AKSEN: Journal of Creative Industry 8(3) special edition
June 2024, 34-44 AKSEN
DOI : 10.37715/aksen.v8i3 (special edition).4626

P-ISSN : 2477-2593
E-ISSN : 2477 -2607

UTILIZATION OF ARTIFICIAL INTELLIGENCE FOR SUSTAINABLE BUILDING ARCHITECTURE

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How to Cite: Widodo, et al (2024). Utilization of Artificial Intelligence for Sustainable Building Architecture . AKSEN: Journal of Design and Creative Industry, 8 (3) special edition, halaman 34-44.
https://doi.org/10.37715/aksen.v8i3 (special edition).4626

ABSTRACT
The rise of artificial intelligence (AI) presents a transformative opportunity for architects seeking to achieve sustainable design goals. AI's ability to extract and analyze vast amounts of data during the pre-design, design and construction, and post-construction phases empowers architects to make data-driven decisions that optimize building performance. This data can provide strategies for material selection, time and energy efficiency, and resource management, ultimately contributing to the realization of Sustainable Development Goals (SDGs) through building design. This research explores the specific applications of artificial intelligence in sustainable building design. To achieve this objective, a systematic literature review and case study analysis were conducted, utilizing academic journals and article reports as primary data sources. Specific keywords were employed to narrow the scope of the research. The analysis involved classifying AI applications and investigating their potential benefits in : 1) analyzing environmental conditions, such as historical and real-time climate data to optimize building orientation, and natural ventilation strategies, 2) facilitating the design process by providing real-time visualization and recommendations for achieving sustainable designs, 3) optimizing building materials and construction efficiency, by analyzing material properties, and providing accurate data during the construction stage to gives broader image on how to build efficiently and 4) simulating building performance, by predicting and doing assessment on the building's energy consumption and thermal performance, allowing architects to refine design for optimal sustainability. By integrating AI into these workflows, architects can address critical challenges like global warming and climate change by creating high-performing, sustainable buildings.

Keywords: *Artificial Intelligence, Energy Efficiency, Global Warming, Sustainable Architecture*

ABSTRAK
Munculnya kecerdasan buatan (AI) menghadirkan peluang transformatif bagi para arsitek yang ingin mencapai desain yang berkelanjutan. Kemampuan AI untuk mengekstrak dan menganalisis data dalam jumlah besar selama fase pra-desain, desain dan konstruksi, serta pasca-konstruksi memberdayakan para arsitek untuk membuat keputusan berdasarkan data yang pada akhirnya mengoptimalkan kinerja bangunan. Data ini dapat memberikan strategi pemilihan material, efisiensi waktu dan energi, serta pengelolaan sumber daya, yang pada akhirnya berkontribusi pada realisasi Tujuan Pembangunan Berkelanjutan (SDGs) melalui desain bangunan. Penelitian ini bertujuan untuk mengeksplorasi penerapan spesifik kecerdasan buatan (AI) dalam desain bangunan berkelanjutan. Kajian ini dilakukan melalui tinjauan literatur sistematis dan studi kasus yang diperoleh dari jurnal akademik dan laporan artikel. Kata kunci spesifik digunakan untuk mempersempit lingkup penelitian. Analisis dilakukan dengan cara mengklasifikasikan aplikasi AI dan menyelidiki bagaimana AI dapat dimanfaatkan untuk : 1) menganalisis kondisi lingkungan, seperti data iklim historis dan real-time untuk mengoptimalkan orientasi bangunan, dan strategi ventilasi alami, 2) memudahkan proses mendesain bangunan dengan memberikan visualisasi aktual dan rekomendasi untuk mencapai desain bangunan yang berkelanjutan 3) mengoptimalkan bahan bangunan dan efisiensi selama konstruksi, dengan menganalisis sifat bahan, dan juga memberikan data akurat selama tahap konstruksi untuk memberikan gambaran lebih luas tentang cara membangun secara efisien dan 4) mensimulasikan kinerja bangunan, dengan memprediksi dan melakukan penilaian terhadap konsumsi energi dan kinerja termal bangunan, sehingga memungkinkan para arsitek menyempurnakan desain untuk keberlanjutan yang optimal. Dengan mengintegrasikan AI ke dalam alur kerja ini, para arsitek dapat mengatasi tantangan penting seperti pemanasan global dan perubahan iklim dengan menciptakan bangunan berperforma tinggi dan berkelanjutan.

Kata Kunci: *Arsitektur Berkelanjutan, Efisiensi Energi, Kecerdasan Buatan, Pemanasan Global*

INTRODUCTION

The construction industry is a significant contributor to global warming, as it is listed as the single largest global consumer of resources (Industry Agenda Shaping the Future of Construction A Breakthrough in Mindset and Technology Prepared in Collaboration with The Boston Consulting Group, 2016) and accounting for nearly 40% of global energy consumption as well as a substantial portion of greenhouse gas emissions (Muthu, 2014). Globally, in developed and developing countries, buildings contribute to 33% of the greenhouse gas (GHG) emissions (Kisku et al., 2017). These derived from building materials, transportation of building materials, and energy consumption of construction equipment (Yan et al., 2010). NASA also announced that summer of 2023 is the hottest on global record since 1880 (NASA, 2023). As the urgency to combat climate change intensifies, architects are increasingly turning to innovative solutions to design and build sustainable buildings.

Traditionally, architects have relied on experience, intuition, and building codes to achieve sustainable design goals. However, these methods can be limited in their ability to comprehensively analyze complex data and optimize building performance. Artificial intelligence (AI) presents a transformative opportunity for architects seeking to push the boundaries of sustainable design. Artificial intelligence is a simulation of human intelligence that is modeled in a machine and programmed to be able to think like humans (Copeland, 2024). AI encompasses a range of sophisticated algorithms and machine learning techniques that can analyze vast amounts of data, identify patterns, and make predictions.

While the potential of AI in architecture is widely acknowledged, there is a lack of comprehensive understanding on how this technology can be effectively integrated throughout the entire design and building lifecycle. Many perceive AI as a complex, black-box technology, leading to apprehension and hesitation in its adoption. This research aims to demystify AI for architects by demonstrating its practical applications in sustainable building design. The research will categorize AI tools into four distinct stages – pre-design, design, construction, and post-construction & building performance – and explore how each stage contributes to optimizing resource use, minimizing environmental impact, and ultimately achieving Sustainable Development Goals (SDGs).

METHODS

This research employed a mixed-methods approach, combining a qualitative literature review with a qualitative case study analysis. The literature review aimed to investigate the potential of various artificial intelligence (AI) technologies for mitigating global warming and climate change in the field of architecture and to identify, also categorize existing AI applications relevant to sustainable building design.

Data Collection

Academic databases such as Emerald and ScienceDirect were searched using a combination of keywords including “artificial intelligence,” “sustainable building design,” “architecture design tools,” “climate change,” and “global warming.” Relevant websites such as Archdaily, DeZeen, Zigurat, AutoDesk, and more were also searched with the same combination keywords as the academic databases, to collect broader information and comparison with the academic databases. A rigorous selection process was implemented to ensure the inclusion of credible and relevant articles. The inclusion criteria for the literature review were studies published within the past ten years and those focusing on the practical applications of AI in architectural design and construction. Meanwhile, the data for the case studies was collected through document analysis of published articles, project reports, and press releases that discussed the implementation of AI in the design and construction process by world-known architects. This selection process resulted in a collection of 15 high-quality articles that formed the foundation for this research.

Data Analysis

The retrieved literature was carefully reviewed and coded to identify key themes related to the different categories of AI tools used in sustainable design. These categories may include:

- Pre-design stage AI tools
  Life cycle assessment tools, climate analysis software
- Design stage AI tools
  Generative design algorithms, design conceptualization tools
- Construction stage AI tools
  Building energy modeling software, material optimization tools, construction simulation platforms
- Post-construction & Building Performance stage AI tools

Building management systems with AI integration, occupant behavior monitoring tools, real-time energy consumption analysis software.

In addition to the literature review, two case studies were conducted to explore the practical implementation of AI tools in real-world architectural projects. The case studies focused on application of artificial intelligence in those four stages – pre-design, design, construction, and post-construction & building performance. Other criteria that become the base of these findings is that the buildings are built already and designed by legendary architects such as Zaha Hadid and Foster + Partners. Thematic analysis was used to analyze the data from the documents and to identify key themes related to specific AI tools utilized, the challenges and benefits of AI integration for the projects, and the impact in achieving sustainable design goals.

By analyzing the literature and case studies through this lens, the research aimed to identify AI technologies with the most significant potential to optimize resource use, minimize environmental impact, and contribute to achieving Sustainable Development.

RESULTS AND DISCUSSION

This research investigated the utilization of artificial intelligence (AI) tools in sustainable building design. The findings reveal a diverse range of AI applications across the building lifecycle, categorized into four primary stages: pre-design, design, construction, and post-construction & building performance.

Pre-Design Stage

The major contributions of AI in this stage are (Nabizadeh Rafsanjani & Nabizadeh, 2023):

1. Historical Data and Design Inspiration: AI can analyze historical architectural design and styles, to provide inspiration and context for architectural projects. By learning from the past, architects can create a design that resonates with the people and the surrounding environment.
2. Code Compliance: AI tools make sure that architects' design complies with the relevant building codes and regulations. By highlighting potential compliance issues, architects can avoid costly revisions and delays.

Some Pre-design Stage AI Tools are mentioned below (ARCH20, 2023):

- Archistar: Provides aerial imagery and site planning regulations, enabling informed decision-making about building placement and compliance with zoning restrictions.

Figure 1. Interface Archistar
Source: archistar.ai, 2021

- Sipremo: Leverages AI to analyze climate data and predict potential environmental hazards, allowing architects to design for resilience against future climate events.

Figure 2. Interface Sipremo
Source: aiforgood.itu.int, 2022

Design Stage

AI brings so much innovation in the design stage, such as (Nabizadeh Rafsanjani & Nabizadeh, 2023):

1. Design Assistance: AI-powered tools assist architects in generating design options based on specific criteria like client requirements,

site conditions, and budget constraints. This can accelerate the design exploration phase and provide architects with more creative and data-driven solutions.

2. Virtual Design and Visualization: AI-powered virtual reality and augmented reality tools can enable architects to visualize and conceptualize their design through experience in immersive environments. This also enhances the design communication towards clients and stakeholders, improving the overall design review process.
3. Sustainable Design Strategies: AI can analyze and give recommendations on sustainable design strategies, such as green roofs, rainwater harvesting systems, and passive heating and cooling technologies, to promote eco-friendly architecture.

These are a few Design Stage AI Tools that supports architects on designing (ARCH20, 2023):

- Autodesk Forma: Employs AI for conceptual design, predictive analysis, and automation, facilitating the exploration of various design options and optimization of building performance.

Figure 3. Interface Autodesk Forma
Source: Autodesk.eu, 2023

- TestFit: Generates rapid design variations based on user input, accelerating the initial design phase, and optimizing space utilization.

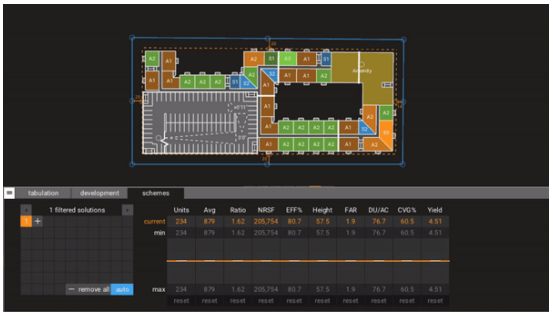

Figure 4. Interface TestFit
Source: testfit.io, 2024

Construction Stage

Building and construction industry is slowly but surely evolving by embracing new technologies, one of them is artificial intelligence, to further enhance the efficiency, productivity, accuracy and safety of the built environments (Baduge et al., 2022). Overall, the main advantages AI can bring to the construction domain are (Nabizadeh Rafsanjani & Nabizadeh, 2023):

1. Construction Planning and Scheduling: AI can optimize construction project planning and scheduling by considering various factors such as resource availability, weather conditions, and site constraints. This leads to better management and reduces project delays.
2. Risk Management: AI can analyze historical project data and real-time information to identify potential risk and hazards that may happen on construction sites. It supports proactively addressing safety concerns and minimizing accidents.

3. Quality Control: Human-centered AI tools can sensors and cameras to monitor the construction process and its quality in real time. By automatically detecting defects and deviation, the construction team can ensure higher-quality outcomes.
4. Construction Safety: AI can monitor workers' movements and behavior on-site while working to identify potential safety hazards and enforce compliance with safety procedures during construction.
5. Real-Time Progress Tracking: AI can facilitate real-time progress monitoring by analyzing data from various sources, such as drones and sensors. This enables the project managers to make data-driven decisions and address issues accordingly.

The AI tools that enhance the construction process are (York, 2024):

- **Planswift:** Offers AI powered quantity takeoff tools, streamlining the estimation process and improving project planning accuracy.

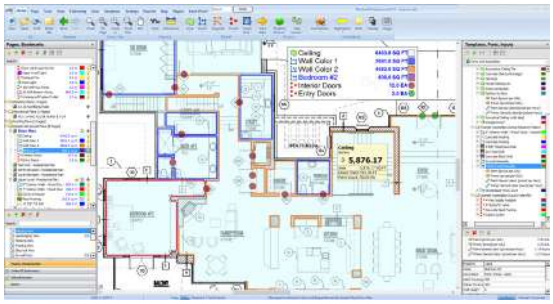

Figure 5. Interface Planswift
Source: planswift.com, 2019

- **OpenSpace.ai:** Captures 360-degree construction site images and maps them to project plans, facilitating progress monitoring and data analysis.

Figure 6. Interface OpenSpace.ai
Source : openspace.ai, 2023

- **Procore & Fieldwire:** Utilize AI for real-time data aggregation and analysis, providing comprehensive insights into construction progress, resource allocation, and potential delays.

Figure 7. Interface Procore
Source: procore.com, 2023

- **viAct:** Leverages AI-powered object recognition to detect safety hazards on construction sites with high accuracy, promoting a safe work environment for all construction workers.

Figure 8. Interface viAct
Source: extranetevolution.com, 2021

Post-Construction & Building Performance Stage

Artificial Intelligence plays a significant role in optimizing energy efficiency in a building, through energy monitoring and control systems based on AI technology, energy consumption patterns can be identified and adjusted to optimize efficiency. Artificial intelligence analyzes consumption patterns along with environmental conditions to determine the best time to control heating, ventilation, and lighting systems. This AI tool can help reduce energy consumption by up to 60% (Pertanto, 2023). These are some AI tools that functions in the post-construction & building performance stage:

- IBM Linux One & IBM Instana (AI for Good, 2022)**:** Employs AI for building energy management, optimizing energy consumption, identifying equipment failures, and reducing operational costs.

Figure 9. IBM Linux One
Source: newsroom.ibm.com, 2023

- AI-EMM (Xiang et al., 2022)**:** The concept of the Artificial Intelligence-based Energy Management Model (AI-EMM) is offered as a smart controller with a broader data collection system and a multi-appliance control interface. The system's inputs include information gathered from sensors and external input or pre-programmed time-varying parameters. Energy management can monitor and optimize a building's energy consumption.

The results demonstrate the significant potential of AI for enhancing sustainable building design practices, especially answering the Sustainable Development Goals (SDGs) number 7, 9, 11, and 12. In the pre-design stage, AI tools like Archistar and Sipremo empower architects to make informed decisions about building location and resilience to climate change. This fosters the creation of sustainable designs that are well-adapted to their environmental context.

"It's meant to capture a vision of a project quickly" said Andrew Kudless, an architect behind Matys Design. Technology may come to be essential in the early stages of projects, taking the place of idea creation (Dreith, 2022) During the design stage, AI tools such as AutoDesk Forma and Testfit accelerate the design process while optimizing space utilization and building performance.

Meanwhile, Planswift, OpenSpace.ai, Procore, Fieldwire, and viAct are AI tools that play a crucial role in the post-construction stage. It further contributes by streamlining project planning and construction site monitoring, leading to improved efficiency and reduced waste. It also provides real-time data insights, enabling proactive management of construction progress, resource, allocation, and safety.

Furthermore, AI-powered energy management systems like IBM Linux One & IBM Instana and AI-EMM, contribute to energy conservation and reduced environmental impact throughout the building's life cycle.

World-known architects like Zaha Hadid and Norman Foster have used artificial intelligence to design in their projects (ZIGURAT Institute of Technology, 2023). For Beijing Daxing International Airport, Zaha Hadid used AI in:

- Design Stage

  Zaha Hadid uses AI algorithms to create design for the airport. The algorithm analyzed various factors such as passenger flows, aircraft movements, and energy efficiency to generate an optimized and visually stunning building design. This shows how AI assist architects in developing unique yet functional structures.

Figure 10. Beijing Daxing International Airport
Source: architecturaldigest.com, 2019

  Foster + Partner uses AI in their project called Bloomberg European Headquarters in London. The implementation of AI in the process is in:

- Pre-Design Stage

  AI was used to analyze the various environmental factors like solar exposures and wind patterns, to inform the building's form and orientation, where these allowed for the creation of a sustainable and energy-efficient design that seamlessly integrates with its surroundings.

Figure 11. Bloomberg European Headquarters
Source : archdaily.com, 2019

CONCLUSION

This research investigated the utilization of artificial intelligence (AI) tools in sustainable building design. The findings reveal a diverse and rapidly evolving landscape of AI applications across the building lifecycle, categorized into four primary stages: pre-design, design, construction, and post construction & building performance. In the pre-design stage, AI empowers architects to make data-driven decisions about building location, environmental resilience, and regulatory compliance. During the design and construction stage, AI facilitates rapid design exploration, space optimization, and project planning efficiency, while also contributing to improved construction site safety by detecting safety hazards in the construction site. Finally, in the post-construction stage, AI plays a critical role in

optimizing building operations, enabling proactive energy management by gathering information derived from the sensors, monitor, and optimize the building's energy consumption, and in the end reduce environmental impact through minimized energy consumption.

Overall, the integration of AI across all stages of the building lifecycle offers a comprehensive and transformative approach to achieving sustainable design goals. By leveraging AI's analytical capabilities for data analysis, optimization, and prediction, architects can create high-performing buildings that minimize environmental impact and contribute to a more sustainable future. The potential for AI to revolutionize the construction industry and significantly reduce its environmental footprint is undeniable. As AI technology continues to evolve and become more sophisticated, its role in sustainable building design is poised to become even more pivotal.

This research provides a foundational understanding of AI applications in sustainable building design. Future research can delve deeper into specific areas, such as:

- Exploring the integration of AI with building information modeling (BIM) for even more comprehensive design optimization.
- Investigating the ethical considerations and potential biases inherent in AI algorithms used for architectural design.
- Analyzing the long-term economic and environmental impacts of AI-powered sustainable building design practices.

By continuing to explore the potential of AI, the architectural field can make significant strides towards creating a more sustainable built environment for generations to come.

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