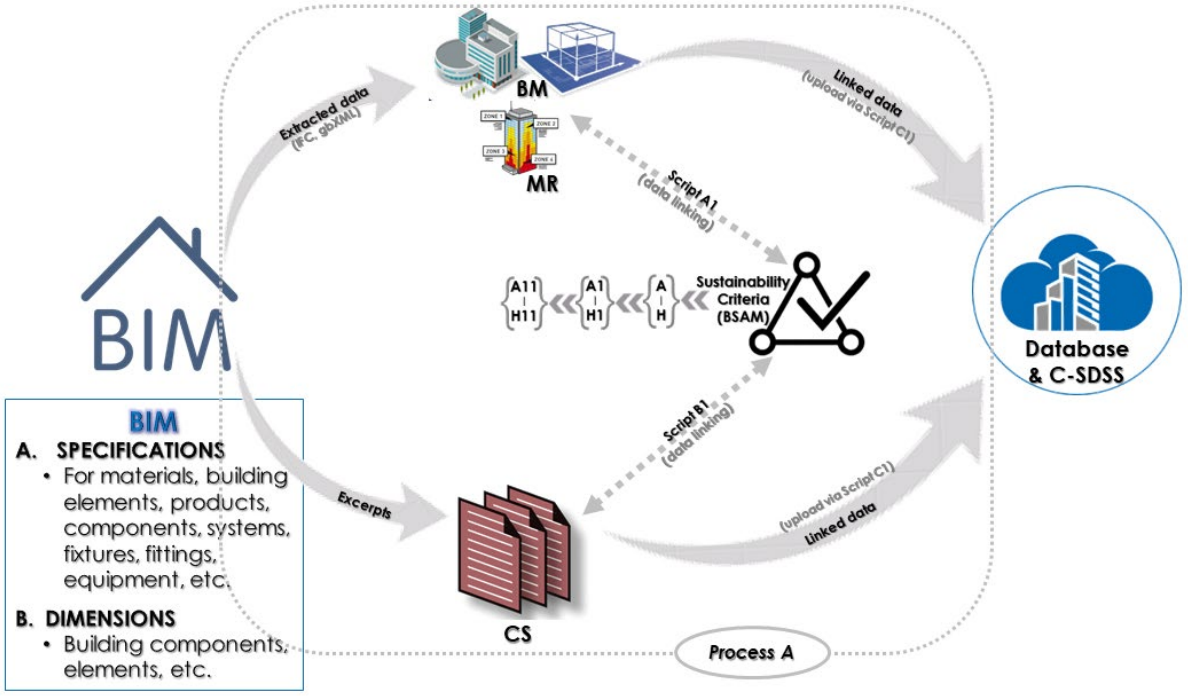


Figure 5: Process map for the BIM System of the GBA framework

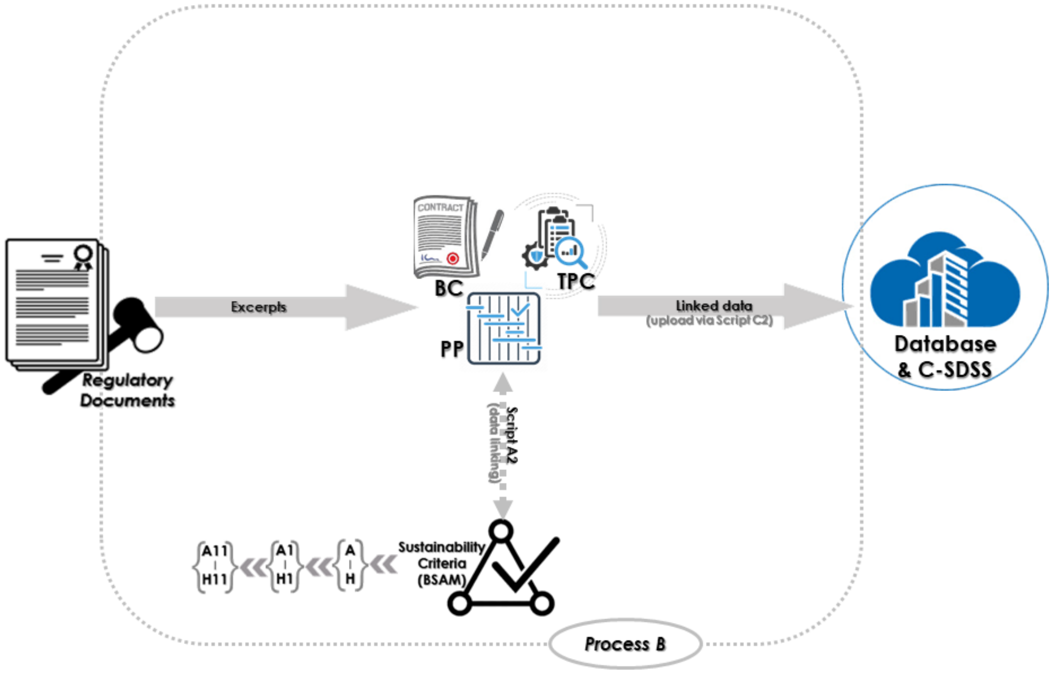


Figure 6: Process map for the Regulatory Documents of the GBA framework

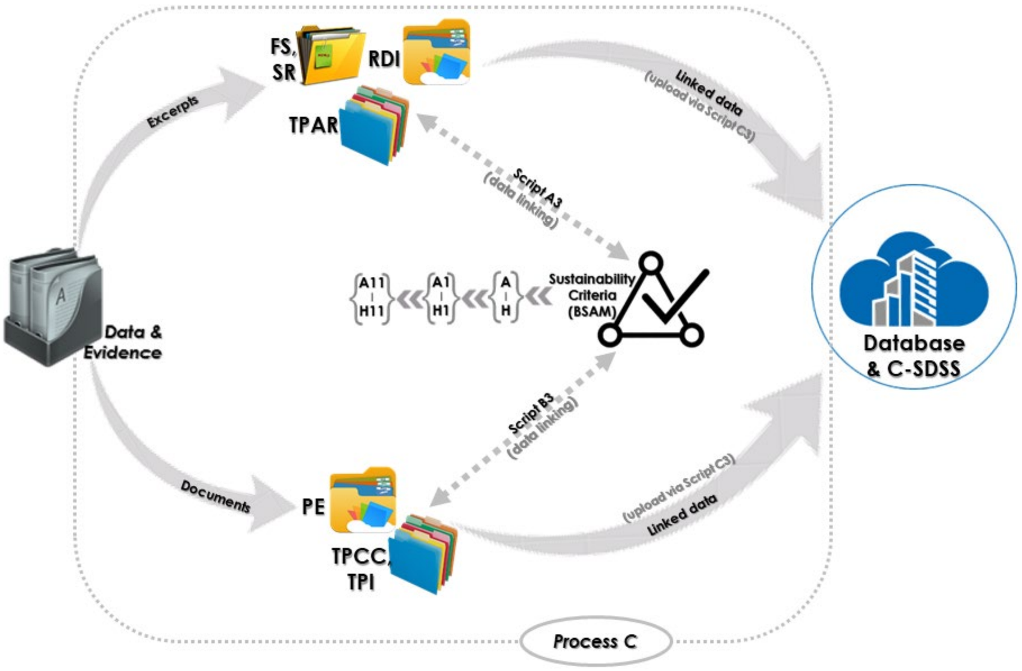
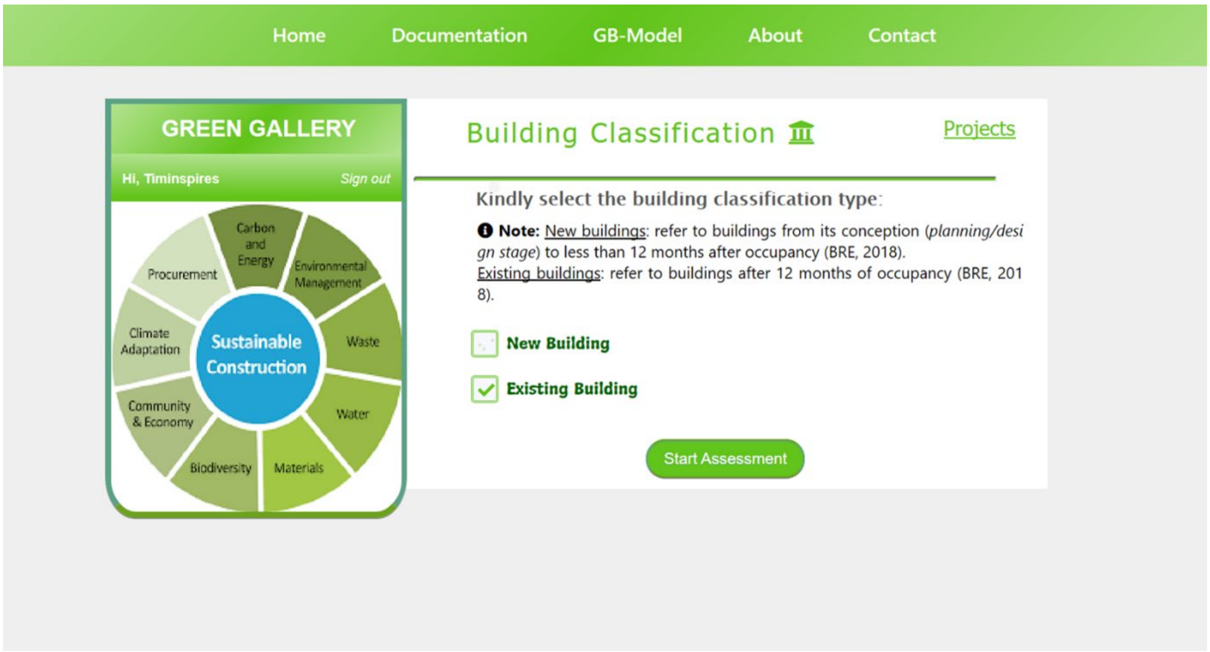


Figure 7: Process map for the Data and Evidence component of the GBA framework



Building Classification

Kindly select the building classification type:

Note: New buildings: refer to buildings from its conception (*planning/design stage*) to less than 12 months after occupancy (BRE, 2018).
Existing buildings: refer to buildings after 12 months of occupancy (BRE, 2018).

☐ **New Building**

☑ **Existing Building**

Figure 8: The C-SDSS system's project assessment interface