Cloud-based Sustainability Assessment (CSA) System for Automating the Sustainability Decision-Making Process of Built Assets

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Abstract

Digital tools help facilitate the implementation of sustainability practices in the built environment in the era of rapid urban developments. However, the extant literature revealed salient gaps in the use of cloud-based systems and digital tools to evaluate buildings' sustainability performance. Consequently, the current study aims to develop and implement a cloud-based sustainability assessment (CSA) system to evaluate and compare the sustainability performance of buildings based on the Building Sustainability Assessment Method (BSAM) scheme green rating system. A design science research (DSR) approach was adopted in designing, developing, and validating the CSA system. The developed CSA system is based on the *SaaS* model of cloud computing. The methods evaluation validation of the CSA system when compared with other systems revealed that the developed CSA system would result in higher time and learning efficiency for the users. The findings from the case study validation of the CSA system, using four building projects, indicate that the developed artefact offers a better secured, automated, reliable, and value-adding tool for the building sustainability assessment process. It also eases the automated process of updating data, evaluating, and comparing building projects towards improving the overall building sustainability profile. More so, the CSA system has a great potential to assist stakeholders in their buildings' sustainability decision-making process and enhancing sustainable development.

Keywords: BSAM scheme; cloud-based system; design science research; digital tool; green building; sustainability assessment.

Nomenclature

ICT	Information and Communication Technology
RFID	Radio Frequency Identification
IFC	Industry Foundation Class
BREEAM	Building Research Establishment Environmental Assessment Method
LEED	Leadership in Energy and Environmental Design
BSAM	Building Sustainability Assessment Method
GCFI	Generalized Choquet Fuzzy Integral method
BSER	Building Sustainability Evaluation Ratio
SER	Sustainability Evaluation Ratio
UML	Unified Modelling Language

MCP	Maximum Credit Point
SC	Sustainability Criteria
FI	Factor index
GW	Global weight
NW	Normalized weight
BIM	Building Information Modelling

1. Introduction

In recent years, there has been an increase in large-scale urban development and interventions in the built environment worldwide due to the need to shore up 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. In this regard, Bengtsson and Gerfalk (2011) and Nazarko (2015) recommended using technological solutions to advance the implementation of sustainability in developing countries and achieve sustainable development.

A plethora of related literature provides evidence on the use of digital technology to address sustainability issues. The increasing expectation of clients and stakeholders in the construction industry to procure and produce green and smart buildings has increased the interest in the use of digital tools for sustainability notions (Chan et al., 2019; Jrade & Jalaei, 2013). Some of the benefits derivable from using digital tools for sustainability processes include performance analysis (Inyim et al., 2015), data management (Wu & Issa, 2012), production of sustainability information (Hellström, 2007), visualization, time and cost efficiency (Ilhan & Yaman, 2016), data interoperability (Vanlande et al., 2008), and facilitating decision-making (Shojaei et al., 2019).

For instance, Ilhan and Yaman (2016), while highlighting the benefits inherent in using BIM, proposed an IFC-based tool useful for extracting information from a BIM model to rate the sustainability potentials of building design using the BREEAM certification process. However, the study only focuses on the materials category of the BREEAM green rating system. In another study, Wu and Issa (2012) proposed a theoretical business framework which utilizes cloud-BIM software to advance the automation of LEED assessment for green projects. However, the proposed theoretical framework is still a long way from being implemented in a real-case scenario.

Furthermore, Banani et al. (2013) emphasized the importance of developing sustainability standards or green building rating systems (GBRS) that fits with the local context of the country and region. This is evident in the existing GBRS (that is, LEED, BREEAM, BSAM scheme, and the like) currently available for building sustainability assessments which vary based on their sustainability criteria and the significance attached to each criteria rating (Alyami & Rezgui, 2012; Xiaoping et al., 2009). In this context, Ansah et al. (2019) reviewed previous studies examining how BIM could be used to integrate selected GBRS for sustainability assessment. Accordingly, the study discovered that BIM model databases in their current forms only permit quantitative data storage and management, whereas the existing GBRS heavily utilized quantitative and qualitative data (Ansah et al., 2019). Hence, there is a mismatch in their requirement.

More so, there is the issue of interoperability which has been widely reported as a barrier to BIM being the "go-to" digital tool for sustainability assessment (Niknam & Karshenas, 2017). Also, according to Ansah et al. (2019), most studies that examined BIM-GBRS integration merely scratch the surface of it, with only very few presenting the actual validation of their developed models. Also, those few articles failed to provide in-depth process of its application, hence, limiting the replicability of such studies (Ansah et al., 2019). Other relevant applications of digital tools for sustainability implementation include the adoption of artificial photosynthesis technology for energy sustainability and sustainable ecosystem (Faunce et al., 2013), BIM-based energy and acoustic analysis (Azhar & Brown, 2009), use of wireless sensing technology, camera network, and other systems to detect occupant presence within a facility (Dong et al., 2010), among others.

Given the limitations of existing technologies, especially BIM, which has found some usefulness for building sustainability assessments in the extant literature, the current study advances the use of cloud-based systems. A cloud-based system will be able to handle both qualitative and quantitative data to which BIM model databases are incapable of embedding in its storage, as argued by Ansah et al. (2019). Moreover, there is a research gap on using digital systems to undertake holistic sustainability assessment of buildings and infrastructures. Few studies, such as Ilhan and Yaman (2016) and those identified by Ansah et al. (2019), only incorporate one sustainability criteria or green building category. Hence, the current study by developing and deploying a cloud-based system offers an automated approach to the holistic sustainability assessment of buildings based on the BSAM scheme as well as offers associated benefits derivable from applying digital solutions for sustainability implementation.

Research aim. This study aims to develop a cloud-based system to facilitate the automated sustainability assessment of buildings based on the BSAM scheme rating system. The proposed cloud-based sustainability assessment (CSA) is also expected to ease the comparative evaluation of the sustainability performance of building projects and for benchmarking purposes. Similarly, the CSA system will enhance the management of the building sustainability data and facilitate reliable and objective decision-making for construction stakeholders. Furthermore, to validate the efficiency, performance, and value of the developed CSA system, a number of validation techniques would be employed in this study – including case studies validation. The novelty of this study lies in its being the first digital tool or software that supports the holistic and automated assessment of the sustainability performance of green buildings.

Research scope. A systematic review of the global adoption of sustainability practices and the use of digital solutions for sustainability processes in the extant literature (*see* Jung & Lee, 2015; Olawumi & Chan, 2017, 2018) shows that Africa lags behind other continents. For instance, in the use of BIM for building system analysis, only 25% of the sampled data in Africa has employed BIM services compared to 37.8%, 53.6%, and 72.5% in Asia, Europe, and North America, respectively (Jung & Lee, 2015). However, the Africa region faired above average in the use of digital tools for other construction purposes such as cost estimating. A key barrier to using digital tools in developing countries in Africa is the high cost of the available commercial digital tools (Chong et al., 2014; Olawumi & Chan, 2020). Hence, the need to develop a cost-free cloud-based tool to enhance sustainability practices in sub-Saharan Africa.

Within this context and to address the lack of relevant sustainability standards in sub-Saharan Africa, Olawumi et al. (2020a) developed a green rating system – BSAM scheme. The BSAM scheme encompasses the three pillars of sustainable development in its sustainability criteria; unlike some existing GBRS like LEED, BREEAM, BEAM Plus, Green Star emphasises the environmental sustainability criteria (Mahmoud, 2017). Hence, the proposed open-source cloud-based tool in this study would embed the BSAM scheme rating scheme.

The next section presents an overview of digital technologies for sustainability implementation and the benefits of using cloud-based systems. Subsequent sections detailed the research approach, discusses the findings, and provides concluding remarks and the research implications.

2. Digital technologies in the built environment: An overview

The increasing use of information technologies has transformed the way things and activities are being undertaken in the construction industry. Various forms of digital tools have been introduced in construction processes, ranging from the widely known BIM (Olawumi et al., 2017) to others like RFID (Motamedi et al., 2013), sensors (Akinci et al., 2006), Internet of Things (IoT) (Zhai et al., 2019), cloud-based systems (Zou et al., 2018), and more recently blockchain technology (Elghaish et al., 2020) to address various issues in the construction industry. Moreover, the increasing fragmentation of the construction processes and lack of coordination between the various supply chain actors has increased the urgency to adopt ICT to overcome these barriers (Olawumi & Chan, 2019a; Wu & Hsieh, 2012). In recent years, some technologies are being integrated with each other, including cloud systems, to enhance their capability (Porkodi & Kesavaraja, 2020; Shojaei et al., 2020; Siountri et al., 2019). For instance, a review of BIM applications by Panteli et al. (2020) highlighted some related sustainability analyses that could be carried out using digital building models. These include solar and light simulation. thermal comfort analysis, energy performance analysis, waste management, CO2 emission analysis. However, BIM need to be integrated with IoTs to facilitate its use for these building sustainability analyses (Olawumi & Chan, 2021).

Moreover, Rivera et al. (2015) classified the practices of using digital technologies to influence and improve a practice or process into three main types: (i) ICT-based practices, (ii) ICT-supported practices, and (iii) ICT-enhanced practices. In a technological-based practice, the process needs to be wholly performed using the adopted digital technology, such as using a cloud-BIM system to share project information and BIM models among the project participants instantly. A good example is the development of a cloud-based system that facilitates the delivery of progress monitoring data of reinforced concrete structure to stakeholders (Matthews et al., 2015). A technological-supported practice is such a process which could be undertaken with or without the adopted technology, but when technology is adopted, it makes the process faster, effective, and improve the overall productivity. The use of blockchain technology to facilitate financial management in construction projects by Elghaish et al. (2020) is a good case.

Meanwhile, a technological-enhanced practice is such in which the adopted technology adds some value to the process. For instance, Jiao et al. (2013b) deployed an integrated system of cloud augmented reality (AR), BIM, and social networking services to support multi-disciplinary users and enable users to render and peruse onsite images in a web3D environment and monitor multiple AR scenarios. The material value in this technological-enhanced practice is that construction stakeholders can manage the construction process by simultaneously visualizing the BIM model and on-site images. Moreover, according to Rivera et al. (2015), the perceptions of a technological application as ICT-based, supportive, or enhanced might also differ depending on context and the users. In utilizing digital technologies (DT) to address construction problems and improve its processes, the construction stakeholders must ensure that such adopted DT is not given an implicit value in the process (Rivera et al., 2015). That is, it must not affect the effective implementation of a process if the DT is excluded.

2.1 Why cloud-based systems for sustainability processes?

The importance and use of cloud-based systems in everyday life have been accelerated by the revolutionization of computer systems to more handy mobile phones. For instance, in year 2009, there was a global smartphone penetration of about 5% (Rivera et al., 2015), and in year 2020, it has increased to about 44.9% of the global population (O’Dea, 2020) in just over a decade. Cloud-based systems are fundamentally used for the exchange of information and communication – from social media sites, taxi-hailing services to smart devices and sensors for green and smart buildings.

In the era of climate change, increasing greenhouse gas emissions, and waste pollutions, Wangel et al. (2013) underscored the potential of digital technologies like cloud systems to enhance the sustainability performance of buildings and the ecosystem. A cloud-based system could fall in any of the earlier highlighted classifications of digital technological practices depending on the context of its use. Cloud computing services are of three main categories – Software as a Service (*SaaS*), Infrastructure as a Service (*IaaS*), and Platform as a Service (*PaaS*) (Chong et al., 2014). Readers interested in the meaning and differences between these services are referred to Chong et al. (2014) and Zhang et al. (2012).

Moreover, several studies have employed cloud-based systems in the built environment. A study by Yousif et al. (2020) developed a web-based cost-estimating system useful to control and manage the cost of construction projects. The cost-estimating system was developed using programming languages such as ASP.Net and C# and offers full automation for the measurement and cost estimation process of substructural and superstructural works. Furthermore, Grilo and Jardim-Goncalves (2013) proposed a distributed cloud marketplaces to facilitate e-procurement activities in Portugal's architectural, engineering, and construction (AEC) industry. A key technological benefit of the deployed e-procurement system is that it helps overcome interoperability issues usually encountered when AEC actors interact in a collaborative environment.

Furthermore, Tao et al. (2011) identified four key advantages of cloud systems which has increase their usage, and this includes: *firstly,* it is economical – cheaper than using standalone software. Users only need to pay for services they utilize. Secondly, cloud systems are flexible in terms of storage and its servers and users, which are available at the user's request. Thirdly, according to Tao et al. (2011), the technology supporting cloud-based systems are very reliable, less error-strewn, always accessible, and available. Lastly, cloud-based systems are user-friendly and could easily be configured based on users' requirements (Tao et al., 2011). More so, per Wu and Issa (2012), investment in cloud-based infrastructure could improve the social capital of a construction firm. Nevertheless, there are some risks involved with cloud systems, such as private data leaks (Chong et al., 2014), vendor lock-in risks (Sarna, 2010), the untrustworthiness of third parties (Dorey & Leite, 2011), among others. Other applications of cloud-based systems in the built environment are related to lifecycle data management (Jiao et al., 2013a), benchmarking users' BIM performance (Du et al., 2014), indoor localization solutions for construction management (Fang et al., 2016), and the like.

Given the above benefits of deploying cloud-based systems, the current study developed a custom-suit cloud-based tool to automate the assessment of the sustainability performance of buildings designed. Moreover, according to Chong et al. (2014), using cloud-based systems helps lower the entry cost for construction firms trying to explore and benefit from computer-intensive analysis and provides a level playing for all AEC actors. Hence, this is more significant in the sub-Saharan region of Africa, where the high cost of using digital applications to facilitate sustainable buildings is an inhibitive factor (Chong et al., 2014; Olawumi & Chan, 2020). As a result, the deployment of cloud-based systems, as in the case in this paper, could stimulate and serve as a catalyst for increased innovation (Marston et al., 2011) in the African built environment. The proposed CSA system utilizes the *SaaS* model of cloud computing. The next section presents the research methods applied to develop the CSA tool.

3. Research Methodology

The study employed a design science research (DSR) method towards developing the proposed CSA system. DSR is a research paradigm that encompasses the development and use of innovative technological tools (artefacts) to solve practical problems within an application domain (Hevner & Chatterjee, 2010a), in this case, the built environment domain. Hevner and Chatterjee (2010b) defined a research paradigm as a set of well-defined and acceptable research activities appropriate within a research community to produce new knowledge. DSR is basically a problem-solving oriented approach (Dresch et al., 2015) which inherently focuses on advancing the creation of new and innovative technologies as one of its main outcomes (Thuan et al., 2019; Venable, 2006); such as the cloud-based system. More so, per Hevner et al. (2004), the purpose of the developed artefacts could be for experiment or innovation, while Brooks (1987) and Thuan et al. (2019) categorized artefacts into four types which are instantiations, methods, models, and constructs. Hence, the proposed CSA system can be categorized under the "instantiations" type as it is an implementable prototype system of the *SaaS* model of cloud computing, as earlier discussed.

The DSR approach has been predominantly used in technical fields such as electrical and computer engineering fields. But since the late 1980s, DSR has found applications in other fields and topics such as healthcare, decision support systems (Goes, 2014; Rai, 2017), architecture, education, construction, and even fine arts due to its effectiveness to improve the utility of technological tools to solve real-world problems and enhance organizational efficiency. Also, according to Gregor and Hevner (2013), the DSR has grown in acceptance as an appropriate research approach in information system development, especially for socio-technical artefacts such as modelling, governance mechanisms, and decision support systems and the like. The proposed CSA system can also be categorized under the decision support system artefact.

Meanwhile, the DSR has found application within the built environment research field, such as in a study by Tommelein (2020), who applied the DSR methodology to develop a SightPlan framework that can model the various strategic decisions of each stakeholder and modifies it towards arriving at a more holistic construction site layout plan. Others include the development of a planning and control model for prefabricated buildings (Kensek, 2012) and a labour workspace analysis tool (Schumacher et al., 2016).

The DSR, like every other type of research, starts with a research question which attempts to define and characterize the artefacts and highlight their contributions. Hence, to this end, Thuan et al. (2019) formulated a typology of relevant research questions (RQ) that researchers could adopt when undertaking a DSR project. Accordingly, the study classifies the DSR research questions into three elemental dimensions (Thuan et al., 2019)– (i) “How?”- Which attempts to identify the values in the design process outcomes; (ii) “Which?”- This helps to highlight the value in the design product outcomes; and (iii) “What is?” - Which identifies the artefacts’ contributions to the knowledge base. Hence, according to Hevner (2007), a DSR project exists in three research cycles that seek to connect DSR activities with the knowledge base, the artefacts’ design process, and the contextual environment on which the DSR activities are being undertaken. These research cycles are rigour cycle, design cycle, and relevance cycle (Hevner & Chatterjee, 2010a), whose appropriate RQ are the “what?”, “which?” and “how?” topology, respectively.

The current study, based on the predefined study’s aim outlined in Section 1 and the RQ typology developed by Thuan et al. (2019), seeks to answer five more key DSR research questions, that is:

i. Which components define the proposed CSA system and its associated sustainability data modules?
ii. Which requirements or constraints define the operational use of the CSA system?
iii. How can the CSA system be implemented to facilitate its effective use for automated building sustainability assessment?
iv. How can the CSA system be evaluated to validate its efficacy and utility for building sustainability assessment?
v. What are the expected contributing values of the artefact (CSA system) to both knowledge and practice?

The answer to a part of the DSR RQ “What?” has been discussed in Sections 2.1. That is, *what prior knowledge on the use of cloud systems or related technologies for sustainability* *processes is available?* The pending answers to the DSR RQ (i-v) would be discussed in the subsequent sections.

Validating an artefact. According to March and Smith (1995), there are two key activities within a DSR project, which are the (i) build and (ii) evaluate processes. Meanwhile, Hevner et al. (2004) pointed out that the evaluation aspect is more critical as it seeks to demonstrate the efficacy and utility of the developed technological artefact, and this is achievable using rigorous evaluation methods. The evaluation process of a DSR helps validate that the newly designed artefact fulfils the intended purpose of its creation (Venable et al., 2012). However, the extant literature provides no specific guidance on what constitutes a rigorous evaluation of a design artefact developed via the DSR method, but as argued by Pries-Heje et al. (2008), it is essential it is validated against the expected value or utility for which it was developed, that is, to solve real-world problems. The expected value could be based on the artefact's design process outcomes, design product outcomes, contributions to knowledge, or a mix of these outcomes.

Meanwhile, according to Hevner et al. (2004) and McKay et al. (2012), the developed artefacts could also be validated in terms of its quality attributes such as accuracy and reliability, usability and performance, completeness, and fit for use. Also, according to Gregor and Hevner (2013), potential validation techniques could be case studies, experiments, analytics, naturalistic evaluations, simulations, among others. Given the above, the case study and experiment evaluation techniques will be used to validate the proposed CSA system.

4. Proposed system design and development

The CSA system was implemented as a cloud-based software application accessible using web browsers (such as Chrome, Safari, and the like) over the internet or intranet. Also, the sustainability data based on the BSAM scheme, comprising its sustainability criteria' descriptors, weights, and certification system, are integrated into the CSA system. The system architecture for the CSA system-sustainability model is based on the MVC (model-view-controller) application design model, a software architectural design framework first advanced by Reenskaug and Skaar (1989). More so, the MVC framework helps separate the business logic layer and the user interface application layer (Poghosyan et al., 2020) of an artefact which improves the scalability of the system.

The traditional use of MVC architecture is basically for desktop software, but its applications have been extended for designing cloud systems – web apps and mobile apps – using programming languages like PHP, Python, Java, and the like. The *model component* of the MVC architecture maintains the data structure of the CSA system and receives input from the user. The *view component* majorly renders the data to the user in form of charts, tables, graphs, textboxes, dropdowns, and the like. It is also called the user interface, and the data presented to the user are from the model component (databases). Lastly, the *controller component* is the request handler for the other two components, which utilizes inputs, validates it, and passes the input to the model or user interface (web browser) using programmed commands (codes). The controller's codes are useful to query the data model to get the relevant sustainability data that fulfils each BSAM scheme criterion and validates the users' input when creating an assessment profile for the building project.

The subsequent sub-sections graphically illustrate and discuss the MVC architecture implementation of the developed CSA system for the sustainability assessment of building projects.

4.1 Integrated CSA system-sustainability data model

The CSA system is supported by three main modules or data sources (Figure 1). The CSA system-sustainability data model provides valuable guidelines to users – clients, project teams, assessors, and the like – in utilizing the CSA system to evaluate the sustainable profile of the project and to benchmark their buildings against other similar projects.

The first module (module 1) of the data model stores the generated sustainability criteria data, which are based on the BSAM scheme GBRS – in which the assigned credit points (weightings) of the respective BSAM scheme sustainability criteria were further evaluated based on the GCFI approach (an MCDM technique). The GCFI algorithms are hard-coded using PHP and JScript within the cloud-based system to generate the NW, GW, FI, and MCP for the BSAM scheme sustainability criteria, which are also stored in the module 1 database and used for further calculations. It should be noted that the assigned credit points of the BSAM scheme's SC are based on its documentation (Olawumi & Chan, 2019b). The BSAM scheme sustainability criteria are a three-level hierarchical structure consisting of eight sustainability indicators, 32 sustainability attributes, and sub-attributes (136) based on the BSAM documentation (Figure 2).

The second module (module 2) data is generated when (i) a new user registers on the CSA system; (ii) a building project is registered; (iii) the user uploads relevant project models and other supporting documentary evidence; and (iv) the building project is assessed based on the BSAM scheme documentation and relevant sustainability values and results are generated; (iv) a user login and out of the CSA system. When a project is registered, a project ID is automatically generated for the project (e.g., BSAM-123456-78), while a new user must predefine a "username" to which all the user's registered projects (*and the sustainability assessment results*) are subsequently linked to within the module 2 database. The modules 1 and 2 databases utilize the MySQL relational database for data storage.

The third module (module 3), on the other hand, is entirely based on the BSAM scheme documentation and the assigned credit points of its sustainability criteria. Module 3 is only available to the user during the building sustainability assessment stages on the CSA system, in which it serves as a guide for the user in allocating the credit points attained by the building project based on the available building data. Module 3 data contains the (i) description of each SC, (ii) credit points allocations details, and (iii) details of the documentary evidence for each SC that needs to be supplied by the project team/client and validated by the assessor. These module 3 data are hard-coded within the CSA system (*using JScript and HTML/CSS*) and accessible within the eight assessment interfaces of the cloud-based system.

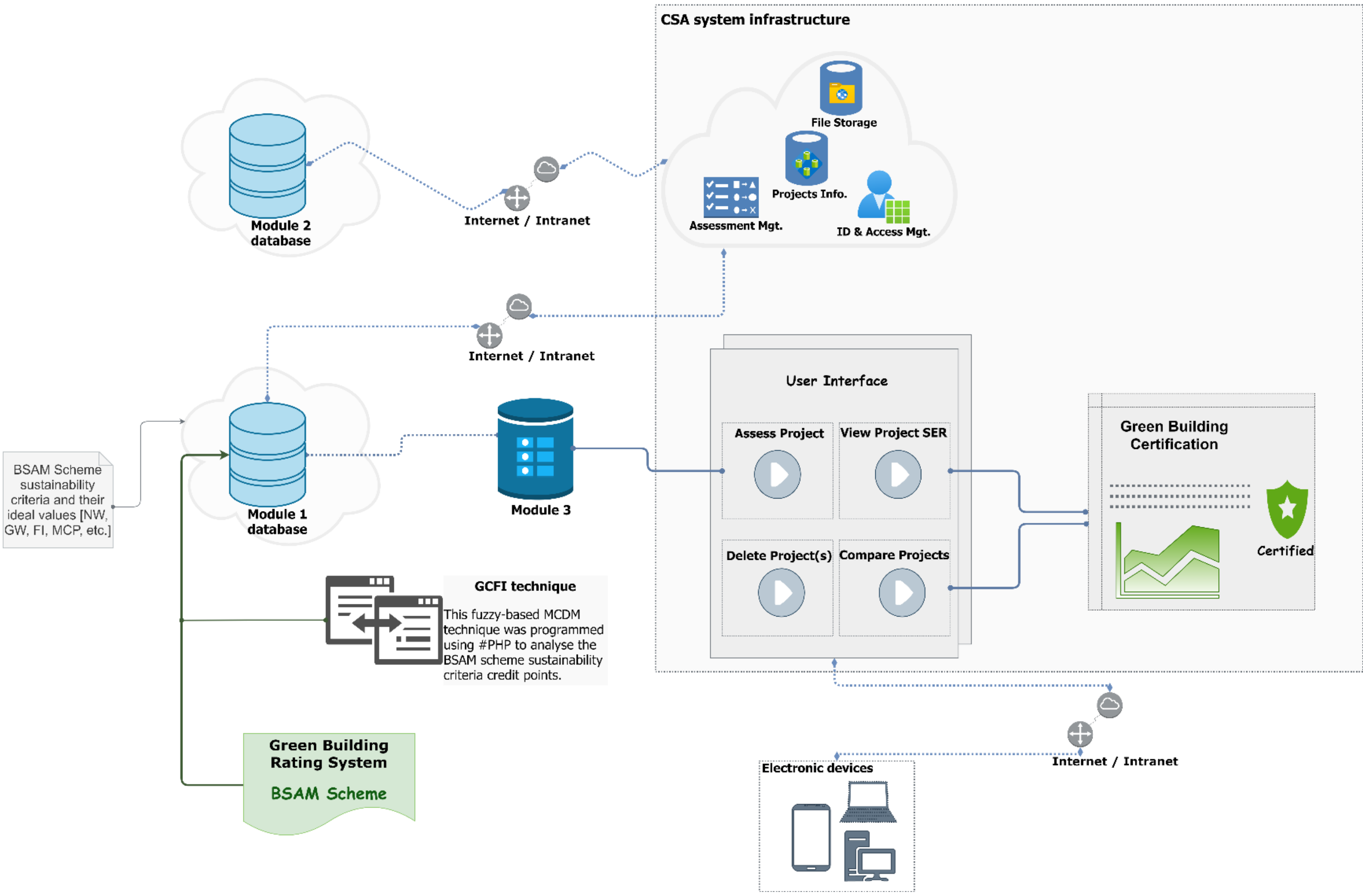


Figure 1: Proposed integrated CSA system-sustainability data model

Given the above, only module 2 data are generated by the users and their activities on the CSA system. Hence, module 2 data can be altered. In contrast, the other modules' data are based on the BSAM scheme documentation, and the sustainability values generated from it. More so, the CSA system must be operational for the user to generate the results of the building sustainability assessments, compare projects, or even delete a project. The relevant calculations and data are obtained based on the previous assessments of the project, and the green certification grade of the building is issued.

The CSA system generates the results based on the three levels of the sustainability assessment of the building projects – which are (i) building sustainability attributes (BSA), (ii) building sustainability indicators (BSI), and (iii) overall building sustainability performance (BSP). The CSA system also graphically plots the BSI against the BSAM certification grades on a line graph and presents the BSP results in a gauge graph for better illustration for the user. The first two assessment levels (BSI & BSA) of the sustainability assessments allows the user to make further evaluations of the building project based on the targeted green certification level, that is, enables the user to pinpoint areas where the building has underperformed and requires remedial improvement measures towards increasing the overall green certification grade of the building project.

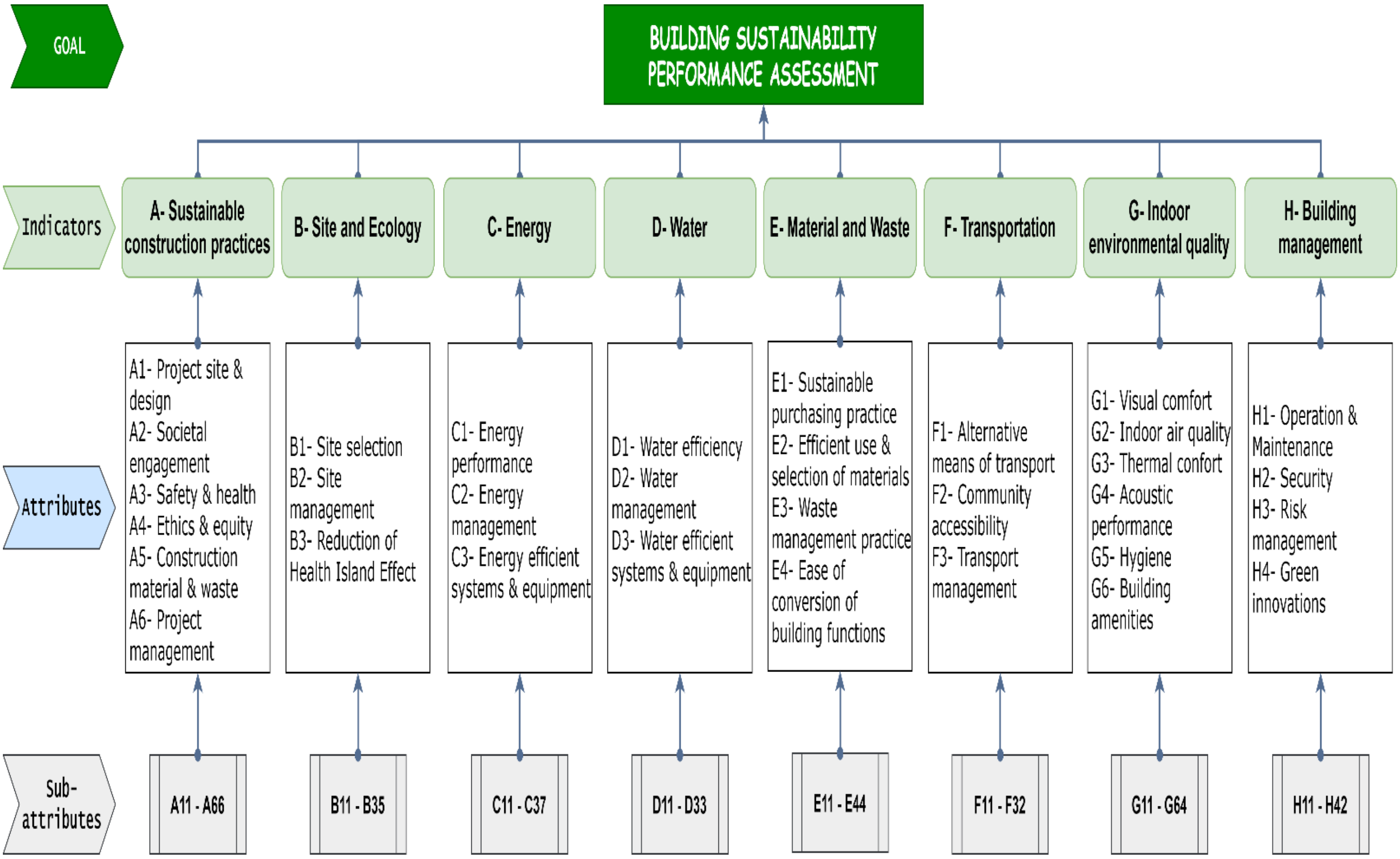


Figure 2: Structure of the BSAM scheme GBRS key sustainability criteria

A constraint of the CSA system-sustainability data model and its implementation is that although the main project sustainability assessment is entirely undertaken on the cloud-based system, the validation of the respective submitted documentary evidence for each BSAM scheme SC is done manually by the assessor.

4.2 Users-MVC interactions in the CSA system

This section presents the dynamic behaviour in the CSA system as the users interact with the cloud platform while performing the sustainability assessment of building projects. Appendix A shows the interaction between the users, the data model, and the controller using a sequence diagram. Sequence diagrams (SD) are a type of UML that illustrate how objects (MVC components) in a system interact with each other. These interactions are shown in the order in which they occur in the *sequence of events* (e.g., 1, 1.1, …10.2 in appendix A). It also shows all the parts of the system. However, for an SD, the user (actor) is always outside the scope of the system as they use the system to achieve a goal. In this case, conduct the assessment of the sustainability performance of building projects using the CSA system.

A typical UML diagram has two categories of actors: (i) the primary actors that initiate the system and are always positioned on the left side of a UML diagram. For the CSA system, the primary actors could be individual clients, project managers, developers, and the like. (ii) The secondary actors are the users whose activities are more reactionary in the system and are positioned on the right side of a UML diagram. For instance, in the CSA system, the assessor is the secondary actor. They will only act after the primary actor has registered the building project and uploaded relevant documentary evidence appropriate for the proper sustainability assessment of the building project. As illustrated in appendix A, the "lifelines" of the *user application interface* and *data module 2* are the most active components of the CSA system. More so, it precisely shows the functional requirement of the users and how the users (*primary and secondary actors*) interact with the CSA system. It also depicts how the controller component of the CSA system handles the request from the users and the data modules.

4.3 System classes and assessment page of the CSA system

The proposed CSA system's data modules 1 and 2 (DB 1 & 2) uses the MySQL relational database schema for data storage and consists of 129 and 9 tables, respectively, for managing the attributes and functions of the sustainability assessment processes. The database schema is also useful to maintain and deploy the functional requirements of the system. Figure 3 illustrates the class diagram of the CSA system, which shows the type of objects (MVC components) and their relationships, the operations and attributes of the objects, and the data type mapped with the attributes. For instance, to register a project on the CSA system, the project name must be a "string" data format (`+projName: string`), while the year of construction is an "integer" data format (`+year: int`). That is, if the user inputs a different data type, the interaction would be discontinued. These are examples of the attributes of the "building project" component of the proposed CSA system, while "`-createProj([project_details])`" is an example of an operation within the "user" component. The class diagram is also a type of UML. As illustrated in Figure 3, a user can register several building projects (0…*); however, each project is associated with a single authorized user. Moreover, the building is assessed based on the BSAM sustainability criteria [A-H].

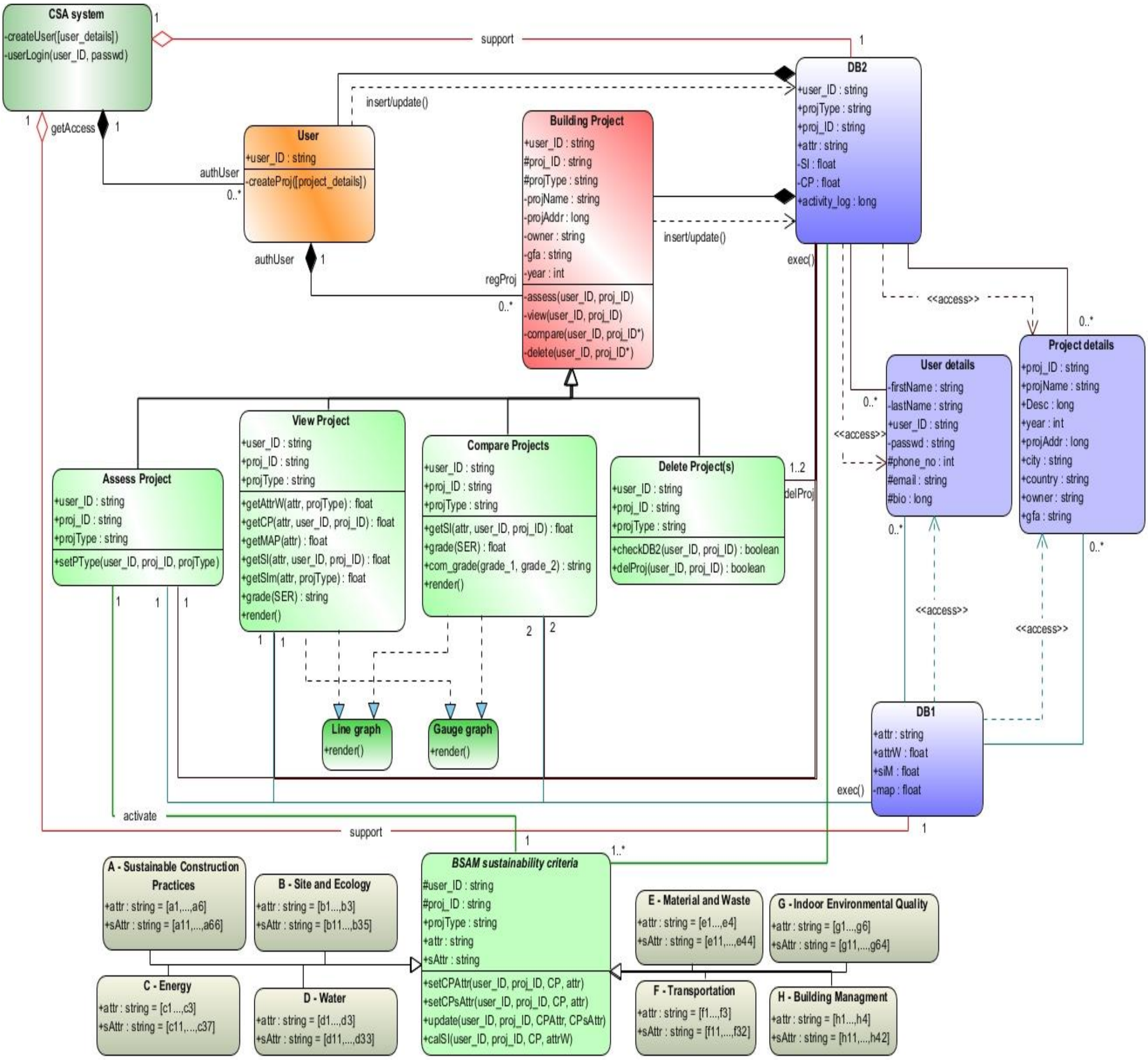


Figure 3: Class diagram for the proposed CSA system

Note: The name of each MVC component in *Figure 3* is 'bolded'; other embedded information is the operations and attributes for each component – (*which are only relevant for readers interested in developing similar systems for the same or other purposes*).

Figure 4 presents a section of the CSA system assessment page (*for the "material & waste" sustainability criteria*). Each SC assessment page gives sufficient information necessary to perform the building sustainability assessment. The *sub-attributes* of each BSAM scheme sustainability *attribute* are embedded under a 'collapsible' section on the page which can be revealed by clicking the section header or the "+" symbol. Also, the descriptions, credit points allocation, and the documentary evidence of each attribute based on the BSAM scheme documentation are accessible to the user on each SC assessment page (e.g., by clicking the "+" of the *Details on E22*).

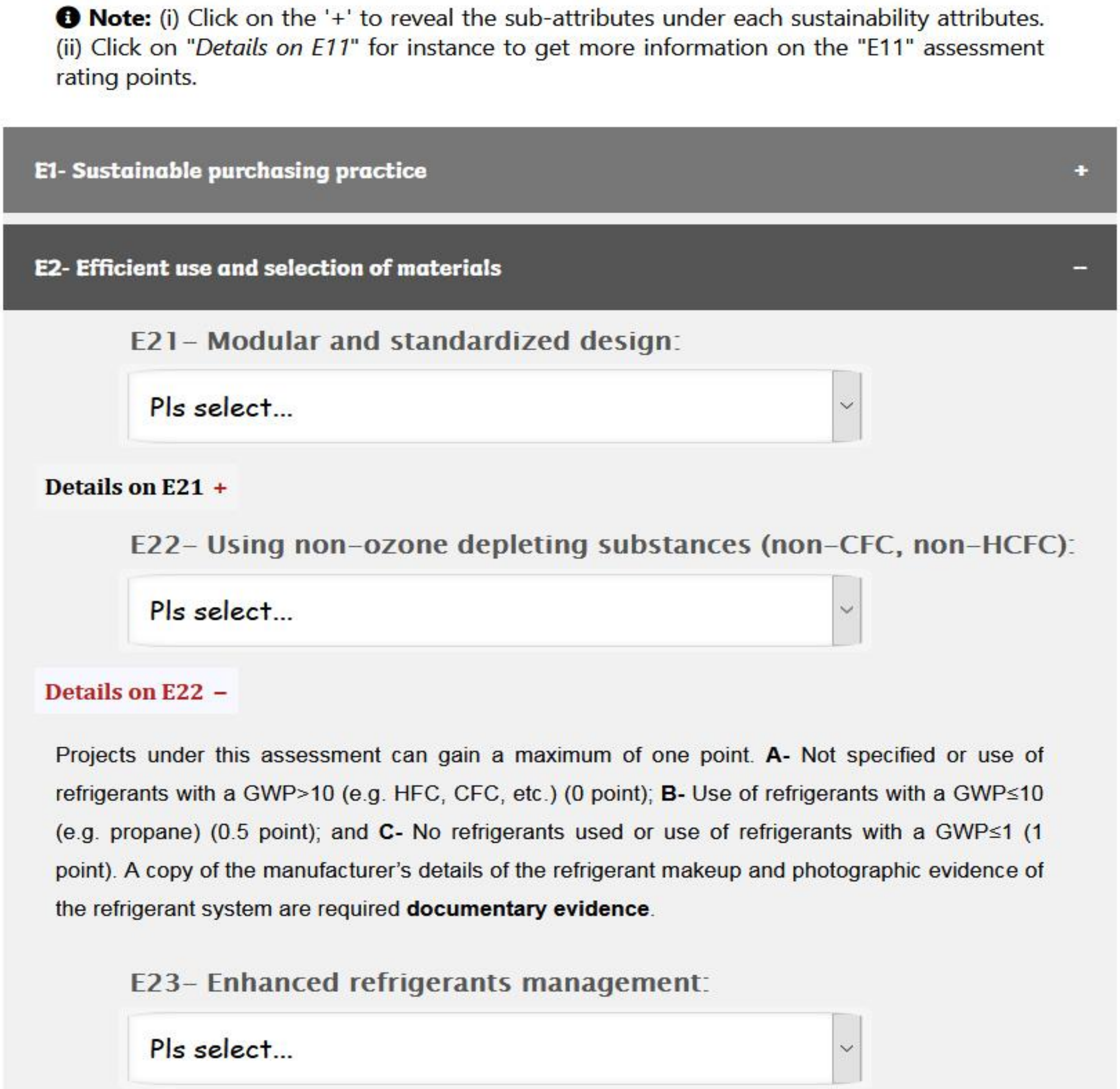


Figure 4: A section of the CSA system assessment page

This information is intended to assist the user to carry out the assessment exercise efficiently and easily by offering practical guidance and scenarios that depict the attainment of a sustainability criterion. In addition, based on the insight provided, the assessor can pick the equivalent level of attainment of the criterion (e.g., for E22 – A/B/C) from the dropdown list.

4.4 Testing and validation of the CSA system

Model or artefact development, including those based on MVC software architecture like the CSA system, can be validated using three approaches (Salah et al., 2014), which are: (i) practical case study evaluation of the proposed artefact based on its real-world application. (ii) evaluating the model or tool by the authors or comparing it with a similar model or method (*experiment method*); and (iii) conducting an expert evaluation of the model or tool. These evaluation methods are also part of the possible validation techniques for developed artefacts proposed by Gregor and Hevner (2013), as discussed in Section 3.

In this study, the first two approaches – which are commonly used for MVC application design models in the extant literature – were used to test and validate the developed CSA system. For instance, a study by Yousif et al. (2020) employed both the practical case study and the author's evaluation approaches to validate a web-based cost estimating tool. Also, previous studies utilized the case study method for a construction safety and health tool (Poghosyan et al., 2020), a BIM-GIS tool for supply chain management (Deng et al., 2019), and a BIM-based decision tool (Ilhan & Yaman, 2016).

4.4.1 Methods evaluation

In this part of the validation exercise, for evaluation purposes, the efficiency and performance of the developed CSA system were compared with the results obtained from MS Excel software and a typical paperwork procedure. Moreover, to facilitate fair and objective comparison, the three systems (*Excel software, paperwork, and CSA system*) were used to compute the sustainability assessment of the same building project (CE duplex building) under the same conditions. The building project and sustainability data used are based on a residential building project in Lagos, Nigeria.

Meanwhile, the three systems were evaluated and compared based on a range of validation factors such as the (i) process time to complete the building assessment; (ii) the ease of updating the data and comparing building projects; (iii) the reliability and validity of the entire process; (iv) how secured the computed data is; (v) type of platform; (vi) the security of data; (vii) ease of automating activities; (viii) user-friendliness of the interface; (ix) cost; and (x) learning curve. The results of the comparative assessment of the evaluation methods are discussed in section 5.1.

4.4.2 Case studies validation

Four building projects located across three states in Nigeria, two of which are in the country's commercial hub, Lagos state, were used as the case studies. These buildings are used to demonstrate the effectiveness and efficiency of the developed CSA system and its data modules to assess the sustainability performance of buildings and obtain requisite green building certification. More so, the building projects were used to showcase the capacity of the CSA system to facilitate the comparative assessment of green buildings along the three sustainability criteria levels: (i) sustainability attributes; (ii) sustainability indicators; and (iii) the overall building sustainability index. As shown in Table 1, two buildings are categorized as *new buildings* and the other two as *existing buildings* based on the BRE (2018) classification of buildings for sustainability assessment.

Case studies data. Moreover, to facilitate the sustainability assessment of the case study projects based on the BSAM scheme, relevant supporting documentary evidence such as BIM model (or CAD drawing), utility records (e.g., energy, water, waste, and the like), building specifications, site layouts, among others as outlined in the BSAM scheme documentation were collated. However, where a piece of documentary evidence is not available reasonable assumptions could be made (Mahmoud et al., 2019). The credit allocation points for each BSAM sustainability criterion as provided in the BSAM scheme GBRS documentation (Olawumi & Chan, 2019b) were used in determining the criterion weightings for each case study based on the submitted building data.

Table 1 presents some of the project information for the case study building projects, and the results of the case study validation are presented in Section 5.2.

Table 1: Profile of the 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	BSAM-280443-99	BSAM-727760-89	BSAM-684201-10	BSAM-504397-18

Note: *The respective project IDs of the case study projects were auto-generated when they were registered on the CSA system.*

5. Discussion of results

This section discusses the findings from the two-way testing and validation of the developed CSA system.

5.1 Methods evaluation

In this section, the quality attributes, utility, efficacy, and value of the developed artefact (CSA system) were comparatively evaluated against other systems – such as Excel software and manual work (paperwork). The ten validation factors highlighted in Section 4.4.1 were discussed and presented here.

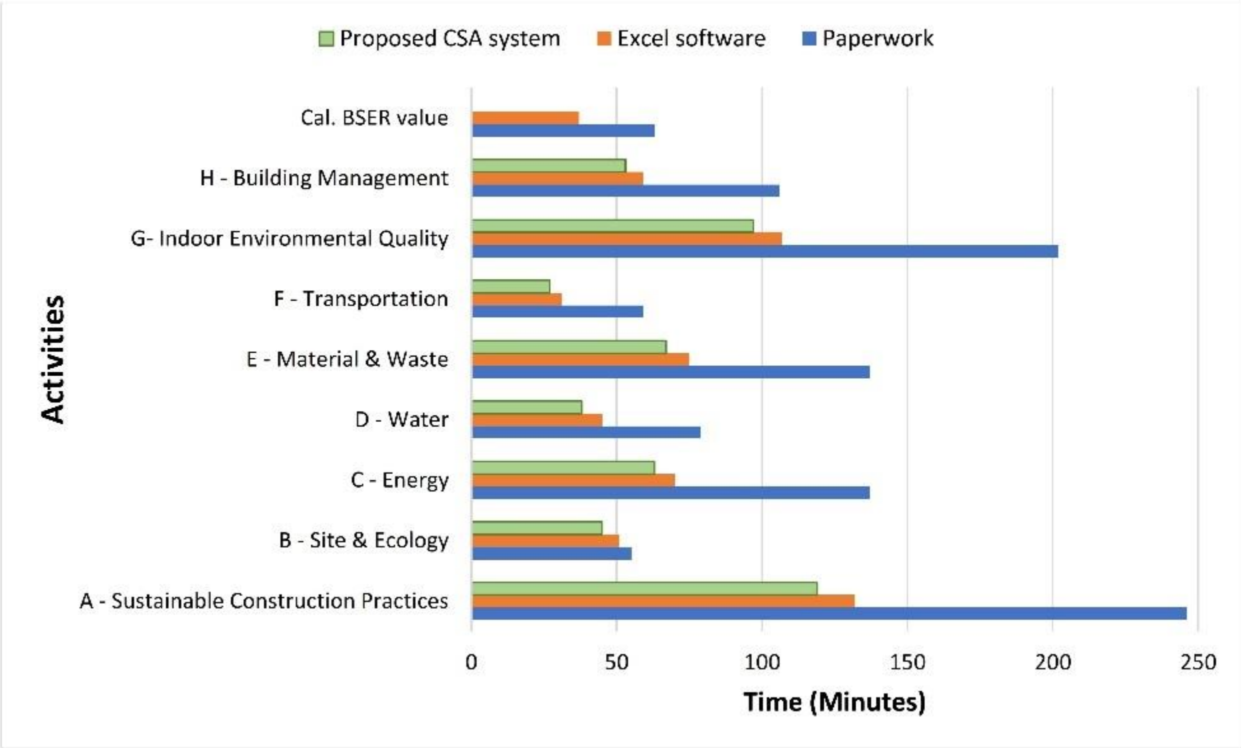
Working or process time. The three systems (*paperwork, Excel software, and CSA system*) were used to implement and undertake the building sustainability assessment of the CE duplex building (Table 1); using the same building data to facilitate a fair and objective comparison. Using the paperwork approach, the computation of the sustainability assessment comprises 22 pages of manual calculations, which average about 50 minutes per page (Figure 5b). More so, as shown in *Figure 5a*, green assessment activities such as "A," "G," "E," and "C" respective are the most engaging computation tasks, and the paperwork method takes a longer time to complete each of these respective tasks. However, no time was spent calculating the BSER value and the green certification grade of the building project in the developed CSA system as the activity is entirely automated on the system.

The tasks involved in evaluating the sustainability performance of a building as factored in the "*working or process time*" validation consist of four steps, such as:

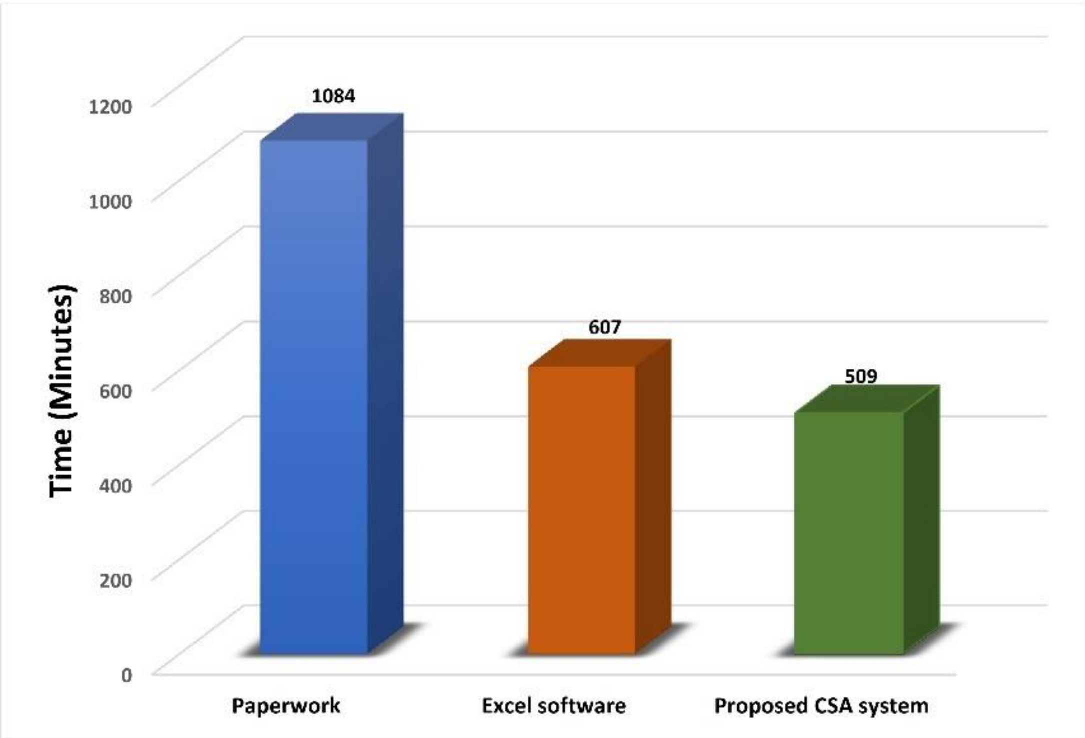
1. Reading and understanding the BSAM scheme documentation for each assessment task (criteria A *to* H and the BSER value).
2. Evaluating the building project data (supporting documentary evidence) for the case study project.
3. Allocating credit points for each sub-attribute of the BSAM scheme sustainability criteria – *based on how the case study project's documentary evidence complies with the credit allocation of the BSAM scheme documentation*.
4. Calculating and verifying the computed data and BSER value.

Hence, for the building sustainability assessment for the case study project (CE duplex building), the processing time summates to about 3 days (that is, 8 working hours/day) for the paperwork method, about 1.5 days (12 hours) using Excel software. Meanwhile, the developed CSA system automated the building assessment activities and reduced the working period to about one working day – 8 working hours (Figure 5b).

More hours are spent on the "step #4" task for the three systems, and since this task is fully automated in the developed CSA system; hence, it has the least overall processing time of the three systems.



(a) Working time to complete each green assessment activity for the three systems.



(b) Total time needed to evaluate a building based on the three systems.

Figure 5: Analysis of the working time to undertake building sustainability performance assessment on the three systems

Learning curve. The learning curve concept was introduced in this study to determine how much time a user is expected to spend based on the efficiency gained after the building sustainability assessment task is repeatedly done for more building projects on the three systems. Generally, a user is more likely to spend more time on a new task when the user is unfamiliar with the process. However, as the user repeatedly performs the task, they tend to gain some efficiency over time. Thus, the task gets done quicker, and there lies the principle of the learning curve. The same principle applies to the cost of producing a product.

The learning curve (LC) concept was introduced in the early 1920s by Wright, who later developed the first LC model in 1936 (Martin, 2021). Wright's LC model established the concept that the cumulative average time per unit (time/cost) decreases by a fixed percentage when the output quantity is doubled (Mislick & Nussbaum, 2015). Wright's model is otherwise called the cumulative average theory. The second LC model in use is Crawford's model developed by researchers at Stanford University. Crawford's model is also referred to as the incremental unit time/cost model (Martin, 2021). According to Liao (1988) and Martin (2021), Wright's model is more suitable for simple LC problems, while Crawford's model is more suitable for production planning problems. However, these two models are the most widely used.

The learning curve is also referred to as the experience curve (Desroches et al., 2013), efficiency curve (Biørn, 1998), improvement curves (Fauber, 1989), among others. According to Moore (2021), the learning curve rate for cloud-based systems ranges from 75% to 90%. If a task has an LC rate of 75%, it implies that 15% efficiency is gained for subsequent cumulative tasks. In other words, the cumulative time spent on a task would decrease by 15% each time the task output doubles. For this study, LC rates of 80%, 86%, and 94% are considered for the three systems (*the CSA system, Excel software, and paperwork, respectively*). Readers are referred to previous studies (*see* Biørn, 1998; Desroches et al., 2013; Moore, 2021) on assigning LC rates to systems and the limitations of its computations. The learning curves for the three systems compared in this study are based on Wright's model are evaluated using equations (i & ii) and illustrated in Figure 6.

$$Y = aX^b \quad ----(Wright's\ LC\ model - 1st\ unit) ----- Eqn\ (i)$$

$$XY = aX^{1+b} \quad ----Cumulative\ total\ time/cost ----- Eqn\ (ii)$$

Where:

Y = Cumulative average time per unit task

X = Cumulative number of units task undertaken

a = time required to complete the first unit task

b = natural slope of the function when plotted on log-log sheet

= log of the learning rate/log of 2.

For example, for the proposed CSA system, the cumulative average time to evaluate the sustainability assessment of ten building project units at a learning curve rate of 80% would be $Y = a10^{1+b}$; where a = 509 minutes (see Figure 5b).

The b-value is calculated as $b = \frac{\log(0.80)}{\log 2} = -0.3219$; and $1 + b = (-0.3219 + 1) = 0.678$

Hence, $XY = 509 * 10^{0.678} = 2{,}425\ mins$

Using Equation (ii) and the respective learning curve rates, Wright's model was used to calculate the cumulative working time and the learning efficiency gained by the users when using the three systems. The a-value for the three systems is 1084, 607, and 509 minutes for the paperwork, Excel software, and the CSA system (Figure 5b). The analysis of the results of the learning curves for the three systems is presented in Figure 6.

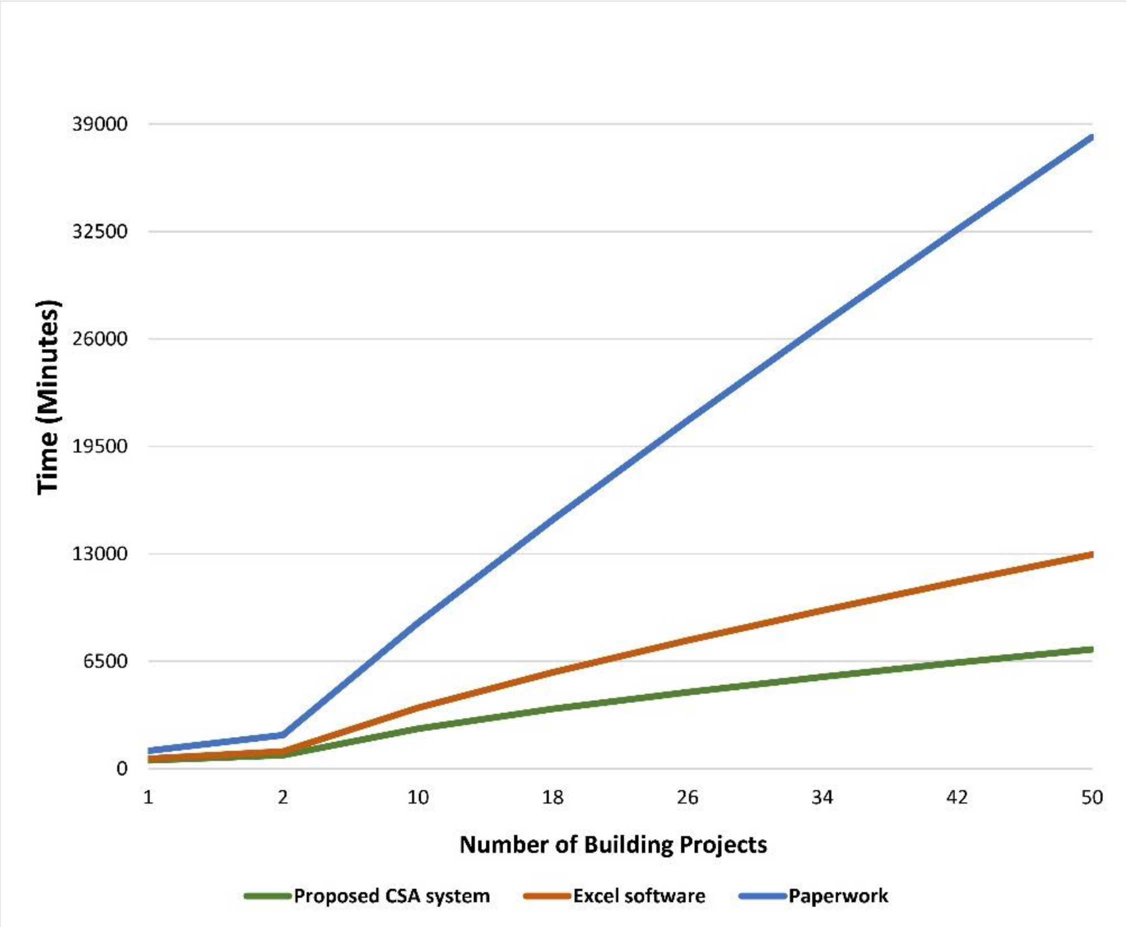


Figure 6: Necessary working time for the three systems (learning curves)

The results revealed that for the first unit of building project assessed using the three systems, the user gained a 1.2% efficiency when the CSA system is used instead of the Excel software and as much as a 2.1% increase in productive working time when the CSA system is used compared with the paperwork method (Figure 6). After accumulating experience in evaluating ten building projects, the learning and efficiency curve significantly improved to 1.5% when a user uses the CSA system rather than Excel software and 3.6% improvement in working time when the CSA system is used rather than the manual work process. When the user has accumulated experience assessing 50 building projects on the three systems; *user A* using the CSA system would be twice as productive as *user B* using the Excel software. Furthermore, *user A* would be five times more efficient and productive than user C, who uses the paperwork approach in evaluating the sustainability performance of buildings. From the learning curve analysis for the three systems (Figure 6), it is evident that a user using the CSA system would perform more unit tasks with less working time.

The learning curve model is helpful for users of the CSA system to predict how long it would take them to undertake a future building assessment based on the cumulative tasks they have earlier carried out on the system and the experience and efficiency gained. Also, the learning curve rate has an inversely proportional relationship with the cost associated with such assessment tasks. As the user spends less working time evaluating the sustainability assessment of building projects (as they accumulate experience on the CSA system), the cost to the client and project team for the green building certification process reduces.

Other validation factors. Apart from the fact that the proposed CSA system improves the user's learning curve and lessens the working time spent for a typical assessment process – the CSA system also facilitates (i) a reliable assessment process, (ii) ease updating computed data, (iii) reduces human errors and (iv) facilitates an automated assessment process. A summary of the comparison of the three systems based on the ten validation factors is presented in Table 2.

Table 2: Comparison of the three systems based on the validation factors

Evaluation methods/ Validation factors	Paperwork	Excel software	Proposed CSA system
‣ Working time	Longer time	Average time	Shorter time
‣ Learning curve	Slow rate	Medium rate	Rapid rate
‣ Ease of updating data	No	No	Yes
‣ Ease of comparing assessed building projects	Not available	Complex	Yes
‣ Process reliability and validity	No	Low	High
‣ Data security	No	Less secure	Very secure
‣ Platform type	Paper-based	Computer-based	Cloud-based
‣ Process automation	No	Little	Fully automated
‣ User-friendliness	Not available	Average	High
‣ Cost	Average to High	High	Low

The use of cloud computing and data modules (database systems) in the developed CSA system and its inherent security give it an edge over the other systems (Excel software and paperwork). Also, being a cloud-based system, the CSA system can be accessed remotely from any location once connected to the internet or the company's intranet, while other traditional means are limited to a single point of access.

5.2 Practical case studies

5.2.1 CSA system: Individual building assessment

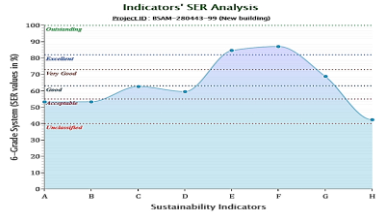
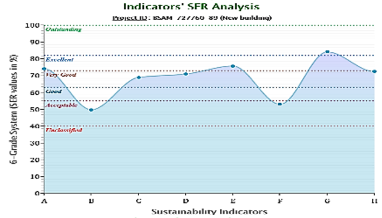
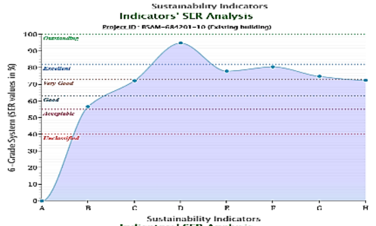
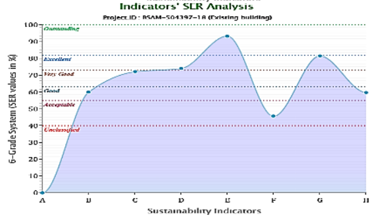
The case study building projects comprise two large-sized, one medium-sized, and one small-sized building project based on their gross floor area, and their specific details have been summarized in Table 1. A user account was created on the CSA system, and the information of the four buildings was registered, and a project identification number was generated in the CSA system for each building. The four buildings were evaluated, and the green certification results were presented based on the CSA system assessment workflow model illustrated in Appendix A.

The case study building projects were assessed individually based on the BSAM scheme sustainability criteria [A-H] (Figure 3), and BSAM scheme credit points (Olawumi & Chan, 2019b) are allocated based on the sustainability credentials attained by each building as evidenced by its submitted documentary evidence. A sample of how the credit point allocation for criterion 'E22' "*using non-ozone depleting substance*" which is a sub-attribute of criterion 'E3' "*efficient use and selection of materials,*" which is also an attribute of the sustainability indicator 'E' "*material and waste*" is illustrated in Figure 4. The four case study projects all attained the maximum CP=1 for this E22 sustainability criterion. Where an input error occurs while selecting the attained CP for a sustainability criterion during a building sustainability performance assessment, the CSA system allows for re-assessment of that criterion for such building, which updates the data module 2 (Figure 1) with the new assessment data. Hence, the CSA system can be said to be flexible in handling such human errors of data entry. The entire assessment process is kickstarted when the user (assessor) access and utilizes the "Assess Project" MVC component, as depicted in Figure 3.

Moreover, for the user (that is, the project manager, client) to access the result of the building assessment process, the "View Project" MVC component of the CSA system needs to be activated. Meanwhile, as shown in Figure 3, this component has a multiplicity constraint of 1. That is, only a sustainability assessment result of a building project can be viewed at a time by the authorized user. The green certification results are presented in a table format for its sustainability attributes and indicators. More so, a line graph is used to plot the relationship between the attained grade levels of the building based on its sustainability indicators against the six certification grade levels of the BSAM scheme GBRS. Moving the mouse over the plotted graph, the user can get the exact SER value for a specific criterion (e.g., *E=84.65% for the CE duplex building* – line graph) or the overall SER value (gauge graph). The rendering on the line graph helps the user to easily pinpoint the sustainability performance of the building based on the BSAM scheme and identify areas for improvement.

The CSA system also allows the user the flexibility to delete the data of a building project entirely from the system. The "Delete Project(s)" MVC component has a multiplicity constraint of `1..2` (Figure 3), which implies only one or two building project data could be deleted at a time from the CSA system. Table 3 summarizes the green certification results for the four-case study building projects and the visual rendering of the SER results on a line graph and gauge graph.

Table 3: Summary of the BSAM scheme sustainability assessment for case studies undertaken via the proposed CSA system.

Building code	Project ID	[1,2] BSAM scheme GBRS criteria SER values								[2,3] Overall SER value (grade)	Visual rendering on a Line graph (Criteria A-H)	[5] Visual rendering on a Line graph (overall SER)
		A	B	C	D	E	F	G	H			
CE Duplex	BSAM-280443-99	53.28	53.4	62.7	59.6	84.65	87.14	68.75	42.4	62.54 (*Good*)		
RA labs	BSAM-727760-89	74.15	49.86	69.04	71.03	75.8	53.09	84.16	72.53	70.05 (*Very Good*)		
[4] SNN building	BSAM-684201-10	-	56.65	72.17	94.76	77.95	80.46	74.79	72.53	75.33 (*Excellent*)		
[4] FT building	BSAM-504397-18	-	59.93	72.08	74.05	93.37	45.6	91.51	59.86	70.29 (*Very Good*)		

Note: [1] BSAM scheme criteria labelling: 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*.

[2] The SER values are in percentages (%).

[3] The BSAM scheme grade certification levels are: *Outstanding* (82-100%); *Excellent* (73-81%); *Very good* (63-72%); *Good* (55-62%); *Acceptable* (40-54%); *Unclassified/Fail* (0-39%) of the SER value.

[4] The sustainability criterion "A" is not accessed for the "*Existing building*" type based on the BSAM scheme documentation.

[5] The six shades of colour as seen in the gauge graphs are the six-grade certification levels of the BSAM scheme GBRS.

5.2.2 Comparative assessment of buildings using the proposed CSA system

The developed CSA system via its “Compare Projects” (CP) MVC component allows users to compare the sustainability performance of buildings which have been assessed. The CP’s component has a multiplicity constraint of 2 (Figure 3), which implies that the CSA system permits only two building projects to be compared at a time. Otherwise, an error message is relayed, and the process is terminated. The CP’s component of the CSA system can be activated from the “Building Project” component via the private function “`-compare(user_ID, proj_ID*)`.” Meanwhile, appendix A illustrates the users-MVC workflow that occurs within the CP’s component.

On activation, the CP component renders the assessment results and highlight the comparative analysis of the assessed building projects at three levels, which are – (i) the sustainability attributes (level 2), (ii) sustainability indicators (level 1), and (iii) the overall building sustainability performance level (level 0). These comparative assessments of building projects help the user to examine the building models/designs or completed building projects at a whole (level 0) or at strategic ‘piecemeal’ of sustainability practices (levels 1 & 2) depending on the user’s predefined project objectives. It also helps the user to clearly identify the underperforming areas of such building projects that require remedial improvement measures.

In this study’s case study comparative assessment, for illustrative purposes, the two new buildings were compared and vice versa with the existing buildings (see Table 4). The SNN building has a higher certification grade (*Excellent*) than the FT building (*Very Good*), with SER values of 75.33% and 70.29%, respectively. However, a user cannot simply rely on this in making a sustainability decision regarding the building project without examining the assessment levels 1 and 2 . If a user (*say, a client or the project manager*) is faced with a sustainability decision between two building designs (for a proposed building project) which have the characteristics of SNN and FT buildings, respectively; and requires a design that better fulfils the sustainability criteria “*E- Material and Waste*” and “*G- Indoor Environmental Quality*.” Then, the best building design would be the FT building rather than the SNN building. Although the SNN building has a better overall sustainability performance, it came short in its criteria E and G’s SER values (see Table 4). Hence, a given comparative assessment of building projects on the proposed CSA system can give rise to several sustainability decisions depending on the user’s predefined objectives.

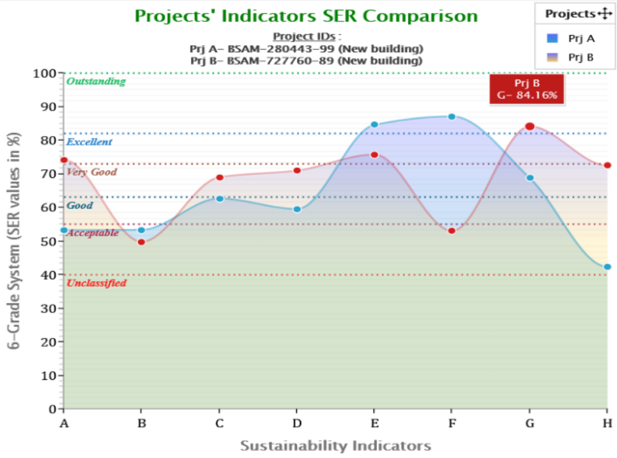
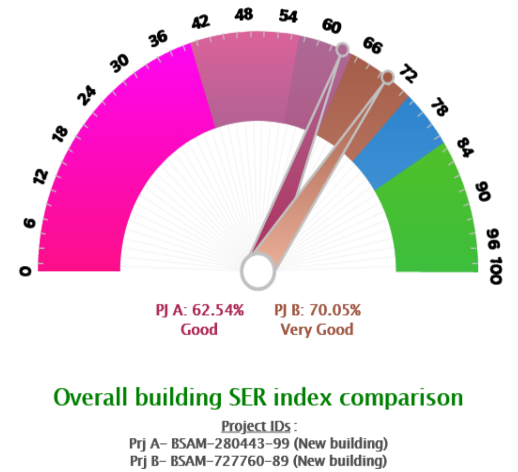
Given the various scenarios that might arise after the comparative assessment, the user could decide to (i) improve the building design and associated systems where it is underperforming sustainability-wise; (ii) chose a better alternative design with a sustainability certification grade close to the predefined objectives; or (iii) seek a new building design tender; among other options available to the user.

Table 4: Summary of the comparative assessment of the case studies via the developed CSA system

<table>
<tr><th>Building code</th><th>Project ID</th><th>[1] Comparison at the 2nd level criteria (sustainability attributes)</th><th>Comparison at the 1st level criteria (sustainability indicators)</th><th>Overall building sustainability performance comparison</th></tr>
<tr><td>CE Duplex
[Prj A]

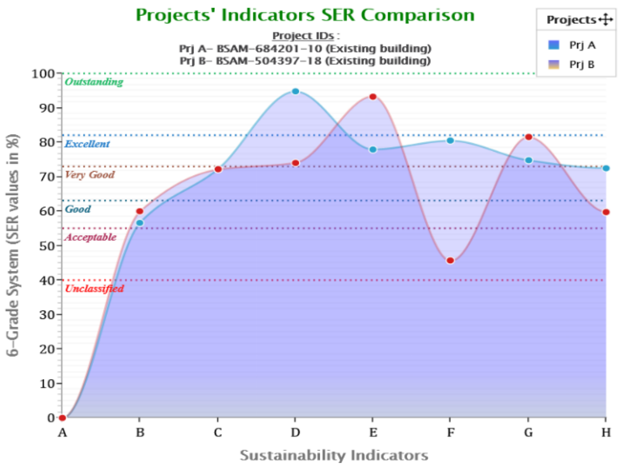
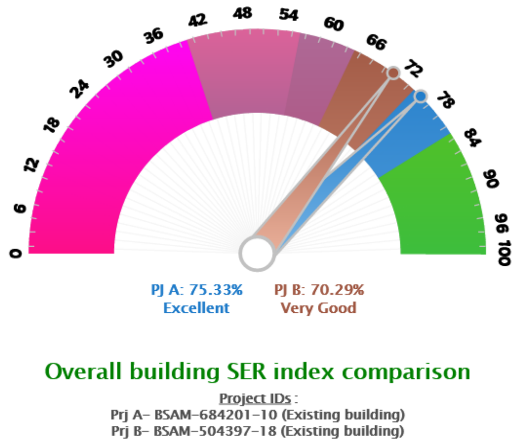
vs

RA labs
[Prj B]</td><td>BSAM-280443-99

BSAM-727760-89</td><td>
<table>
<tr><td>G5- Hygiene</td><td>0.16322</td><td>0.18362</td><td>+Prj B</td></tr>
<tr><td>G6- Building Amenities</td><td>0.13339</td><td>0.11116</td><td>+Prj A</td></tr>
<tr><td>H1- Operation & Maintenance</td><td>0.18377</td><td>0.30628</td><td>+Prj B</td></tr>
<tr><td>H2- Security</td><td>0.02783</td><td>0.08350</td><td>+Prj B</td></tr>
<tr><td>H3- Risk Management</td><td>0.09731</td><td>0.12974</td><td>+Prj B</td></tr>
<tr><td>H4- Green Innovations</td><td>0.03101</td><td>0.06201</td><td>+Prj B</td></tr>
<tr><td colspan="4">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.</td></tr>
</table>
</td><td>
</td><td>
</td></tr>
<tr><td>SNN building
[Prj A]

vs

FT building
[Prj B]</td><td>BSAM-684201-10

BSAM-504397-18</td><td>
<table>
<tr><td>G5- Hygiene</td><td>0.17681</td><td>0.18860</td><td>+Prj B</td></tr>
<tr><td>G6- Building Amenities</td><td>0.12844</td><td>0.15413</td><td>+Prj B</td></tr>
<tr><td>H1- Operation & Maintenance</td><td>0.35390</td><td>0.30081</td><td>+Prj A</td></tr>
<tr><td>H2- Security</td><td>0.09648</td><td>0.03216</td><td>+Prj A</td></tr>
<tr><td>H3- Risk Management</td><td>0.14991</td><td>0.14991</td><td>equal</td></tr>
<tr><td>H4- Green Innovations</td><td>0.07165</td><td>0.07165</td><td>equal</td></tr>
<tr><td colspan="4">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.</td></tr>
</table>
</td><td>
</td><td>
</td></tr>
</table>

Note: [1] A section of a plotted table in the "View Project" MVC component of the proposed CSA system shows how the two building projects compare based on the assessed BSAM scheme criteria (*attributes*). The line and gauge graphs are also rendered within this CSA system component, as described in *Figure 3.*

5.3 Practical research implications and novelty

The developed CSA system provides stakeholders with a tool for holistic and automated sustainability assessment of building projects in the sub-Saharan region of Africa. Also. It is expected that the deployment of the CSA system will accelerate the use of technologies for sustainability analysis in the region. One of the significant barriers to the development of green buildings in the region is the high cost of purchasing and maintaining the relevant digital tools and software for building sustainability simulation and analysis. Hence, the CSA system, a free-to-use (open source) cloud-based application, contributes to lowering the entry cost for clients and other stakeholders to implement sustainability in building projects.

Moreover, benchmarking of project data is quite common in the region. Hence, the developed CSA system will allow stakeholders to effortlessly compare the sustainability performance of building projects at miniature and holistic levels of sustainability practices. Also, it will enable users to clearly identify underperforming aspects of the building project that might require further remedial improvement measures towards enhancing its overall green building certification grade. Hence, this capability of the CSA system help improves the sustainability decision-making process of construction stakeholders at any stage of a building project.

Meanwhile, the developed CSA system enhances the efficiency of the overall sustainability assessment process by automating the key tasks. Therefore, it could help reduce the cost to be paid by the client to the project assessor when compared to the other two systems evaluated in this study. Also, the CSA system can evaluate and store both qualitative and quantitative data to which BIM model databases are currently incapable of embedding.

The novelty of the paper lies in its (i) being the first development of an automated approach for holistic green building sustainability assessment, comparison, and benchmarking via the use of a cloud-based system; (ii) as an open-source tool capable of influencing and promoting the application of green practices in building projects; and (iii) helping stakeholders make informed sustainable decisions.

6. Conclusions

Sustainability practices in the built environment, especially for built assets, are gaining momentum partly due to the rapid urban developments and the need to minimize the environmental impacts of buildings and contribute to sustainable development. Hence, digital technologies are being promoted and advanced to facilitate sustainable practices in construction projects. In this context, this study addressed a pertinent research gap in the use of cloud-based systems to evaluate the sustainability performance of buildings towards improving the sustainability profile of buildings.

The design science research approach was employed in developing and implementing the proposed CSA system and outlining its operationalization for use in the construction industry. The DSR approach fits within the study research design as the CSA system is an instantiation type of artefact based on the *SaaS* model of cloud computing. More so, the study presented the MVC system architecture, sequence diagram, and class diagram, which can assist construction stakeholders in using the CSA system. The CSA system architecture was implemented using PHP, JScript, and supported by the MySQL database system. Moreover, the proposed artefact (CSA system) was evaluated to demonstrate its efficacy, value, quality, and utility. The study employed two evaluation techniques– experiment (methods evaluation) and practical case studies validation– using four building case study projects.

The validation results show that the developed CSA system is secure, facilitates work automation, reduces working time while enhancing user's efficiency, has a very user-friendly interface, promotes a reliable and valid assessment process, and eases the process of updating the computed data and comparing building projects, among others. The practical contributions, implications, and novelty of the study have also been succinctly discussed. Also, the CSA system has some technical advantages over the other systems (Excel software and paperwork) in areas such as, firstly, computational-wise, the CSA system being a cloud-based artefact, has enough bandwidth to accommodate multiple building sustainability assessment tasks the same time. However, for Excel software, such large computations will take a portion of the RAM capacity of the electronic device (e.g., computer). Manual work would consume many papers and hence, not a sustainable means. Secondly, the CSA system has enough storage capacity to store the building data and other generated sustainability assessment results.

Meanwhile, using Excel software could affect the limited hard-drive space of the device. Thirdly, the building project sustainability analysis data generated and saved on the CSA system are safer and secure, as regular backups are done on the cloud system to keep data safe and secure. In contrast, project assessment data saved on offline desktop software and Excel macros are prone to loss due to data corruption, system crashes, and the like.

Limitations of the study. Firstly, the developed CSA system embeds only the BSAM scheme GBRS (which is only suited for the context of sub-Saharan Africa) as its primary rating system. Hence, the CSA system in its current form can only be used for the sustainability assessment of green buildings located in the region. Secondly, no previously developed cloud-based schemes or software embeds the BSAM scheme or other GBRS. Thus, no further comparative assessment of the CSA system could be conducted. Thirdly, the LC rates used for the three systems are based on LC rates of related software in the extant literature. Future research can replicate the MVC architecture and UML diagrams of the CSA system in developing related cloud-based tools that embed other existing GBRS. Also, future research could improve the learning curve analysis by evaluating the cost implication to the client or project team when an assessor is given the task to undertake the green certification process.

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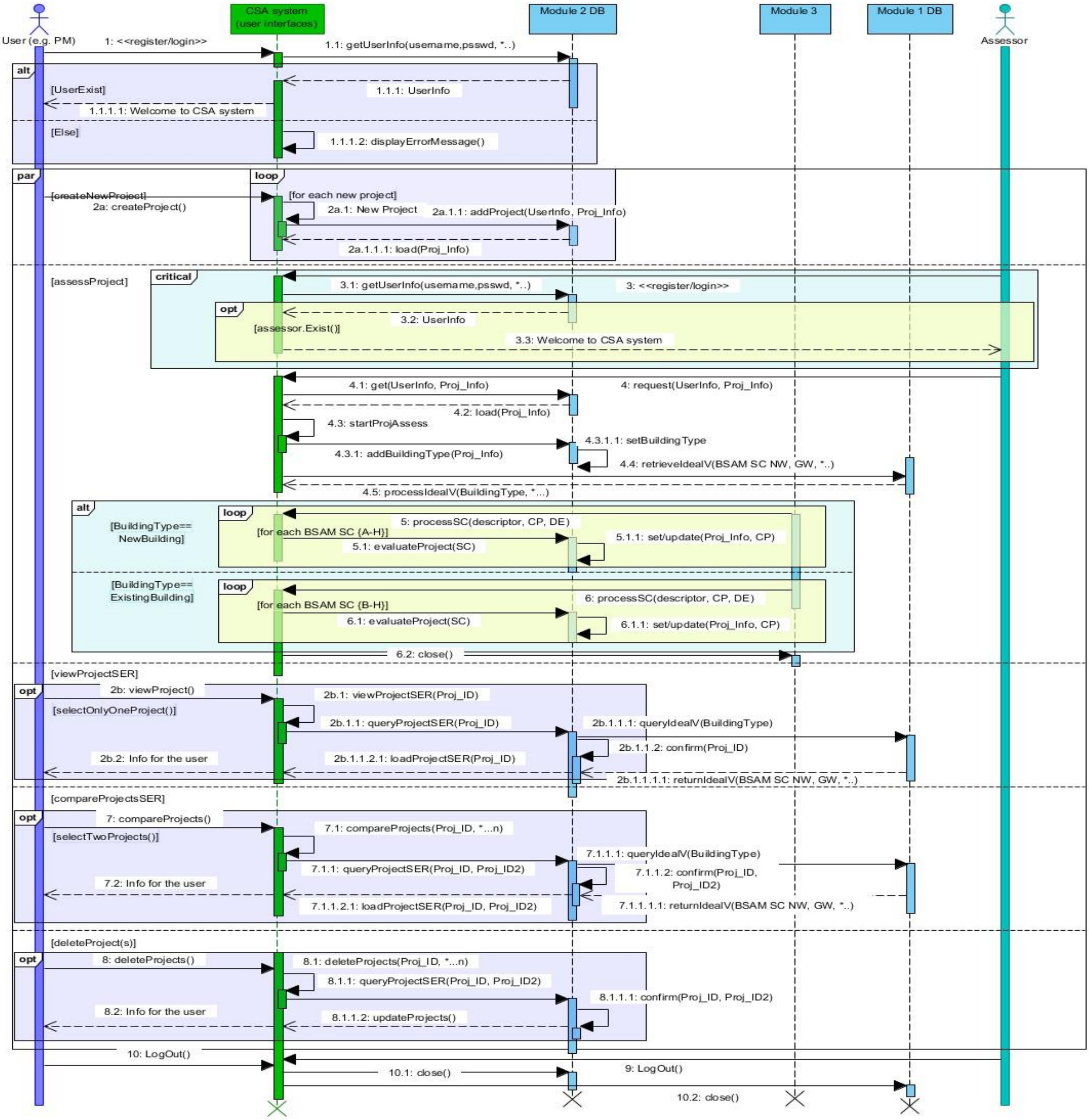
APPENDIX A



Sequence diagram showing the Users-MVC workflow in the CSA system

Note: This Users-MVC workflow of the CSA system portrays the internal workings of the various components of the CSA system as illustrated in Figure 3. For the readers, this sequence diagram (SD) might be technical in nature. Hence, to understand the SD, a knowledge of database management and the Unified Modelling Language (UML) are needed.