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The Integration of Geographic Information Systems and Building Information Modelling to Sustainably Manage Development Sites in Gaborone, Botswana

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ABSTRACT

For many years, site development professionals and urban planners have worked in silos, yet they share a similar objective of providing a better built and natural environment. Moreover, there seems to be a stereotype in terms of focus areas; with urban planners more on the macroscale while their site development counterparts are more on the micro end. The two professional groups speak in different languages and use different instruments. For example, urban planners have introduced Geographic Information Systems (GIS) while site development professionals like architects, engineers, contractors, and facility managers advocate for Building Information Modelling (BIM). The increasing complexity of site development, their related environmental, geographical, and surrounding infrastructure is highly desired to support informed decision-making. Advancements in computer science and data technologies can make this integration easier. However, the understanding of GIS and BIM integration is still in its infancy, as innovative applications of their fusion is yet to be explored comprehensively. Therefore, this study investigates how GIS and BIM can be integrated to derive big data to support site development in Gaborone, Botswana. It will further propose a conceptual framework for integrating BIM and GIS for better site development and sustainable urban management in Gaborone.

Keywords: Building Information Modelling, Geographic Information Systems, Sustainable Urban Management, Sustainable Construction Projects, BIM-GIS Integration, Conceptual Framework

INTRODUCTION

For many years, urban planners and site development professionals have worked in silos, yet they have the same objectives of delivering better built infrastructures and natural environments. Despite having similar objectives, they speak different languages and use different instruments. For example, urban planners usually focus on macroscale projects such as city-wide information. In contrast, their site development counterparts are more on the micro end such as specific building information of a particular project. Therefore, this causes interoperability issues when these professionals share this information to other stakeholders involved, leading to information mismatch, improper documentation of developmental stages, and unnecessary confusions.

Proper documentation is necessary for building management as there are several professionals involved in a construction project. Throughout a building project, different forms and formats of information are gathered, exchanged, and recorded for efficiency and effectiveness. Moreover, Chen et al. (2015) stress that proper information management is important for decision-making as it ensures that accurate information is always available on time and in the right format to the appropriate person. For example, a building project requires 3D models, material properties and quantities, map, geographic information, ground levels etc., which can be provided by technologies like Geographic information Systems (GIS) and Building Information Modelling (BIM). The GIS can be used to process and store spatial and non-spatial data of the construction project. While BIM can be used to represent and manage information for designing, constructing and operating buildings.

The lifecycle of a building project comprises of initial plans, land acquisition, inception, finance, design, construction, operation, maintenance and finally demolition or revitalization. All these stages require data that GIS and BIM can adequately process and store. However, Lu and Tam (2013) argue that current decision-making throughout the site development life cycle is based on missing, incorrect and even outdated information. Very

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often development sites have missing information of one stage to another of a life cycle hence creating a disconnect and 'information islands' which can negatively impact the progress of the project (Lu and Tam, 2013).

A BIM-enabled site facilitates an environment where professionals like architects can develop conceptual, schematic, and detailed designs directly in BIM software such as ArchiCAD and Autodesk Revit. The design would then be passed to engineers for engineering designs such as mechanical, electrical, carpentry, and plumbing services. During the construction and operation stage, various information will be generated which should be synchronized properly and timely in the BIM. A suggestion by Karan (2014) is that BIM information should further include the geometry of the areas of interest, their semantic and topological information. For building projects, geometric information entails the three-dimensional form of a building such as size, shape and volume; while semantic information provides descriptions of the properties components; and topological information documents of the relationship between building components, such as sunlight emission for greenhouses, connectivity of rooms, their thermal requirements and evacuation measures, and building performance analysis means.

A successful integration of GIS with BIM can lead to a cyber-physical system which is a concept that combines the physical and computational elements to facilitate smarter decisions of various industries including construction (Song et al., 2017; Wan Abdul Basir et al., 2018; Wu and Zhang, 2016). BIM aims to form a shared, single and interoperable platform where site development stakeholders such as contractors, engineers, facilities managers and clients can communicate and share information and experiences. GIS on another note is a system of capturing, storing, manipulating, analyzing and disseminating geospatial data. It has many applications related to planning, engineering, transport and logistics, management, insurance, telecommunications and business. The versatility of GIS and its 'geoinformation' connotation facilitates a basic index variable for all other information such as cartographic information, urban environment infrastructure characteristics, geo-statistics, geotechnical conditions, rock morphology and the earth topography. Moreover, GIS techniques continue to provide avenues for scientific enquiries on sustainability, governance and development.

The objective of this study is to provide insights in the form of a conceptual framework on the key components that construction professionals can focus on to sustainably build and manage construction projects by integrating BIM and GIS technologies for efficiency and effectiveness. Sustainable Development Goal 11 which emphasizes the need to make cities and human settlements inclusive, safe, resilient and sustainable will be the main anchor and guiding principle of this study.

This study is structured as follows. Section 2 provides a review of literature regarding previous works that investigated possibilities of integrating BIM and GIS for various activities. In Section 3, a methodology for integrating BIM and GIS for sustainable construction is presented. A conceptual framework for integrating BIM and GIS for sustainable construction is then proposed in Section 4 which highlights key strategic areas of BIM and GIS integration to address challenges of Sustainable Development Goal 11 (SDG 11). Section 5 then discusses and concludes the main findings of this study and outlines further research directions.

LITERATURE REVIEW

A sizeable number of research has investigated the integration of GIS with BIM to address issues of big data in construction projects in their local communities. For example, Han et al. (2020) discussed an application prospect of GIS-BIM integration technology in construction projects particularly in site scheduling, material management, and safety management of construction personnel. Their study revealed that the application of the two technologies in construction management can save construction cost, improve project safety, and facilitate a culture of collaboration of different disciplines and aid data sharing between stakeholders.

An environmental information modelling framework was developed by Gao et al. (2020) to bridge a gap between GIS and BIM systems. The need to integrate BIM with GIS technology emanates from the notion that the former barely supports processes of construction supply chain because of its limited geospatial ability (Gao et al., 2020). The construction industry is dependent on the efficient and effective delivery of materials and equipment, environmental protection, and proper management of waste products over long distances. Therefore, GIS provides avenues to use geospatial information for transportation planning, construction and monitoring to improve efficiency in construction projects.

For high-rise buildings GIS and BIM have been integrated to address a challenge of the towering vertical construction method as it lacks comprehensive risk mitigation strategies (Elsheikh et al., 2021). The combination of the two technologies can ensure that all project phases are well planned for. In addition, they can help establish how materials are delivered to the site in a cost-effective manner, outlining all pertinent safety measures for all stages of development. Moreover, GIS and BIM technologies can assist project managers anticipate problems before they occur and outline plausible mitigation measures in a timely manner (Thiis and Hjelseth, 2008).

A study by Hadi Hor et al. (2018) investigated possibilities of linking network technology with GIS and BIM. An intelligent Web model for urban mobile utility was presented with the goal of benefiting professionals on a wide range of methods and modalities of displaying and analyzing construction data on the internet. An integrated graph database platform was developed by Hadi Hor et al. (2018) which enabled professionals to interact with a comprehensive graph data model, perform detailed construction data mining spatial analysis in it for improved efficiency and decision-making.

BIM and GIS integration depend on big data analytics to make informed decisions (Sani and Abdul, 2018). This refers to the practice of basing decisions on the analysis of data rather than purely on intuition. Big data is popular because it has benefits, including the power of prediction, and improved decision-making. Nonetheless, Lu et al. (2018) argue that the euphoria of big data analytics for BIM and GIS integration is yet to be seen in managing developmental sites. Even though a review of literature mostly paints the BIM – GIS integration on a positive note, there are some challenges of the two technologies that need to be highlighted.

Challenges of integrating BIM with GIS Technology

Integrating GIS with BIM for construction projects can be highly beneficial, but it also comes with several challenges which include: a) data interoperability issues, b) complexity of models, c) differing levels of detail, d) cost and resources, e) organizational silos, f) legal and privacy concerns, and g) change management. The sub-sections that follow will briefly describe these challenges for a better understanding of their route causes.

Data Interoperability

Data interoperability is concerned with the creation of a seamless data exchange between two or more communication platforms. However, GIS and BIM often use different data formats and standards. Therefore, interoperability issues may arise, making it difficult to transfer spatial and non-spatial data between the two technologies (Janečka, 2019) (Figure. 1).

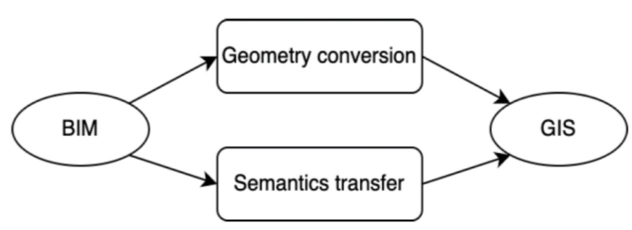

Figure 1. Data interoperability issues of integrating BIM with GIS

Complexity of models

For large scale construction projects, BIM models can be complex, which can be a challenge when integrated with GIS data. Moreover, the need to manage and update these complex models while integrating them with GIS can require extensive computational resources and expertise (Wan Abdul Basir et al., 2018).

Differing levels of detail

It is common knowledge that GIS typically deals with large scale geospatial data. In contrast, BIM focuses on detailed building information. A desire to integrate these two datasets can be challenging as a result of differences in scale and level of detail (Zhu and Wu, 2022). Moreover, it can be a challenge to harmonize these datasets to ensure consistency and accuracy throughout the project lifecycle.

Cost and resources

The integration of BIM with GIS requires investments in technology and human resources (Sheina et al., 2022). Resources need to be allocated to acquire the necessary tools, software, to develop interoperability standards and train personnel to utilize the integrated system effectively (Han et al., 2020). This can be a stumbling block to smaller companies or projects with limited budgets.

Organisational silos

Usually, organisations are managed by different departments, which subsequently leads to organisational silos and lack of collaboration (Cilliers and Greyvenstein, 2012). It is essential to overcome these challenges for a successful integration of BIM and GIS.

Legal and privacy concerns

GIS data can comprise of sensitive information such as land ownership, infrastructure details and environmental data. Therefore, integrating this data with BIM can raise some legal and privacy concerns regarding data ownership, exchange and security (Liu et al., 2017). It is crucial to ensure compliance to regulations and to protect sensitive information when integrating BIM with GIS.

Change management

For organisations to implement an integrated BIM and GIS solution, changes in existing workflows, processes and organisational culture are required (Celeste et al., 2022). It should be noted that any resistance to change from any stakeholder involved, or lack of buy-in from decision makers, and inadequate training or appropriate personnel can hinder the successful adoption and implementation of the integrated system.

To address the outlined challenges requires coordinated efforts from all stakeholders involved, particularly industry professionals, policy makers, the private sector and academia. In addition, it is necessary to design a methodology that comprehensively addresses most of the challenges identified while considering sustainability issues, particularly those of SDG 11.

MATERIALS AND METHODS: INTEGRATING BIM AND GIS FOR SUSTAINABLE CONSTRUCTION

As stated earlier, the methodology of this study is guided by the Sustainable Development Goal 11 (SDG 11) initiative which is concerned with making cities and human settlements inclusive, safe, resilient and sustainable (Bernegger et al., 2022; Moghadam et al., 2016; T. Wang et al., 2019). The synopsis of SDG 11 stresses that cities are hubs for ideas, commerce, culture, science, productivity, social, human and economic development. Additionally, it highlights that urban planning, water, sanitation, waste management, disaster risk reduction, access to information, education, and capacity building are all relevant issues to sustainable urban development.

This study argues that the integrating of BIM and GIS technologies can address most challenges identified in SDG 11, particularly the following targets: a) Target 11.3 – enhancing inclusive and sustainable urbanization and capacity for participatory, integrated and sustainable human settlement planning and management in all countries, b) Target 11.5 – significantly reducing the number of deaths and the number of people affected by natural disasters, including water related disasters, with a focus on protecting the poor and people in vulnerable situations, c) Target 11.7 – provision of universal access to safe, inclusive and accessible, green and public spaces, d) Target 11c – supporting least developed countries, through financial and technical assistance, in building sustainable and resilient buildings utilizing local materials.

The following sub-sections discuss key application areas where BIM and GIS Integration can address the SDG 11 Targets outlined.

BIM-GIS for enhancing inclusive and sustainable urbanization

BIM plays a vital role in GIS integration (Wang et al., 2019). It can assist many professionals to work simultaneously on a project reducing chances of miscommunication and errors while it handles its documentation seamlessly. It is a single source of truth for the project information, making sure that everyone is on the same page. Three Dimensional (3D) models developed by designers in BIM can be augmented with data for asset management, which can later be extracted by GIS (Carrasco et al., 2022). This seamless data integration provides a platform for contractors to visualize and validate data of the current project, as well as bring models from different projects into a federated GIS scene which gives clients the capability to appreciate the project in a 3D environment. It further gives them the opportunity to view the design and provide insights and design guidance as the project moves from a schematic design to a conceptual design.

With BIM and GIS one can create realistic 3D models that help stakeholders visualize the final product before the actual physical implementation. This not only helps the clients understand the project better, but also assists designers to identify and resolve potential issues before they become costly problems.

BIM-GIS integration facilitates for large volumes of data to be extracted for the digital twin technology (Shi et al., 2023). Such data can then be utilized for an effective asset management throughout the lifecycle of an infrastructure project. They can provide better services for clients and improved workflows which makes the construction of a project more efficient.

Nowadays, construction companies are exploring avenues to provide digital infrastructure solutions to their clients. This entails leveraging technology and innovation in the infrastructure design community to reshape the way in which large and most complex infrastructure projects are delivered. Solutions envisaged with such technologies include cloud-based and Web-based solutions which make it possible for contractors to seamlessly access, analyse and store large volumes of data to efficiently manage maintenance schedules, track asset performance and plan for future upgrades or renovations.

BIM-GIS for a universal access to safe, inclusive and accessible green and public spaces

It is crucial for design build project successes to have a firm grasp on the larger contextual environment vehicle in which it exists (Gann and Salter, 2000). BIM and GIS integration can help improve the way companies design, build, and maintain assets with consideration for the real-world activities around them. It is essential for developing robust and sustainable solutions to problems like population growth, water scarcity and climate change. For example, BIM technology can be used to improve the management of green buildings where their various functions such as energy use, carbon emissions and ventilation analysis are used to support the sustainable development of buildings (Lu et al., 2017). According to Wang et al. (2019) the emergence of GIS-based simulation models can solve environmental and planning problems in a more accurate way for low carbon cities to test the impacts of urban layouts and building types. For example, they can be used to test the energy performance, carbon emissions, solar potential for urban design projects for sustainable urban development.

BIM-GIS for reducing the number of deaths and people affected by natural disasters,

BIM-GIS technologies can be used to identify, map, and assess locations likely to be affected by flooding through flood analysis computations and predictions. It gives users the opportunity to simulate flood occurrences directly in a 3D contextual model as well as animating those events. The determination of early flood risk assessments, urban floodplains and coastal areas can be aided by the execution of practical flood simulations along river lines and coastal areas (Dhiman et al., 2019). Through the utilization of BIM technology, a determination of the design of buildings, materials to be used and their overall structural reinforcements in such areas can be established. Additionally, GIS technology can be utilized to establish the extent to which flood water levels can affect buildings within a particular distance from the river and adequate mitigation measures outlined (Moreri et al., 2008).

Applications of BIM-GIS in energy management to support least developed countries, through financial and technical assistance

For building projects, sustainability includes energy and cost efficiency considerations. Projects that utilize both BIM-GIS technologies can benefit from energy conservation management and efficiency schemes at both building and city levels (Wang et al., 2019). For example, GIS can facilitate the development and computation of energy-saving methods for buildings, such as the assessment and quantification of energy efficiency, mapping energy consumption and improving the targeting of regional energy supplies. Technological advancements such as smart city developments and the Internet of Things (IoT) have provided an environment where contractors can integrate BIM and GIS to develop spatially seamless digital infrastructure for urban environmental analysis (Liu et al., 2017) and climatic adaptation of buildings (Thiis and Hjelseth, 2008). The increasing affordability of sensor networks and computation power makes it possible to collect large volumes of real-time data for informed decision making in construction projects.

The IoT is concerned with enabling communication between physical and virtual devices to collect, analyse, exchange and disseminate construction information in real-time (Isikdag, 2015). It involves the utilization of sensors and area field communication technologies such as Global Positioning Systems (GPS) devices, smart mobile phones, and Radio Frequency Identification (RFID) readers to communicate with each other to create either a smart building or city. For example, a door in a smart building would connect with a fire alarm for a responsive and timely emergency evacuation. For a smart city, a bus would communicate with a bus stop in terms of estimated times of arrival at a particular bus stop. It is necessary for BIM and GIS technologies to be integrated into facilities management and smart city initiatives such that benefits associated with emergency response, urban surveillance, urban monitoring to smart buildings may be achieved from this fusion (Lu et al., 2018).

RESULTS: CONCEPTUAL RAMEWORK FOR INTEGRATING BIM AND GIS FOR SUSTAINABLE CONSTRUCTION

The conceptual framework of this study is a result of key targets identified in the methodology section which comprehensively discussed how the integration of BIM-GIS technologies can adequately address challenges of Sustainable Development Goal 11 (Figure 2). The framework for SDG 11 outlines a thorough approach to transform cities and human settlements into inclusive, robust, safe and sustainable environments. It emphasizes integrated planning, resilience building, inclusive governance and partnerships as critical components to achieve sustainable urban development worldwide.

It is anticipated that the proposed conceptual framework will facilitate an environment for better site development and sustainable urban management of construction projects in Gaborone, particularly addressing issues of SDG 11 targets.

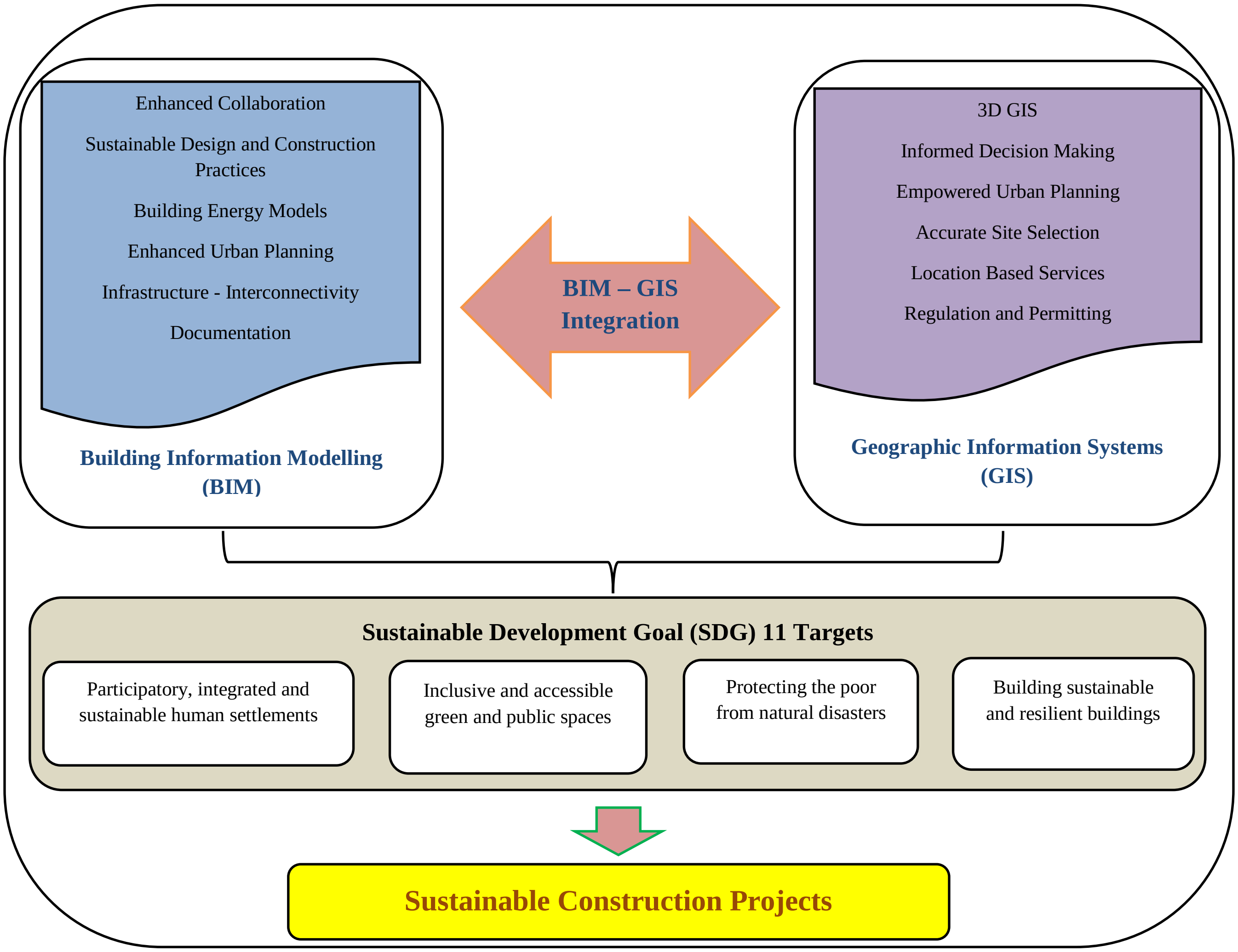

Figure 2. The conceptual framework for BIM-GIS Integration for sustainable construction projects

BIM FRAMEWORK COMPONENTS

Enhanced collaboration

BIM facilitates collaboration among project teams which improves information dissemination and sharing. Nonetheless, Wang et al. (2022) argues that challenges like unwillingness to collaborate, lack of standards and regulations inhibit effective collaboration processes in BIM enabled projects. Despite these challenges, BIM provides better communication and collaboration among various project members and key stakeholders for improved project quality and increased profits (Svalestuen et al., 2017).

Sustainable design and construction practices

Sustainable design and construction practices with BIM entail enhancing the quality of information provided in making critical design decisions regarding the environmental impact of buildings. BIM can assist in the following areas of sustainable design: selection of building orientation to reduce costs; reduction of waste and carbon footprints; effective water harvesting avenues; and reduction of material needs and increasing the use of recycled materials (Dowsett and Harty, 2013).

Building energy models

BIM offers an extensible medium for parametric information storage of Building Energy Models (BEM) (Elnabawi, 2020). For example, it facilitates the development of energy simulation processes to be integrated with sustainable and low energy building designs which include thermal zones, weather files and occupancy operating schedules.

Enhanced urban planning

Enhanced urban planning is concerned with the development of smart cities. As such, BIM can help constructors build energy-efficient buildings in a cost effective manner while seamlessly sharing and exchanging information to all stakeholders involved (Goyal et al., 2020).

Infrastructure interconnectivity

It is crucial to establish a real-time information source on a construction site. According to Hewage and Ruwanpura (2006) workers need opportunities to view 3D and 4D (with 3D timeline) drawings, technical information, safety information, weather updates for proper management of materials on site. A BIM information booth can give constructors onsite access to updated drawings, a greater degree on the utilization of resources and other important information related to the project.

Documentation

Considering BIM as a documentation option facilitates an environment where builders can specify and input any type of information into the model at any time of the project for sufficient consumption and use by other professionals in the project. However, Wan Abdul Basir et al. (2018) argue that it can be used negatively as a tool for disseminating false information. For example, software packages have been designed to provide default values which users have to modify to input actual values of a particular project of interest. If such information is not provided, default values would be deemed inaccurate for that project.

GIS FRAMEWORK COMPONENTS

3D GIS

Three Dimensional (3D) models in GIS allow planners to visualize construction activities, identify potential sources of hazards and better plan for them prior to the actual implementation on the ground (Ebrahim et al., 2016). Unlike the traditional 2D drawings, 3D models consider locational and spatial aspects of a project which are critical in developing executable construction plans which consider consequences of surroundings on a construction plan.

Informed decision making

With GIS, workers are able to access and process information quickly which allows them to improve planning and informed decision making to promote better organizational integration and knowledge management.

Empowered urban planning

GIS can help urban planners to simulate and evaluate environmental impacts of their projects for a better understanding of the urban environment. As a result of the continuous increase in the world's population, GIS can further empower urban planners to design innovative solutions, construct energy efficient and cost-effective structures for local communities.

Accurate site selection

Traditional means of site selection in construction projects is usually done manually based on experience. However, the complexity of current construction projects and consideration of social, environmental and economic factors for sustainability, renders traditional means insufficient. Therefore, GIS techniques are critical in construction projects as they can produce interactive multi-layered maps that allow queries to be performed to obtain optimal solutions that meet set criteria (Bansal, 2012).

Location based services

Locating construction assets such as equipment and workforce during construction is important for improving productivity and safety. Therefore, GIS can facilitate a two-way communication channel between workers and supervisors by tracking them in a 3D environment for forensic and performance analysis purposes (Shirowzhan et al., 2017).

Regulation and permitting

GIS can be used to produce cadastral maps overlaid with zoning maps to obtain insights and propose policies for land regulation and permitting. To recognize potential problematic areas, current and tentative zoning maps can be compared through different spatial criteria and thresholds for a detailed site investigation to eventually achieve a new zoning map (Lin, 2000).

DISCUSSIONS

The low accessibility of information regarding construction projects in Botswana are the main causes of inefficient actions regarding their timely execution and completion. For existing building projects, the lack of 'as-built' documentation (building components, installations, materials used, etc.), the complex task of determining the current status of materials used, and detailed record of previous maintenance work, makes it difficult for professionals to properly plan, schedule and make improvements therein such buildings. Moreover, construction sites can also be a source of noise and dirt which creates traffic congestions that impede mobility and cause noise pollution.

Therefore, it is important for construction activities to be conducted timely using comprehensive data from BIM-GIS integration technologies. This requires reliable and accurate data on the building site as a basis for effectiveness and efficiency in planning and building. These can be achieved by an adequate integration of BIM and GIS through the conceptual framework proposed in this study.

CONCLUSION

Big data formed from GIS and BIM is the core to the success or failure of a development project. Thus BIM-GIS integration aims to create a future with an infrastructure that is more resilient and sustainable to make responsible use of the resources of our country and to cultivate conditions that are conducive for the growth of our cities and populations. This study through the utilization of the proposed framework, argues that the utilizing of BIM and GIS technologies can facilitate enhanced workflows and help project managers make quality driven decisions for sustainable construction projects. Since BIM is a digital representation of a building in the life cycle phases from design, construction, operation and finally maintenance, it is crucial that all stages are well documented and easily accessible by all stakeholders through a GIS platform. Future work will entail the implementation and evaluation of the effectiveness of the proposed framework in a case study area in Gaborone, Botswana.

DECLARATIONS

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Data availability

The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

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Authors' contribution

First Author performed the experiments and wrote the manuscript. Second Author analyzed the data obtained. Third Author designed the experimental process and revised the manuscript. Fourth Author assisted with the initial data collection and community engagement processes. All authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests in this research and publication.

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