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Research Article

Proposed Framework for Bioclimatic Design Criteria Using Building Information Modeling (BIM) in Residential Buildings in Egypt

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Abstract:

Modern residential buildings in Egypt, especially in hot climates, face increasing challenges related to high energy consumption and low levels of thermal comfort. This study aims to explore the potential for enhancing the sustainability of residential buildings by integrating bioclimatic design criteria with Building Information Modeling (BIM) technologies. The study followed a descriptive-analytical approach, including a comprehensive review and in-depth analysis of published research and studies covering the period between 2015 and 2025, which addressed this integration within the Egyptian context and regions with similar climatic conditions. The results concluded that applying BIM techniques in bioclimatic design can improve energy efficiency by between 22% and 46%, while achieving significant improvements in indoor thermal comfort levels. It also demonstrated the benefits of integrating BIM systems with energy simulation tools during the early stages of design, enabling accurate and in-depth data-driven decisions. However, the study revealed a few technical and economic challenges, including difficulties in software integration and high implementation and training costs, which hinder the widespread adoption of these practices. The study concluded that combining bioclimatic design with BIM technologies represents a strategic opportunity to support sustainable development goals in the Egyptian housing sector. Accordingly, the study recommended the development of supportive policies and local standards that address technical climate issues, as well as investing in professional capacity building and encouraging pilot projects to promote and expand the application of these innovative solutions.

1. Introduction

The global construction sector, particularly in Egypt, faces increasing challenges related to sustainability and resource efficiency. The building sector is one of the largest consumers of energy globally, accounting for approximately 40% of total energy consumption and a third of greenhouse gas emissions.[1] In hot climates like Egypt, these pressures are exacerbated by the high demand for continuous mechanical cooling, which places additional pressure on electricity grids and natural resources.

Traditionally, Egyptian architecture included design solutions developed in response to its climatic environment. For example, the interior courtyard (hosh), mashrabiyas, wind catcher elements, and materials with a high thermal mass enabled the interior environment to be comfortable without a high-energy demand [2]. However, with the transition to modern global architectural styles, which often disregard the particularities of the local context, there has been an over-reliance on mechanical air-conditioning systems, which consume excessive amounts of energy, and promote inadequate thermal conditions during power outages.

In this context, bioclimatic design serves as a design strategy that strives to refocus architecture to relate to the natural environment. Bioclimatic design begins with analyzing local climate characteristics and using natural resources like sunlight and wind, to provide thermal and visual comfort with minimal energy use [3]. In the meantime, Building Information Modeling (BIM) has resulted in a digital transformation in the construction sector, changing it from a simple three-dimensional tool to an all-encompassing approach to the management of project information during its life cycle by creating a digital model filled with data [4].

This study is significant in its investigation of the connection between bioclimatic design and BIM and their potential synergy for sustainability purposes. Bioclimatic design provides the necessary foundations and standards to improve the environmental efficiency of buildings, and BIM provides valuable analysis and simulation tools to evaluate these strategies early in the design stage and to facilitate decisions backed by accurate data. While the potential for this integration is promising, particularly in the Egyptian housing sector, application is limited due to technical, economic, and institutional barriers, as well as an insufficient awareness and skill set.

This study tested the gap by developing a complete theoretical framework outlining the pathways to integrate bioclimatic design criteria into Egyptian residential buildings using BIM. The study establishes the basic concepts of both fields and evaluates scientific literature and past research to establish the theoretically best standards and strategies for a local experience. In this way, the study intends to produce usable support for professionals and policy makers to achieve a more sustainable and comfortable built environment with the frame of the Sustainable Development Goals and Egypt Vision 2030.

2. Research Problem

Even though there is some exciting potential to introduce bioclimatic design thinking into Building Information Management (BIM) systems, the application of this as a methodology is still limited in the Egyptian housing sector facing a number of challenges. The research problem can be seen as an obvious gap between the theoretical potential of these types of technologies and their practical uptake in consumer housing, and this can be summed up in the following points: [5].

1. A lack of appropriate methodologies: This includes a lack of a viable practical methodology (or methodologies) that is contextually applicable to the Egyptian example, to support fully integrate BIM and bioclimatic design processes.
2. Technical and economic factors: This mainly contravenes the issues, though not confined to, that result from having software costs, training in the software, and process, as well as dealing with the lack of software interoperability between bioclimatic design and construction software.
3. Weak awareness and professional capabilities: Professionals and developers lack awareness of the long-term benefits of this technology, along with a lack of the technical skills necessary to implement it effectively.
4. Lack of supportive policies: The absence of government regulations and policies that encourage or mandate the use of these technologies in housing projects.

3. Research Questions

Considering the research problem, this study aims to answer the following questions:

1. How can the integration of BIM with bioclimatic design standards help improve the sustainability of residential buildings within the Egyptian context?
2. What are the most prominent bioclimatic standards and strategies appropriate to the local context, and how can they be implemented using BIM tools?
3. What are the most significant technical, economic, and institutional challenges hindering the application of these methodologies in Egypt? What are the possible ways to overcome them?

4. Research Objectives

The study aims to achieve a set of main objectives, most notably:

1. Analyze previous studies and scientific literature to provide insights into the current status of applying bioclimatic building design using BIM in Egypt and similar contexts.
2. Identify and classify the most effective bioclimatic strategies and standards for improving the environmental performance of residential buildings.
3. Analyze the most prominent obstacles facing the spread of these applications, while developing practical recommendations to address them.
4. Proposing a conceptual framework that contributes to facilitating the integration of

bioclimatic design and BIM in Egyptian residential projects.

5. Research Importance

The importance of this study lies in its contribution on three main levels:

• **Scientific Importance**: The study provides a qualitative contribution that fills a research gap in the Arab and local literature by integrating sustainable architecture with information technology in an in-depth and thoughtful manner.

• **Practical Importance**: It provides practical solutions and recommendations for decision-makers, developers, and professionals in the construction sector, supporting the improvement of the quality and sustainability of housing projects in Egypt.

• **Societal Importance**: It supports the achievement of the Sustainable Development Goals and Egypt Vision 2030 by offering proposals that reduce energy consumption and promote sustainable building practices, positively impacting the quality of life for individuals and Egyptian society.

6. Research Hypothesis

This study focuses on testing the following hypothesis: The systematic and integrated application of Building Information Modeling (BIM) in the early stages of residential building design in Egypt may significantly contribute to enhancing the effectiveness of bioclimatic design standards. This would lead to improved energy efficiency, increased thermal comfort, and reduced operating costs in the long term.

7. Research Methodology

The study adopts a descriptive and analytical approach based on a set of carefully considered steps as follows:

1. Systematic Literature Review:

A comprehensive and systematic review of scientific research published in reliable academic databases such as Scopus, Web of Science, and Google Scholar will be conducted during the period from 2015 to 2025. Precise keywords will be identified and adopted to ensure comprehensive coverage of the topic under study.

2. Content Analysis:

The selected studies will undergo a systematic content analysis process to extract and classify data on the methodologies applied, the tools used, the quantitative and qualitative results, and the recommendations they offer.

3. Comparative Analysis:

An analytical comparison will be conducted between the results of various studies to identify prevailing trends, highlight strengths and weaknesses, and identify existing research gaps that have not been adequately addressed.

4. Conclusion and Inference:

Based on the results of the previous steps, the main conclusions of the research work will be drawn, and an integrated conceptual framework will be developed to support the application of practical recommendations in the context of bioclimatic design.

8. Study Terminology:

This section intends to delineate a straightforward and collective understanding of the central terminology employed within this report informed by scientific literature:

• **Bioclimatic design**: A methodology which seeks, within building design, to produce buildings that will respond to their local climate with the goal of achieving thermal and visual comfort for their inhabitants while decreasing their reliance upon energy from conventional sources. Bioclimatic design is based upon an extensive assessment of a building's climatic environment and will employ passive design solutions [6].

• **Building Information Modeling (BIM):** Is a process for synthesizing, altering and managing a digital [virtual] model of the physical and functional characteristics of a building. BIM uses a shared and reliable source of information about a building to aid in the decision-making process throughout the built environment's life cycle from initial design to demolition [7].

• **Thermal comfort**: This refers to "the condition of mind that expresses satisfaction with the thermal environment" [8]. Thermal comfort is governed by six key factors: air temperature, radiant temperature, air velocity, humidity, clothing insulation, and the level of physical activity.

Passive design strategies involve architectural approaches that rely on natural phenomena to ensure indoor comfort. In terms of temperature regulation, these strategies utilize solar radiation, convection processes, and naturally ventilated airflow, delivering a comfortable indoor environment without relying on mechanical systems [9].

• **Building Performance Simulation (BPS):** represents a reliable methodology for testing and assessing the energy efficiency and performance of buildings—whether in the design phase or for existing structures. These simulation tools evaluate factors such as energy consumption, thermal comfort, and daylight access, aiding designers in making informed decisions about building performance. [10].

• **Life Cycle Assessment (LCA):** is an integrated procedure for evaluating the environmental impacts associated with each stage of a building's or product's life cycle. This encompasses everything from the extraction of raw materials to manufacturing, usage, and eventual recycling or disposal [11].

9. Theoretical Framework:

Fundamentals and principles of bioclimatic design:

Bioclimatic design has witnessed renewed interest that began with the energy crisis of the 1970s. However, at its core, it revives traditional architectural principles that harmonize with the local climate. The book "Designing with Climate" by the Olgyay brothers (1963) [3], can be considered a cornerstone, as they presented a scientific methodology for analyzing climate data and employing it in creating architectural design solutions. They also developed the "bioclimatic map" to identify human thermal comfort zones and proposed nature-based design strategies to achieve this in varying climate patterns.

Later, Baruch Givoni (1998) [12] expanded on these principles by introducing the "psychometric map of buildings," a tool that helps designers choose the best passive cooling or heating strategies for buildings based on factors such as temperature and humidity. Bioclimatic design is based on three main principles that define its essence:

Solar Radiation Control:

- Optimal Orientation:

Proper building orientation is a crucial step. In the Northern Hemisphere, particularly in Egypt, it is preferable for the main facades to face south to take advantage of the lower solar heat during the winter and to obtain shade during the summer, where the sun is at a sharp angle. Eastern and western facades are more susceptible to excessive heat in the summer, requiring careful shading solutions [9].

- Shading:

Essential shading techniques aim to reduce the amount of heat gained in the summer, whether through design elements such as horizontal canopies on southern facades or vertical canopies on eastern and western facades, or by using natural elements such as trees and climbing plants [13].

Natural Ventilation:

- Cross Ventilation:

Cross ventilation is achieved when openings are carefully distributed on opposite facades, allowing air to flow through interior spaces and improving thermal comfort by removing excess heat and humidity [14].

- Stack Effect:

This principle relies on the ascent of hot air and ensuring a natural flow by designing lower openings for the inflow of cool air and upper openings for the outflow of hot air, such as using skylights or wind vents. This method provides steady airflow even in the absence of external winds [15].

Thermal Mass:

Thermal mass refers to the ability of building materials to store and gradually release heat. In hot and dry climates such as Upper Egypt, high-thermal-mass materials, such as bricks and thick stone, are used to absorb daytime heat and prevent it from entering the building, while releasing it during the cooler nights to maintain internal temperature balance [12].

Thermal Insulation:

Thermal insulation relies on reducing heat transfer through building components such as walls, ceilings, and floors. Effective insulation is important in every climate as it mitigates the demands of mechanical cooling or heating through preventing the penetration of heat; in the summer and minimizing the loss of heat during the winter temperatures [16].

Building Information Modeling (BIM) as an Integrated Approach

BIM relates to a major development and evolution of Computer Aided Design (CAD) tools as a more sophisticated process. BIM does not create two- or three-dimensional drawings that consist of lines and shapes. Instead, BIM works through making an intelligent digital model of the building composed of "objects" such as walls, doors and windows, which contain rich information regarding the physical and functional information [4]. BIM principally relies on its rich data model, which contains several dimensions integrated:

Dimensions of Building Information Modeling (BIM): [17]

- 3D (three-dimensional modeling): Creates an accurate representation of the building which contributes to more coordinated design and earlier identification of conflicts between different systems (architectural, structural, and electromechanical) prior to the construction of the building. **- 4D (Time Management): The** 3D model is incorporated into the project schedule to model construction sequencing as well as resource management, in a more streamlined manner.

- 5D (Cost Management): The model is associated with physical variables and costs so that a more accurate cost estimate can be created and costs can be tracked throughout the project.

-6D (Sustainability): Concentrates on assessing the model's energy and environmental performance, then looking at environmental performance issues for each alternative design option.

-7D (Facility Management): Involves documenting how a building operates and maintenance needs to manage the building throughout its lifecycle, once construction is finished.

Integrating BIM and Bioclimatic Design:

Moving Towards Sustainable and Equitable Outcomes This project embodies the use of BIM technology for the visual representation and efficient execution of bioclimatic design principles. The methodology embraces different overlapping strategies.

Utilizing BIM as a tool for early-stage analysis and simulation:

BIM provides the ability to quantitatively evaluate various options before final design decisions are made. Its most prominent applications include:

- Energy simulation: Engineering and information models generated by BIM platforms such as Revit or ArchiCAD are used in energy simulation tools such as Energy Plus and Design Builder to analyze annual energy consumption and heating and cooling loads, allowing for testing multiple strategies such as changing the type of glass or designing thermal shading devices [15].
- **Natural lighting analysis:** BIM platforms support tools for analyzing light distribution within interior spaces, providing indicators such as "daylight factor" or "daylight independence," which enhances window design optimization and reduces reliance on artificial lighting [20].
- **Computational fluid dynamics (CFD):** To evaluate natural ventilation accurately, Building Information Modeling (BIM) models were created and used in conjunction with CFD software to simulate airflow and temperature both internally and externally around the building, and to quantify the airflow effectiveness of opening for ventilation.

BIM as an Iterative Design and Optimization Process:

The iterative nature of BIM allows rapid assessment and optimization. A variety of building design changes including orientation, size of windows, and depth of shading can be quickly evaluated for their influence on environmental performance and to optimize the balance between performance, cost, and aesthetics.

BIM as Platform for Multidisciplinary Design Collaboration: Effective collaborative design within different fields of engineering is crucial for successful bioclimatic design implementation. BIM provides a common space in which practitioners from different disciplines, including architects, mechanical engineers, and structural engineers can connect together in the same model space; thus, facilitating adequate design coordination between the disciplines while minimizing potential conflicts and enhancing the design process. An example of this integration is mechanical engineers producing air conditioning systems in tandem with the architect's passive cooling systems. [23]

10. Literature Review:

This part of the research presents a detailed analytical commentary of previous literature on bioclimatic design and Building Information Modeling (BIM) practices in different climatic contexts, while focusing specifically on hot arid environments closely resembling Egypt's climate. It is organized into three significant themes that correspond with the aims of the research:

- The first theme outlines bioclimatic design techniques to enhance thermal comfort and reduce energy use in desert climates.

- The second theme discusses these similar types of project outcomes, whether aligned with BIM technologies, environmental, economic, and social outcomes with particular emphasis on their role in sustainability. The third axis insights from the preceding sections by exploring research that combines bioclimatic design principles with BIM technologies, commonly referred to as Green BIM, emphasizing its potential to bolster efforts toward sustainable building solutions in hot climates. In summary, the review underscores a growing interest from both academic and professional communities in advancing these overlapping fields.

The analysis did identify a significant gap; namely, there is no holistic and tangible framework to address the challenges of sustainable residential buildings in an Egyptian context using these advanced methods. This study acknowledges and aims to fill this gap through new methodological proposals and frameworks.

First Axis: Research Into Bioclimatic Design Strategies:

This section focuses on research related to design techniques that work with the climatic context of a location, that is, on maximizing thermal comfort and minimizing mechanical systems in buildings. Basyouni (2021) indicated that study focus in an Egyptian context as the study investigated a prototype housing project which was designed in Siwa Oasis by incorporating bioclimatic design principles. Good design flow was achieved while enhancing thermal comfort and reducing energy demand were the primary goals of the project. Analysis of the site traditional architecture and computer simulation studies were utilized, and the author confirmed the benefits of traditional strategies including the use of native materials (kersheef), an optimal building orientation, a courtyard internally to the dwelling, and the minimization of window openings to improve a better indoor living environment. The author even recommended that these traditional principles be used as a framework for incorporating into modern dwelling designs in desert climates.[24] Bera & Nag (2022) addressed bioclimatic principles to identify affordable and thermally comfortable rural housing options in India. The results, which integrated analytical, According to research and practical studies, relatively easy strategies—such as correct orientation of buildings, sufficient natural ventilation, and locally sourced materials with suitable thermal properties—were shown to improve indoor comfort while reducing dependence on artificial systems. These strategies also support sustainability and efficiency benefits. The authors suggested implementing these strategies as practical and economical interventions, especially in terms of housing provision in rural communities.In terms of methodology, Daemei et al. (2019) presented a generic framework to implement bioclimatic design principles to humid subtropical (Cfa) climates. This framework was founded upon a thorough scientific review and serves as a useful reference for designers while demonstrating how to implement key strategies—like ventilation, shading, and thermal mass subject to seasonal changes. The authors stressed the integration of these strategies to facilitate performance as much as possible. The framework aims to provide systematic approaches to an otherwise arbitrary process of justifying and implementing design strategies in response to climate for humid subtropical climates. [[26] Al-Obaidi et al. (2017) examined the use of biomimicry ideas in the design of smart building skins that could react to changes in the environment dynamically. In their theoretical discussion, they highlighted the benefits of suggesting models based on nature, such as using cooling processes from the skin of living organisms, or movement patterns from plant leaves to design systems that would be capable of self-regulation for temperature, ventilation, and lighting. They proposed a broader focus of study on applied practices inspired by the natural world to explore innovation in building design for sustainability [27].

The second axis focuses on synthesizing research that explores the role of Building Information Modeling (BIM) technology to improve sustainability.

through changed portions of the project lifecycle. BIM technology has transitioned from a 3D design tool to an advanced digital analysis tool to support sustainable decision-making and performance enhancement in numerous sectors.[28] For example, the Egyptian context, Marzouk et al.'s (2016) work is a worthy start to research in the area. It includes a framework that is an amalgamation of BIM technology and the sustainability of low-income housing projects. Through the testing of their framework theoretically on a project, the study showed BIM to assist with data analysis and choices around sustainable materials while also showing to enhance energy efficiency in the earlier stages of a project. It is recommended along the journey that this framework be implemented in the country on a national level to develop the sustainability of such housing projects. [29] Refaat and Hussein (2019) also studied large projects and referenced the BIM technology on the Canadian University project in the New Administrative Capital. Their purpose was to create a model for analyzing and managing green building design within sustainability constraints. The results expressed that BIM proved to be highly efficient in managing complex projects and encouraged the adoption of BIM as an appropriate standard tool to achieve sustainability goals. Meanwhile Georgiadou (2019) review of BIM in the UK housing sector reported that there are benefits BIM can achieve such as enhanced coordination, reduced errors, and improved cost estimation accuracy all outweigh costly challenges of BIM technology or training internationally. The researchers advocated for crafting a nationally oriented strategic plan regarding the training of employees and establishing common settings that would encourage broader usage of that technology by practitioners.[30] Ahmad and Thaheem (2018) considered the economic aspect of sustainability in relation to BIM by developing a system to assess building lifecycle costs rather than simply focusing on the initial expenses. They stated that the 4D and 5D BIM models play an important role in establishing a framework that supports sustainable economic decisions for projects. Their study recommended that lifecycle analysis be included as one of the elements essential to sustainability assessment in projects.[31] Another study by Ahmad and Thaheem (2017) identified the social aspect of sustainability. Comfort, safety, and social interaction have been identified as significant components for the assessment of residential buildings. These aspects were evaluated indirectly using a model based on BIM technology. It was highlighted that social aspects should be prioritized over the project planning and evaluation phases

[33]. In terms of buildings' operational phases, Rogage et al. (2020) considered how live sensor data (BIM) could be linked with live sensor data that would leverage real-time information to enhance performance metrics once the building was completed.They found gaps between the anticipated operational performance and the actual performance they measured of the buildings, and they suggested that if we practiced the use of "digital twin" more often, they may improve operational performance and benefit other discussions related to buildings after construction was complete.[32] Regarding the construction stage, Ciribini et al. (2016) concentrated on the application of the integrated operations construct using BIM in a housing project in Italy. Teamwork based on a unified BIM platform greatly reduces technical errors and interoperability issues and improves job productivity and costs. This study recommended expanding the application of this methodology. [34] Studies have emphasized the importance of BIM technology in more effectively achieving sustainability objectives and fostering sustainable digital practices globally. Liu et al. (2018) pursued the development of a Building Information Modeling (BIM)-based algorithm that streamlined the planning and installation of residential wall panels to minimize materials and resource waste. Their results showed that automation of operations through BIM provides a significant advantage over traditional operations that would waste more than one building site would consider acceptable. The research paper highlights that BIM automation will encourage waste reduction while providing opportunities to improve environmental and economic sustainability on-site. Notably, the authors suggest pursuing enhanced applications of BIM automation to increase construction resource efficacy and add long-term maintained value on-site.[35]

The third axis: Conjoining Sustainable Design and Building Information Modeling (Green BIM)

This strategy champions the use of BIM's analytic ability and integrating sustainable design principles to enhance building performance and creative design solutions. Nabawy et al. (2025) presented an integrated model that uses BIM techniques and sustainable strategies to enhance efficiency for housing development projects in Egypt. This innovative study indicates that Green BIM could be applied not just for sustainability but also to improve performance in construction practices. This study developed a theoretical framework and applied it to a case study of a residential building, identifying systematic steps for utilizing BIM in analyzing thermal performance, utilizing natural light, and selecting green construction materials to produce more efficient designs. The authors concluded that the model serves as a practical guide for designers and architects to increase sustainability in residential housing. [36] Lastly, Bakir et al. (2022) also put BIM software to work practically, looking to evaluate and enhance the energy performance of a residential building using BIM software and energy simulation techniques. They developed a BIM model and evaluated different strategies, such as increasing insulation and utilizing energy-efficient glass. The results indicated that improving design components accounted for an improvement in energy consumption. It suggested increasing the use of BIM tools to make evidence-based decisions on energy efficiency for future projects. [37] From a technical perspective, Elnabawi & Hamza (2019) discussed issues related to data transfer between BIM platforms and energy simulation software. Upon analyzing the BIM model developing from Revit through various platforms, the analysis concluded that, despite technical issues, using BIM reduces time and effort when compared to developing a new model if the tools are developed and practical for interoperability. To address this issue, they suggested that in order to utilize design and analysis platforms effectively, combined data standards should be developed and users should be trained to ensure quality in the exports of models. [38] Lastly, Ali et al. (2020) evaluated the effectiveness of passive roof cooling measures, such as green roofs and cool roofs, in reducing energy consumption in buildings impacted by the hot and dry climate of Upper Egypt. The simulation analysis showed that passive cooling features reduce cooling loads and thereby reduce energy consumption. BIM technology was brought forward as an effective tool for comparing and determining appropriate fixtures in the climate context. Combining sustainable solutions is suggested in the discussion, such as green roofs and cool roofs, to implementation in new and established buildings in hot and dry climates to facilitate energy reduction and promote overall performance of the buildings. [39]

11 - Utilization of the research methodology for the literature review

The study followed a descriptive-analytical method with the goal of providing a detailed and comprehensive understanding of the topic "Bioclimatic Design Standards Using BIM (Building Information Modeling) for Residential

Buildings in Egypt". The research methodology followed the following steps:

1- A Systematic Literature Review

A systematic search of peer-reviewed scientific studies of the research project was undertaken in identifiable academic databases Scopus and Google Scholar and other studies between the years 2015 and 2025. To ensure that the literature was comprehensive and useful data for the research planned and the scope of the topic, studies were selected based on specific keywords that were included in the literature search. These keywords included: "Bioclimatic Design", "BIM", "Sustainable residential buildings", "Egypt", and "Hot Climate". From this exercise, 16 main studies were identified that represented the development of the field and its diversification in applications specifically related to the Egypt context or similar hot climate contexts.

2- Content Analysis

To derive key findings and determine scientific trends associated with the selected studies, a comprehensive content analysis was performed. The analysis entailed classifying information related to the methodologies involved, key research instruments, notable quantitative and qualitative findings, and included recommendations. The following table contains a comparative representation of the content analysis of each study: **(table (1) a detailed comparison of all selected studies).**

3- Comparative Analysis

By examining and analyzing the 16 studies listed in the table, a set of general trends, along with strengths, weaknesses, and research gaps, were identified as follows:

- General Trends:

- There is clear scientific consensus highlighting the importance of bioclimatic design as a key element for achieving sustainability in buildings, especially in hot environments (Bassiouni, 2021; Bera & Nag, 2022; Ali et al., 2020).
- There is growing recognition that BIM technology has transcended its traditional function as a 3D modeling tool to become a comprehensive platform for analyzing various dimensions of sustainability (environmental, economic, and social) (Marzouk et al., 2016; Ahmad & Thaheem, 2018; Ahmad & Thaheem, 2017).

The most advanced trend is the integration of bioclimatic design with BIM (Green BIM) technology, where BIM's analytical capabilities are leveraged to quantitatively evaluate passive design strategies during the early stages (Nabawy et al., 2025; Bakir et al., 2022; Ali et al., 2020).

- Strengths of the studies:

- **Geographical diversity**: Covering diverse geographic and climatic contexts (Egypt, India, the United Kingdom, Italy), allowing for a comprehensive and in-depth overview of the challenges and opportunities of sustainable design.
- **Methodological diversity**: Using multiple methodologies including theoretical reviews, framework development, case studies, quantitative simulations, and field experiments.
- **Focus on all phases of the building life cycle**: Studies span all phases of the building life cycle, from design (Marzouk et al., 2016), through construction (Ciribini et al., 2016), and on to operation (Rogage et al., 2020).

- Weaknesses and Research Gaps:

Despite the wealth of existing studies, the analysis revealed clear research gaps:

- Bioclimatic design studies tend to be limited to qualitative methods or simulations of specific strategies without placing them within a comprehensive framework that integrates modern assessment tools.
- Studies related to BIM technology often focus on technical aspects but do not sufficiently leverage traditional architecture and climate principles appropriate to local contexts.
- Studies integrating green BIM in the Egyptian context (e.g., Nabawy et al., 2025; Bakir et al., 2022) are promising but need to develop a more detailed framework or focus on all aspects of sustainability rather than just a specific aspect such as energy consumption.

4- Conclusion and Implications

Based on the previous analysis, the need to develop a comprehensive and integrated framework for sustainable residential buildings in the Egyptian context is evident. This framework should consider the following:

1. Rely on bioclimatic design principles inspired by traditional architecture suitable for Egypt's hot and dry environment.
2. Achieving a balance between the three dimensions of sustainability: environmental, economic, and social.
3. Employing BIM technology as a central tool for analysis, evaluation, and simulation throughout all stages of design and implementation.

This study aims to fill the research gap by presenting a proposed framework applied to a real-life case study to serve as a practical reference and guide for architects and developers in Egypt. The proposed framework will help them design and implement residential buildings that are efficient and sustainable and meet the needs of the local environment and users.

10. Results and Recommendations

After reviewing and analyzing the theoretical framework and previous studies and employing a descriptive and analytical approach to a variety of recent research, this study reaches its concluding stage, which focuses on drawing conclusions and providing practical recommendations. Through a systematic analysis of the literature, there has been growing scholarly interest in the intersection of bioclimatic design, Building Information Modeling (BIM), and sustainability dimensions. However, a clear gap remains: the absence of an integrated framework suited to the Egyptian context, combining local architectural heritage with modern digital technology tools to enhance the sustainability of residential buildings.

Study Results

Based on content analysis and a comparative and deductive approach, the study concludes that achieving sustainability in the residential building sector in Egypt requires adopting an integrated framework. This framework should go beyond partial solutions and emulate a combination of global trends, inherited local expertise, and the capabilities offered by modern digital tools.

The results of this analysis are summarized in the presentation of a " **Proposed Framework for Bioclimatic Design Criteria Using Building Information Modeling (BIM) in Residential Buildings in Egypt**," which includes three main interconnected dimensions containing a set of basic principles and criteria.

1-Dimension One: Bioclimatic Design Principles Shaped by Local Context

- Main Idea: Comparative analyses (Bassiouni, 2021; Bera & Nag, 2022; Ali et al., 2020) support that passive design strategies based on local climate and vernacular architecture provide the best means to minimize energy use and achieve comfortable indoor temperatures**.**

- Standards and Principles: Comprehensive design strategies can enhance building thermal performance and minimize energy demand based on several interrelated principles.

1.1 Building Massing and Orientation: The literature identifies orientation as a principal, low-cost aspect that impacts building performance significantly**.**

Scholars have prioritized orientation in their consideration of building form/design to optimize natural ventilation, sun exposure and shading, to enhance sustainability in architectural design**.** Architectural forms should be oriented to reduce heat gain in the summer, particularly from the eastern and western facades, while enhancing heat absorption in the winter.

- Standards include orienting the longitudinal axis of the building toward east-west, minimizing the area of the eastern and western facades relative to the rest of the facades, and using compact designs that minimize the area of external surfaces exposed to the sun.

1.2. Building Envelope Design:

- The building envelope plays a crucial role in determining a building's thermal performance through walls, roofs, and windows.

- Standards include the use of local materials with high thermal mass and effective wall insulation, and the application of methods such as cool roofs with reflective colors or green roofs, which have proven effective according to recent studies. [39] For windows, emphasis is placed on reducing their relative area on hot facades and using low-emissivity double-glazed windows and innovative shading systems.

1.3. Natural Ventilation:

- Natural ventilation presents an opportunity to limit air conditioning use, particularly in moderately warm conditions in the inter-season.

The criteria listed focus on architectural designs that engage natural ventilation and thermal comfort through an intentional approach to design. These include designs that direct airflow from one opening to another, engaging internal courtyards to facilitate vertical airflow through a chimney effect, and evaporative cooling features that introduce water bodies and/or fountains in the internal courtyards. These strategies represent an integrated approach to sustainable architecture, which aims to optimize the thermal performance of buildings, promote lower environmental impacts, and enhance the comfort of building occupants.

2-The second dimension considers different areas of sustainability, including environmental, economic, and social issues:

Research demonstrates that energy efficiency alone, while important, is inadequate for true sustainable sustainability. In addition, Ahmad and Thaheem (2018, 2017) and includes argument by Marzouk et al. (2016), have suggested that sustainable buildings must go beyond energy efficiency alone to be economically feasible, healthy, and pleasing to people.

- Proposed Principles and Criteria:

2.1 Extended Environmental Sustainability

- Outcomes:

Sustainability in the context of project planning involves much more than just energy efficiency; it consists of many aspects that are intended to contribute positively to a project's whole impact and long-term success. Some of the criteria to achieve sustainability includes:

- **Water efficiency**: Using systems such as energy-efficient fixtures, rainwater collection systems and greywater reuse for irrigation to save resources and reduce dependence on traditional water sources.
- **Sustainable materials**: Selecting materials that are locally sourced, recycled, have low carbon footprint and do not produce harmful VOCs to protect the environment and inhabitants' health.
- **Donated and recycled construction waste**: Managing development waste by separating out then recycling materials from the construction process to contribute little, if at all, to landfills and have a circular approach to using resources.

2.2 Economic Sustainability (Life Cycle Costs)

Outcomes: If you consider only first costs, you will incur a substantially greater operating and maintenance cost over time. Thus, it is essential to consider life cycle cost as an informed, comprehensive approach**.**

Proposed Criteria:

- **Life Cycle Cost Analysis (LCCA):** Perform a complete analysis over the life cycle of the building including everything from construction, occupancy, and maintenance to decommissioning the building. This will allow an acceptable and comprehensive comparison of design options, striving for long-term value and sustainability.
- **Design for Durability and Maintainability**: Choose durable materials and finishes that will require little maintenance and replace part of the cost, minimizing repair and replacement costs. This will improve the economic resilient option while relieving operational capacities.

2.3- Social Sustainability (Indoor Environmental Quality)

Outcomes: Indoor environments knowingly influence the physical health, comfort, and productivity of building occupants and demonstrate the value of ensuring good air quality, lighting, and thermal comfort in their design.

Suggested Principles:

• **Comfort and Temperature:**
Strive for thermal comfort through passive design strategies first and only move to mechanical systems as required. If additional systems are needed, seek to utilize high performance, energy efficient HVAC to keep building occupants comfortable for a long time.

• **Indoor Air Quality (IAQ):** Seek to maintain healthy IAQ levels through ventilation and selecting building materials with low VOC emissions. Seek to control sources of moisture to control mold or mildew.

• **Light and Views:** Seek to provide the greatest access to natural daylight within interiors while controlling direct sunlight and glare. Provide views of natural green spaces as those views have proven to support mental health and nurture a bond with nature.

3-Dimension Three: Employing Building Information Modelling (BIM) as a Comprehensive Assessment Tool Key Finding:

Research suggests that BIM may be a transformative medium for integrating and assessing fundamental design principles and evaluation criteria, facilitating a move towards a more holistic and coherent design paradigm. Research by Nabawy et al. (2025), Bakir et al. (2022), and Elnabawi & Hamza (2019) confirmed its effectiveness in supporting this transition.

Stated Principles and Criteria:

3.1. Utilising BIM to Increase Integration of Design - Observation:

Traditional workflows sometimes demonstrate compartmentalized instincts within disciplines (e.g. architecture, structural engineering, electromechanical systems, etc.), contributing to fragmentation and improper coordination through the project process.

- Suggested Criteria:

Establish a single building model using BIM as a common reference point for all disciplines involved, adopting the model as the single source of truth. Ciribini et al. (2016) promotes the idea that shared models create collaboration between disciplines and that possible conflicts can be identified earlier in the process through a BIM model.

3.2. Employing BIM for Environmental Performance Simulation

- **Findings:** An early review of environmental performance indicators, such as energy use and lighting assessments, is a necessary step in progressing towards sustainable design objectives and to undertake effective action.
- **Proposed Criterion:** Conduct dynamic energy simulations modeled within a BIM framework to better understand overall energy use by year. This will allow for investigation of different design alternatives, such as glazing type or insulation type, to make decisions based on enhanced understanding and sustainability.
- **Daylighting Simulation:** Assess daylighting distribution to ensure adequate illumination in different spaces while minimizing glare and other issues.
- **Solar Radiation Analysis:** Conduct solar radiation analysis to assess the impact on the building envelope to identify areas of heat gain for

development of appropriate shading strategies, therefore improving thermal performance.

3.3. The BIM Tool to Evaluate Economic and Operational Sustainability

- Findings: BIM offers advantages that go beyond being just a tool for 3D visualization; it also delivers valuable support for various needs across all project phases.

- Proposed Measures:

- 4D and 5D Modeling: Use the BIM model to link the design with schedule and cost estimates and accurately quantify material quantities to minimize waste (Liu et al., 2018).

- 6D Modeling: Utilize BIM to link building components to maintenance, lifespan, and replacement costs information to perform lifecycle analysis and enhance building operating costs analysis in future.

- 7D Modeling (Facility Management): Delivering an "as-built" BIM model to the facilities management team as a live database for maintenance and operations management and linking it to live sensors to create a "digital twin," as recommended by Rogage et al. (2020).

12.1 Recommendations:

Based on the study results and the proposed conceptual framework, the study reached a set of recommendations that can be categorized according to the target audience:

1- Recommendations for architects and designers

- Adopting an integrated design approach: Moving from traditional design to an integrated design approach that includes all disciplines (architectural, structural, electromechanical, and sustainability consultant) from the outset of the project, relying on a common BIM platform.

- Prioritizing passive strategies: Starting with passive strategies such as orientation, massing, exterior envelope design, and natural ventilation, and enhancing them using BIM simulation before considering mechanical systems.

- Leveraging architectural heritage: Studying traditional elements such as local materials, the interior courtyard, mashrabiya, and malaqaf, and re-adapting them using modern techniques similar to those indicated in Bassiouni's study (2021) [24].

- Considering the comprehensive life cycle: Expanding the scope of designer responsibility to include environmental and economic impact throughout the building's life cycle, using tools such as LCCA with the help of BIM technology to make informed and sustainable decisions.

2- Recommendations for Real Estate Developers and Construction Companies

- Consider BIM as a Strategic Investment: Recognize that adopting BIM technology reduces errors and waste during implementation and enhances the project's marketing value while reducing operating costs, as Ahmed and Thahim (2018) [33] pointed out.

- Market performance and sustainability: Focus on marketing points such as energy efficiency, indoor air quality, and thermal comfort, rather than marketing based on aesthetic and finish.

- Capacity and Training: Emphasize capacity building and training to upskill technicians and engineers on BIM tools and energy simulation to ensure BIM technology is used effectively, as shown by Elenbawi and Hamza (2019).

3-Decision-makers and government recommendations

- Stipulate building codes: Elevate the Egyptian building codes to require energy efficiency and sustainability, while providing incentives for energy efficiency projects or projects that have a green building certification.

- Encourage and promote BIM at a national level: Launch a national campaign for encouraging the building industry to adopt BIM technology by developing national codes and standards; providing jurisdictions, agencies, and the building industry with technical support, while demanding adoption in larger, major buildings, similar to what other countries have experienced, such as the United Kingdom.

- Advocate for awareness of the significance of sustainability: Organize campaigns to raise awareness of the benefits of sustainable housing and to persuade citizens to start to demand sustainable housing.

4- Suggestions for academic and research institutions

- Revising university programs: Revising the curricula in architectural and engineering programs at Egyptian universities to include advanced topics such as sustainable design, Building Information Modeling (BIM), and environmental performance simulation.

- Promoting applied research: Encouraging research to test local build materials, develop new solutions that address local problems, and analyze the performance of existing building stock.

- Establishing living laboratories: Transforming university projects into "living laboratories" to apply the latest sustainable construction technologies, allowing students to learn through real-world experience.

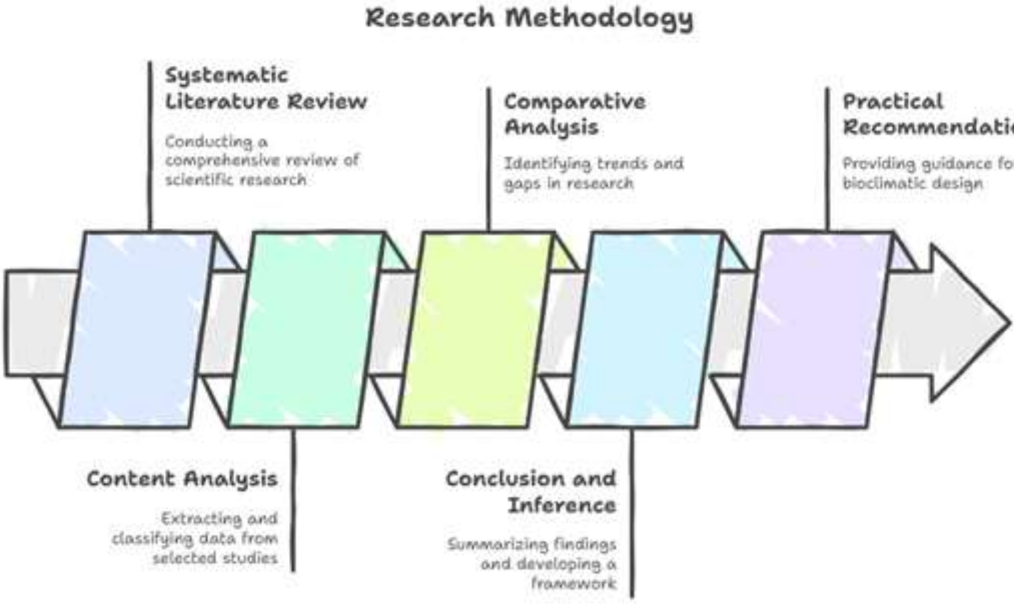

Figure 1. *The study methodology.*

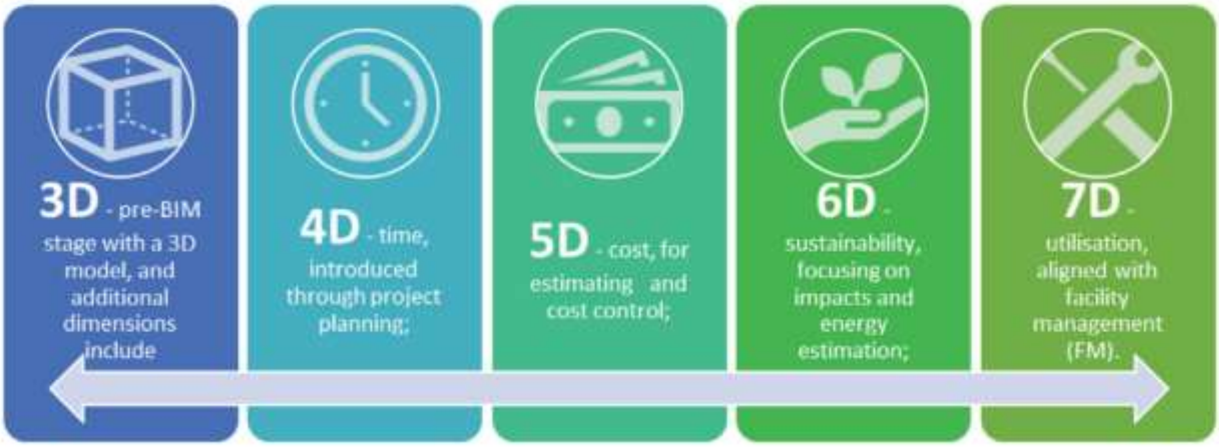

Figure 2. *As exhibited in Figure 1, BIM Dimensions [18].*

Table 1. *Content Analysis for Literature Review [24-39]*

	Study (Reference)	axis	Main Objective	Methodology	Sample / Case Study	Main Results and Recommendations
1	**Basyouni (2021)**	**bioclimatic design**	Developing a prototype for a sustainable desert dwelling in the Siwa Oasis.	The study relied on applied analysis and computer simulation.	Exploring the traditional architecture of the Siwa Oasis.	Evaluating the effectiveness of traditional strategies, such as the use of local materials and interior courtyard design, while presenting an improved model for greater sustainability.
2	**Bera & Nag (2022)**	**bioclimatic design**	Applying bioclimatic design principles to low-cost rural housing	It relies on a combination of field analysis and simulation.	The study targets rural housing in India,	where simple solutions such as proper orientation and effective ventilation have proven to significantly improve comfort levels,

						contributing to enhanced economic sustainability.
3	**Daemei et al. (2019)**	**bioclimatic design**	Preparing a comprehensive guide to clarify bioclimatic design strategies.	A comprehensive and in-depth literature analysis and critical review were conducted.	Relevant scientific literature was presented.	A clear framework was developed to classify the various strategies to ensure sustainable and integrated outcomes.
4	**Al-Obaidi et al. (2017)**	**bioclimatic design**	Exploring biomimicry as a tool for designing dynamically adaptive building envelopes	An analytical and theoretical study focusing on concepts and practical applications	A review of current literature and related prototypes	Inspiration from nature may open new avenues for revolutionary innovations that reduce energy consumption and enhance environmental efficiency
5	**Marzouk et al. (2016)**	**BIM** Application for Sustainability	Developing a comprehensive framework for assessing the sustainability of low-income housing projects in Egypt using Building Modeling (BIM) .technology	The project includes developing an integrated theoretical framework along with conducting a practical case study	applied to a low-income housing project in .Egypt	BIM technology is a powerful tool to support more efficient and sustainable design decisions, especially in the early stages of a project, such as selecting appropriate materials and analyzing energy .efficiency
6	**Refaat & Hussien (2019)**	**BIM** Application for Sustainability	Analyzing the use of BIM technology in a megaproject to support green building .requirements	An Analytical .Case Study	Canada building in the New Administrative .Capital	BIM technology is an essential tool for managing and coordinating complex, .sustainable projects
7	**Georgiadou (2019)**	**BIM** Application for Sustainability	Identifying the benefits and challenges of adopting BIM in the UK housing .sector	A comprehensive review of studies and case .studies	المشاريع السكنية في المملكة المتحدة.	Despite these challenges, studies and practical experience indicate that the long-term benefits of using BIM outweigh the .drawbacks
8	**Ahmad & Thaheem (2018)**	**BIM** Application for Sustainability	Designing an integrated framework for assessing economic sustainability using BIM techniques.	Developing a theoretical framework	A comprehensive review of the literature on residential buildings	BIM, in its four and five dimensions (4D/5D), is an effective and accurate tool for supporting this type of assessment.
9	**Rogage et al. (2020)**	**BIM** Application for Sustainability	Exploring the integration of sensor data with BIM to evaluate actual building performance.	Experimental case study	Residential building.	We will highlight the gap between anticipated and measured performance and discuss the "digital twin" framework as an effective tool for assessing performance and incorporating lessons learned.
10	**Ahmad & Thaheem (2017)**	**BIM** Application for Sustaina	Designing a framework for assessing social sustainability	Forming a theoretical framework	Reviewing the literature on	A framework was developed to assess the most important social dimensions, leveraging

		bility	aspects, such as comfort and safety, in residential buildings.		residential buildings in general	BIM technology to analyze and enhance assessment accuracy and improve sustainability implementation.
11	**Ciribini et al. (2016)**	**BIM** Application for Sustainability	Improving coordination and efficiency using BIM technology during the construction phase	Case Study: Experimental Project	BIM technology was applied to a residential project in Italy.	Using a common BIM platform significantly reduced conflicts and errors during the construction process.
12	**Liu et al. (2018)**	**BIM** Application for Sustainability	Developing a custom algorithm to automate the panel installation planning process to reduce material waste.	Developing and testing the algorithm.	Using BIM models specifically designed for residential buildings	BIM-based automation improves efficiency and significantly reduces material waste compared to traditional manual methods.
13	**Nabawy et al. (2025)**	Green BIM integration	Developing a Green BIM Framework to Support Sustainable Housing Development in Egypt.	The project includes the development of an integrated theoretical framework, along with a real-world case study.	The practical application of the framework is the analysis of a residential building.	This framework will consider BIM technology to assess different environmental factors (e.g. thermal performance, light distribution, and material choices) soon in the design and building process.
14	**Bakir et al. (2022)**	Green BIM integration	Using Green BIM technology to evaluate and improve the energy efficiency of a residential building.	The work includes a case study and energy simulation.	The residential building is located in the New Administrative Capital.	Implementing passive and active design strategies significantly contributes to reducing energy consumption.
15	**Elnabawi & Hamza (2019)**	Green BIM integration	A study of the technical challenges related to interoperability between BIM-based design software and energy simulation software.	Experimental research	Based on a BIM model of a single building.	Using BIM offers numerous advantages, such as improved time efficiency and reduced errors. However, addressing the challenges associated with data transfer requires expertise and specialization to ensure The intended combination or collaboration..
16	**Ali et al. (2020)**	Green BIM integration	Evaluating passive rooftop cooling technologies in Upper Egypt using Building Information Modeling (BIM).	A case study and simulation.	The study includes a model of a standard building.	The results confirm that rooftop cooling technologies significantly contribute to reducing cooling loads, and BIM has proven its effectiveness as a tool for selecting optimal solutions to achieve sustainable

						cooling.

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- **Ethical approval:** The conducted research is not related to either human or animal use.
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