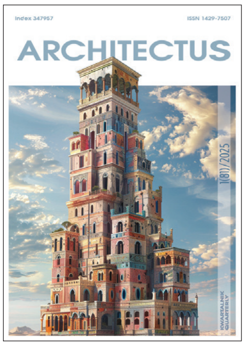

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Małgorzata Kurcjusz*, Anna Stefańska**

Transformative integration of Artificial Intelligence in architectural design

Abstract

The introduction of Artificial Intelligence (AI) into architectural design is transforming traditional practices. This paper presents the typological applications of AI in architecture, focusing on its contributions to conceptual design, performance optimization, and sustainability, highlighting its transformative impact on workflows in the Architecture, Engineering, and Construction (AEC) sector.

The aim of the authors of the paper was to categorize and analyse the hierarchical applications of AI in architectural design. The primary objective – to evaluate AI's roles in fostering creativity, enhancing efficiency, and supporting sustainable practices. Methodologically, the research incorporates a comprehensive review of typological classifications, experimental validations, and case study analyses. By synthesizing findings from recent literature and real-world implementations, the paper assesses both the potentials and limitations of AI across various stages of architectural design.

The results of the study indicate a typological hierarchy of AI applications in architectural design, revealing its multifaceted contributions. In conceptual design, AI-driven generative tools empower architects to explore vast design spaces, enabling the creation of innovative and diverse solutions. In performance optimization, AI demonstrates significant efficiency gains by reducing design iteration times, minimizing material waste, and enhancing energy efficiency through advanced simulations. For sustainability, AI's predictive analytics facilitate informed decisions on material selection and compliance with environmental standards, supporting the achievement of green building certifications. However, these advancements come with challenges, including a dependency on high-quality data, ethical concerns regarding decision accountability, and the demand for specialized expertise. Based on the results, it can be concluded that AI enhances creativity, precision, and sustainability in architecture, but its successful integration requires a collaborative human-AI approach, supported by robust ethical frameworks and ongoing skill development.

Key words: Artificial Intelligence (AI), algorithms, parametric equations, contemporary architectural design

Introduction

Architectural design is associated with the ingenuity and creativity of the human mind. Traditional design processes have relied heavily on manual calculations, experience, and intuition to create functional and aesthetically pleasing structures. However, these traditional methods often need to be revised regarding efficiency, precision, and the ability to explore various design alternatives needed in the contemporary multicriterial optimisation in the AEC (Architecture, Engineering, Construction) sector. In recent years, Artificial Intelligence (AI) has started to impact architectural design, paving the way for significant changes in the industry. AI's capacity for handling complex algorithms and large datasets enables architects to explore innovative possibilities, venture into unconventional design territories, and discover groundbreaking solutions. AI-driven tools can simulate numerous design scenarios in a fraction of the time it would take through traditional methods, providing architects with valuable insights and data-driven recommendations to streamline their creative process.

To fully understand the role of AI in architectural design, it is essential to outline its levels of sophistication and recognise its current stage of development. AI is generally categorised into three stages: Artificial Narrow Intelligence (ANI), Artificial General Intelligence (AGI), and Artificial Superintelligence (ASI). Presently, the architectural industry operates within the ANI stage, where AI systems are designed to perform specific tasks within a limited scope.

* ORCID: 0000-0002-9703-2118. Institute of Civil Engineering, Warsaw University of Life Sciences, Poland.

** ORCID: 0000-0002-5070-3877. Institute of Civil Engineering, Warsaw University of Life Sciences, Poland, e-mail: anna_stefanska@sggw.edu.pl

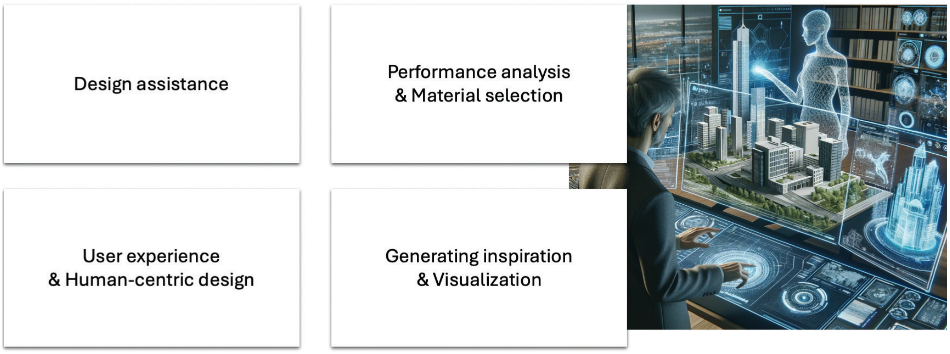

Fig. 1. Major contributions of AI to the architecture domain. Image on the right was generated by AI ChatGPT-4, using the Image Generator (elaborated by M. Kurcjusz)

Il. 1. Główny wkład AI w dziedzinę architektury. Obraz po prawej stronie został wygenerowany przez AI ChatGPT-4 przy użyciu Image Generator (oprac. M. Kurcjusz)

Examples include image recognition tools, recommendation systems, and simulation algorithms designed to optimize energy efficiency or material utilization. These tools, classified as ANI, improve performance and aid decision-making, but are limited by a lack of creativity and an inability to adapt beyond predefined tasks. The next stage, AGI, represents a level where AI can perform diverse tasks at a human-like level, including solving complex design challenges autonomously. Researchers have proposed classifying AGI into levels like competent, expert, and superhuman, depending on the extent of its capabilities. Behind AGI lies ASI, a theoretical concept that refers to AI that surpasses human intelligence in all domains, including creativity, decision-making, and problem-solving. At this level, AI would possess unparalleled analytical capabilities and the ability to self-improve, potentially revolutionizing fields like architecture. Currently, AI applications in architecture remain focused on ANI, where they assist with generative design, energy simulations, and predictive maintenance. Recognising these stages helps clarify AI's current limitations and its transformative potential for the future of architectural design (Abioye et al. 2021).

However, AI's role in architectural design is not limited to the creative process as an illustration-generating engine. It extends to various stages of project development, from initial concept to final construction and building operation systems. AI applications assist in optimising building performance, enhancing energy efficiency, and ensuring structural integrity. They also facilitate better project management by predicting potential issues, streamlining stakeholder communication, and automating routine tasks. The architectural design is currently undergoing a significant transformation brought about by the emergence of AI. While rich in history and creativity, traditional design methodologies often fall short in efficiency, adaptability, and the capacity to explore many design alternatives (Fig. 1). Integrating AI in architectural design heralds a new epoch where these limitations are being addressed, paving the way for groundbreaking innovations and solutions (Kineber et al. 2024). The utilisation of AI extends beyond the realm of ideation, permeating every facet of project development, from conception to implementation.

Applications of AI in architectural design

Generative AI holds significant promise for revolutionising structural design in architecture. It uses machine learning algorithms to analyse historical designs, assimilate diverse data types, and craft new, optimised structural configurations. This technology can greatly improve both efficiency and innovation by automating the layout process, optimising material use, and complying with mechanical and empirical standards, which in turn reduces design times and costs (Liao et al. 2024). Architecture meets advanced technology, where AI is pivotal in offering inspiration and innovative solutions. AI-based algorithms enable the creation of diverse and innovative design options, broadening the horizons for designers. Furthermore, they expedite the design process by allowing for quick analysis, optimisation, and forecasting of project-related aspects. AI significantly aids in enhancing the energy efficiency of buildings through energy simulations and identifying and eliminating design flaws at early stages. By analysing customer preferences, AI tailors design to meet individual needs, increasing time efficiency in the designing process. The algorithms assist in cost analysis budget management and improve collaboration with other fields, such as structural engineering and urban planning. AI also advances research on innovative materials and structures, paving the way for groundbreaking and sustainable solutions (Elwy, Hagishima 2024). It supports decision-making processes through data analysis and helps identify design trends.

The construction industry faces significant challenges, such as cost and time overruns, health and safety issues, productivity issues, and labour shortages, limiting its growth and productivity. One major issue is the lack of optimization; it is one of the least optimized industries globally, leading to inefficiencies in project management, cost control, and decision-making processes. AI technologies, including machine learning, computer vision, and robotics, have optimized other industries like manufacturing, retail, and telecommunications by improving profitability, efficiency, safety, and security. These technologies present numerous opportunities for the construction industry, including activity monitoring, risk management, resource and waste optimisation, and enhancing overall project efficiency (Ganiyu et al. 2020). Various AI techniques are already being used in construction, such as machine learning for health and safety monitoring, cost estimation, risk prediction, and robotics for site monitoring and performance evaluation.

Future AI applications could include AI-driven waste analytics, AI-integrated Building Information Modeling (BIM) for cost and time prediction, and AI-powered construction site analytics. BIM is a methodology and tool for creating a comprehensive digital building model incorporating geometric, material, and functional information. However, in its basic form, BIM relies on programming, data management, and rule-based processes rather than AI. While BIM and AI are distinct technologies, combining them can significantly enhance the efficiency of building design, construction, and management (Abdulfattah et al. 2023). Integrating AI algorithms – such as machine learning, data analysis, or generative design – into BIM workflows would make it possible to create more sophisticated tools that enable smarter design, advanced analysis, and more efficient data management. In such cases, AI acts as a supporting element that augments the capabilities of BIM, transforming it into a more intelligent and predictive tool. Therefore, while BIM does not inherently qualify as AI, it can benefit from AI technologies to achieve greater automation, optimization, and innovation throughout the design and construction process (Khan et al. 2024).

However, key barriers to AI adoption in construction include cultural resistance to change, high initial deployment costs, security concerns, and the need for explainable AI. AI has the potential to significantly improve health and safety in construction through predictive analytics, integration with wearable technology, and advanced data analytics to foresee and mitigate risks. Additionally, AI can enhance construction contract management by automating tasks like contract optimizing and dispute resolution and ensuring compliance, thus reducing human error and increasing efficiency (Abioye et al. 2021).

AI algorithms are optimizing the field of architectural design by enabling the generation of diverse and innovative design options, thus opening new perspectives for designers. These algorithms facilitate the analysis, optimization, and prediction of various design-related aspects, tailoring projects to individual needs. AI supports cost analysis and budget management, enhancing collaboration with other disciplines. Furthermore, AI aids research into innovative materials and constructions, paving the way for novel and sustainable solutions. It also supports decision-making processes by providing data analyses and identifying design trends. AI technologies are making significant contributions to architectural design. AI-based tools assist architects in generating design options based on specific criteria such as client requirements, site conditions, and budget constraints. AI enhances user experience and human-centred design by analysing user behaviour and preferences, enabling more human-focused design decisions. AI-driven building systems can adapt to changing environmental conditions and user needs, optimising lighting and temperature based on occupancy and time of day. Moreover, AI can analyse building performance data, including energy consumption, daylighting, and thermal comfort, helping architects optimize energy efficiency and sustainability designs. Architects can create more environmentally friendly and cost-effective buildings by considering these factors early in the design process. Additionally, AI can assist in selecting suitable building materials based on environmental impact, durability, and cost, leading to more informed decisions and greener building practices.

A traditional Building Management System (BMS) monitors and manages building installations, such as heating, ventilation, air conditioning (HVAC), lighting, and security systems. However, in its standard form, a BMS operates based on predefined rules and manual programming, which does not qualify it as AI. A BMS can be classified as AI when it incorporates algorithms that enable the system to learn from collected data and predict optimal settings automatically. By analysing a building's usage patterns, external conditions, and occupancy data, AI-powered BMS systems can dynamically adjust system settings to meet better-changing needs. For example, AI can automatically lower the temperature in rarely occupied rooms, optimize energy usage based on real-time demand, or increase ventilation during peak usage hours. These capabilities allow the BMS to operate more efficiently, reduce energy consumption, and enhance user comfort without manual intervention, distinguishing it as an intelligent system rather than a conventional one (Ruiz et al. 2022).

The integration of machine learning in AI involves several key steps. Initially, it is crucial to define the AI model's objectives and scope and gather the necessary data for its creation. This is followed by preliminary data processing to address missing values, outliers, and inconsistencies. Data pre-processing ensures consistency across different sources and scales, preparing the data for input into AI models. Feature engineering involves identifying and extracting relevant features from the data, which can be used as inputs for the AI models. Subsequently, appropriate AI models are selected based on the analysis goals. The model training phase divides the dataset into training, validation, and test sets. The AI model is trained using the training set, with adjustments to model parameters and architecture as needed. The validation set is used to evaluate the model's performance during training, guide hyperparameter tuning, and help prevent overfitting by providing an independent dataset for model assessment. AI is gaining increasing importance in architecture, transforming how designers approach the creation and personalizing of buildings. Software tools such as Midjourney, DALL-E, and Stable Diffusion enable image generation from text, becoming essential tools in the early stages of architectural projects. These advancements underscore the potential of AI to enhance creativity, efficiency, and sustainability in architectural design.

The paper delves into the selected aspects of AI's application in architectural design in the 21st century. It provides an understanding of how AI is personalizing architectural design, offering a glimpse into a future where AI and human creativity work in tandem to create spaces that are beautiful, functional, intelligent and adaptive.

State of research

AI is used in the AEC industry for planning, managing, controlling, and personalized work, but it often neglects human-related input. The benefits of human-centred AI include personalized architectural processing, enhanced design and engineering capabilities, data-driven project management, improved collaboration, and increased safety. However, implementing human-centred AI presents challenges, particularly in personalizing AI systems and providing specific training. Natural Language Processing (NLP) and Machine Reading Comprehension (MRC) are crucial in understanding human interests, preferences, languages, and behaviours, facilitating better human-AI interaction (Hu, Castro-Lacouture 2018; Nabavi et al. 2023). In architecture, AI can assist in generating design options, analysing historical data for inspiration, and optimising building performance, though current tools remain predominantly machine-cantered. In engineering, AI supports complex structural analyses, geotechnical engineering, smart infrastructure planning, and predictive maintenance, yet it still lacks integration of human expertise. In construction, AI aids in project planning, risk management, quality control, and predictive maintenance, but the domain faces significant challenges in adopting AI (Rafsanjani, Nabizadeh 2023).

The proposed method by Chen et al. (2023) leverages an improved diffusion model to generate high-quality architectural designs based on textual prompts, significantly enhancing creativity and efficiency in the design process. Key highlights include the creation of a new dataset featuring designs from eight renowned architects, which helps train the AI model to produce designs in specific styles. The method overcomes the limitations of traditional diffusion models that struggle with specified styles and high-quality designs. The research demonstrated that the improved diffusion model outperformed mainstream models like Stable Diffusion, Midjourney, and DALL E2, particularly in generating designs with consistent architectural styles (Kawar et al. 2023). Additionally, the study introduces a set of guiding words to control design aspects, improving the generation process's controllability. This AI approach promises to optimise the architectural design workflow, reducing the reliance on intensive manual labour and accelerating the industry's shift towards intelligent transformation (Chen et al. 2023).

Integrating AI in education promises new perspectives, visualisations, and interactive tools, though it also poses challenges, such as ensuring the authenticity and reliability of AI-generated content. The potential of AI makes the educational process more engaging by bridging theoretical understanding and practical application through innovative visualisations of historical architectural styles and structures (Fareed, Nassif and Nofal 2024).

The three-step generation stack proposed in the research by Stanislas Chaillou (2020), encompassing footprint massing, program repartition, and furniture layout, exemplifies a novel and sophisticated framework for architectural design. Incorporating geographic information system (GIS) data from the city of Boston for training models further enhances the contextual relevance of the generated designs. The paper provides a detailed account of the methodology, training processes, and results, showcasing the potential of GANs in reshaping architectural workflows through a collaborative machine-human interaction paradigm.

The exploration of bottom-up methods underscores their conceptual alignment with traditional design approaches, such as mind mapping and physical model making. These methods demonstrate adaptability through static or adaptive aggregations of predefined building blocks, incorporating heuristic metrics like spatial relationships, environmental performance, and structural efficiency (Yang, Xia 2023). Additional layers during the aggregation process offer flexibility and user interaction, presenting a robust framework for architectural exploration. Top-down methods, effective in scenarios with fixed boundary constraints, are discussed, particularly in urban design. Acknowledging their limitations in exploratory design stages, the review emphasises the need for diverse representation in datasets. It addresses concerns regarding the lack of appropriate curation for architectural, spatial, or cultural qualities in current large-scale datasets (Weber, Mueller and Reinhart 2022).

A proposed hierarchical framework by (Liao et al. 2024) categorises the levels of AI integration from L0 to L5, with current progress mainly achieving levels L1 and L2 where AI supports human designers. Reaching higher levels, where AI could lead or independently manage the design process, demands additional technological advancements. Major obstacles include the need for more high-quality training data, the complexity of identifying and learning from sparse features in design drawings, and the necessity to incorporate multiple constraints into AI models. Overcoming these challenges is vital for further enhancing AI capabilities in structural design. Future research should develop advanced data representation techniques, refine learning algorithms to manage complex constraints, and increase the precision and reliability of AI-generated designs. Promoting open-source data sharing within the architectural community is essential for accelerating progress and fostering innovation. This thoroughly assesses the current state, potential advantages, and future directions for using generative AI in building structural design (Liao et al. 2024).

Technically, floor plan analysis research aims to construct the structural model by automatically extracting meaningful information from diverse sources. This involves tasks like recognising walls and non-structural elements, detecting and classifying rooms, and 2D/3D reconstruction. This interdisciplinary process spans various disciplines within computer science, including image processing, pattern and symbol recognition, object vectorisation, and graph modelling, highlighting the intricate nature of floor plan analysis (Pizarro et al. 2022).

AI in architectural design optimisation

Designing assistance using AI in architecture leverages advanced technologies to enhance various stages of the design process, from conceptualisation to final execution. Architectural design uses AI assistance in conceptual design, planning, optimisation, and simulations (Chen 2019). However, it is more important because it enables real-time collaboration and automated documentation integration in BIM environments. The AI assistance also enhances creativity and efficiency in the concept stage of architectural design, improving error reduction, sustainability and cost-effectiveness.

Architectural analysis

AI in architecture enhances the design process through advanced simulations and analyses, significantly improving energy efficiency, structural integrity, and overall sustainability. By simulating various environmental conditions, AI helps optimise energy consumption, daylighting, and thermal comfort, ensuring buildings meet green standards and real-time interior adjustments to given basic parameters. Structural analyses assess load-bearing capacities and material performance under different conditions, while life cycle and carbon footprint assessments evaluate the environmental impact of building materials (Liao et al. 2024) AI-driven acoustic and lighting simulations enhance indoor comfort, and safety simulations optimise evacuation routes and fire safety protocols. Additionally, urban microclimate and environmental suitability analyses ensure that buildings positively interact with their surroundings. These capabilities result in precise designs, cost savings, and improved safety, enabling architects to make informed decisions throughout the design process.

Foster + Partners has achieved significant advancements in architectural design by developing a real-time floor plan analysis system that evaluates spatial and visual connectivity (Fig. 2). These metrics are crucial for assessing the performance of a floor plan, particularly in office settings, where they help determine the effectiveness of visual navigation, walkability, the balance between private offices and shared spaces, and the promotion of serendipitous collaboration. However, traditional methods of conducting such analyses are time-consuming, especially for large-scale floor plans (Tsigkari, Tarabishy, and Kosicki 2021).

The Applied Research and Development (ARD) team at Foster + Partners aimed to reduce the workflow duration to a near real-time experience, making the analysis more accessible and intuitive for designers during the design process. Initially, state-of-the-art algorithms and parallelisation techniques were used to reduce the analysis time to minutes. However, this was insufficient for real-time performance. Consequently, the team explored machine learning to train a surrogate model capable of mimicking the analysis output (Tsigkari, Tarabishy, and Kosicki 2021).

To achieve this, the team developed a parametric model that could generate basic office floor plans incorporating both open-plan and compartmentalised workspaces, complete with walls, doors, and furniture. This generative parametric model produced a synthetic dataset of thousands of floor plans. Using Hydra, the team ran spatial and visual analyses on these synthetic plans. This resulted in a comprehensive dataset of floor plans (inputs) and corresponding spatial and visual connectivity analysis results (outputs). This dataset was then used to teach a machine learning system, enabling it to provide spatial and visual connectivity analyses of any floor plan without additional simulation. The machine learning model continuously refined its predictions during training by comparing its outputs with the provided results. Initially, the model's predictions were inaccurate, but its accuracy improved as it learned from the feedback. Ultimately, the model developed its method for mapping input floor plans to outputs with correct spatial and visual connectivity analyses (Tsigkari, Tarabishy and Kosicki 2021).

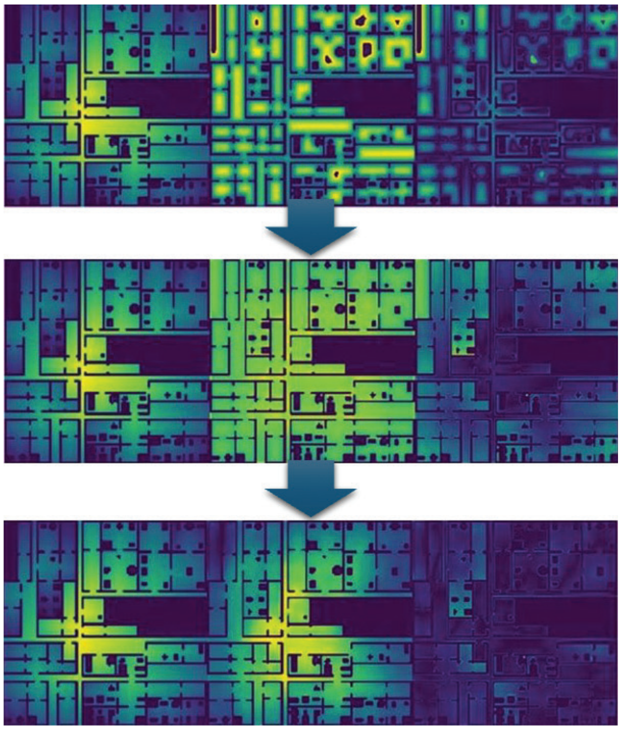

Fig. 2. The model's floor plan analysis based on Tsigkari, Tarabishy, and Kosicki (2021) (source: © Foster + Partners)

Il. 2. Analiza planu piętra modelu na podstawie: Tsigkari, Tarabishy i Kosicki (2021) (źródło: © Foster + Partners)

The efficacy of this machine-learning model is illustrated through a series of images (Fig. 2). The top row displays sample floor-plan outputs from the parametric model, including compartmentalised and open-plan workspaces. The middle row visualises the spatial connectivity analysis results, while the bottom row shows the visual connectivity analysis results. Over time, the model's predictions became increasingly accurate, the model's analysis steadily improved and converged with the correct outputs.

Visualisations

Initially, researchers tried matching text with images using straightforward methods. A big leap came with the invention of Generative Adversarial Networks (GANs) in 2014, improving image quality through a generator and a discriminator. Further advancements include the Deep Dream program and diffusion modelling, which involves refining images from noise. Dall-E 2, created by OpenAI, generates images from text descriptions by combining an understanding of language and visuals. It is versatile, user-friendly, and useful for creative tasks. Midjourney generates images based on text inputs, which is beneficial for quickly visualising ideas, especially in art and design (Fig. 3). Diffusion Bee produces realistic images from text descriptions, ideal for advertising and creating digital content. It stands out for its simplicity and effectiveness. Motionleap is a mobile app that turns text into high-quality images effortlessly and is known for its fast processing

Fig. 3. Images generated in AI software Adobe Firefly (elaborated by M. Kurcjusz)

Il. 3. Obrazy wygenerowane w programie AI Adobe Firefly (oprac. M. Kurcjusz)

and ease of use. Dall-E, Midjourney, Diffusion Bee, and Motionleap each have distinct methods for processing text descriptions and different user interfaces, offering a variety of visual creation tools. The suitability of these technologies for architectural visualisation varies, with each having specific features and technical abilities that affect their utility. Examining Midjourney queries highlights common architectural visualisation trends, demonstrating how AI tools facilitate creative exploration and design (Hanafy 2023). Text-to-image generation uses machine learning methods, specifically generative models, to transform textual descriptions into visually appealing images that closely match the semantic intent of the text. These models, which include Autoencoders, GANs, Deep Boltzmann Machines, and Diffusion models, learn to create new images by analysing vast training data. Diffusion models stand out for their efficiency in image creation by gradually adding and then removing noise to form the final image. This process involves several innovative techniques to understand and process textual inputs, including tokenisation and embedding (Fareed, Nassif and Nofal 2024). Generative models find applications across various fields, from creating images based on text descriptions to enhancing computer vision and image recognition capabilities. The conditioning technique, crucial in these models, guides the noise reduction based on textual descriptions facilitated by advanced tokenisation and embedding methods. These steps convert text into numerical values that the model can understand, allowing for generating contextually relevant images (Fareed, Nassif and Nofal 2024).

Recent advancements in AI art generation tools are significantly enhancing the capabilities of architects and designers, capturing the attention of professionals worldwide. The paper by Ploennigs and Berger (2023) delves into AI's current and potential applications in architecture, comparing the technologies behind three leading AI art platforms, analysing their use cases, and sharing practical workflows derived from extensive experience with these systems. Generative AI models, especially text-to-image generators, are at the core of these platforms, leveraging GPT-3 for generating text and specialised versions for predicting image pixels from textual inputs. Diffusion models, evolving from initial proposals to more sophisticated systems like OpenAI's GLIDE and DALL-E, play a crucial role by generating new images through a reverse diffusion process from noise-added images. DALL-E, Stable Diffusion, and Midjourney support diverse image generation tasks from user prompts, including image modification, inpainting, outpainting, and super-resolution (Ploennigs, Berger 2023). It is essential to employ encoding methods that effectively capture the intricate details of topology, geometry, spatial information, and other relevant aspects of building structure design. When these encoding methods are paired with suitable generative AI algorithms, they can significantly enhance the generation of structural designs. However, it is crucial to acknowledge that no single method can capture all design features fully, necessitating a focus on multi-modal data fusion to improve understanding and representation of building designs, a general representation technique to address the sparsity of architectural information, and the importance of sharing open-source data within the architectural community to foster innovation (Liao et al. 2024).

The advent of AI in architectural visualisation has revolutionised the speed and efficiency with which visual representations of designs can be created. AI-driven visualisation tools, such as Adobe Firefly, enable rapid generation and modification of graphics based on input data, whether textual descriptions or existing images (Fig. 3). This case study explores the capabilities and limitations of AI in the context of architectural visualisations. AI-powered visualisations can produce detailed and accurate images quickly, significantly reducing the time required to create high-quality visual content. These tools allow for extensive customisation, enabling users to adjust lighting, viewing angles, styles, effects, and reference materials to achieve the desired aesthetic. The process begins with inputting data, which can be descriptive text or pre-existing images. The AI then processes this input to generate visualisations that align with the specified criteria. This capability allows designers to quickly explore multiple design options and variations, facilitating a more iterative and flexible design process. However, despite its advanced capabilities, AI-driven visualisation technology has limitations. One of the primary challenges is that the AI may not always produce results that perfectly match the user's expectations. While AI can generate highly detailed and contextually appropriate images, achieving the desired outcome may require additional manual adjustments and iterations. This limitation underscores the importance of human expertise in guiding and refining the outputs generated by AI. Moreover, as AI technology evolves, enhancing its ability to interpret and execute complex design instructions accurately remains an ongoing challenge. AI tools are proficient at handling straightforward tasks and generating initial design concepts. However, they still require significant input and oversight from human designers to ensure that the final outputs meet the nuanced demands of architectural projects.

Spectrum of AI applications in architecture

By leveraging advanced tools and algorithms, architects and engineers can address complex challenges, streamline processes, and deliver innovative solutions that meet modern needs. Table 1 provides an overview of the spectrum

Table 1. Spectrum of AI applications in architecture (elaborated by M. Kurcjusz)
Tabela 1. Spektrum zastosowań AI w architekturze (oprac. M. Kurcjusz)

Category	AI application	Work performed	Effectiveness assessment	Examples of tools
Concept design	Generative Design	generates multiple optimized design options based on constraints like materials and cost	reduces design time, provides innovative and optimized solutions	Autodesk Fusion (generative design AI), Hypar, Autodesk Forma
	Parametric Design	creates dynamic, rule-based design variations for complex forms	facilitates precision and flexibility in complex geometric design	Rhino Grasshopper (AI Plugins)
Building performance	Energy efficiency optimization	virtual reconstruction of heritage sites	reduces energy costs and improves building performance	Autodesk Forma
	Simulations (thermal, daylight, noise, wind)	simulates thermal comfort, daylighting, and energy efficiency	enhances comfort and sustainability while ensuring regulatory compliance	ClimateStudio (AI-assisted analysis), Autodesk Forma
	Structural integrity analysis	assesses structural stability and material performance	minimizes structural costs and improves safety by predicting failure risks	T2D2 (AI Structural Damage Detection)
Design automation	Layout optimization	automates the creation of optimized floor plans and layouts	reduces design time and improves spatial efficiency	ArchiGAN, Autodesk Fusion, Hypar
	Code compliance checking	ensures compliance with local building regulations	reduces human error, ensuring regulatory alignment and avoiding costly revisions	Bamroc
Material and resource use	Smart Material selection	selects sustainable, cost-effective building materials	reduces environmental impact and optimizes costs	Cove.Tool (AI for sustainable design)
	Resource and waste optimisation	minimizes material usage and waste during design/construction	cuts material costs and reduces waste significantly	SmartWaste
Construction management	Scheduling and resource allocation	predicts timelines, allocates labour/resources effectively	improves project delivery by reducing delays and overruns	ALICE Technologies, nPlan
	Site safety monitoring	detects safety risks in real-time using AI and computer vision	reduces accidents on-site, enhancing worker safety	Smartvid.io

Table 1 continued. Spectrum of AI applications in architecture (elaborated by M. Kurcjusz)
Tabela 1 cd. Spektrum zastosowań AI w architekturze (oprac. M. Kurcjusz)

Category	AI application	Work performed	Effectiveness assessment	Examples of tools
BIM integration	Data analysis and prediction	AI analyses BIM data to predict workflows and maintenance	optimizes project timelines and reduces lifecycle costs	Spacio AI
	Generative BIM Models	automates creation of intelligent BIM models	improves efficiency and accuracy during design phases	Revit Dynamo (AI-Integrated), BricsCAD BIM, WiseBIM
Sustainability and climate	Carbon footprint assessment	evaluates environmental impact of materials and design choices	enables reductions in embodied carbon	One Click LCA (AI-based analysis), Autodesk Forma
	Climate-responsive design	adapts building design to local climate for efficiency	reduces operational energy consumption and improves occupant comfort	Autodesk Forma
Post-Occupancy management	Smart Building Management Systems (BMS)	learns from real-time data to adjust HVAC, lighting, and security	reduces energy use while improving building comfort	Siemens Desigo CC
	Predictive Maintenance	predicts equipment failures and schedules proactive maintenance	cuts maintenance costs and downtime	IBM Maximo Manage AI, Schneider EcoStruxure
Visualissation and design	AI-Powered Rendering Tools	creates high-quality, realistic visualizations of designs	reduces visualization time while improving quality and stakeholder communication	MidJourney, DALL-E 2, Stable Diffusion
	Text-to-Image Generation	generates conceptual imagery from text prompts	enhances creativity and reduces early design iteration times	Adobe Firefly, MidJourney
Human-cantered design	User Experience Analysis	analyses behaviour to optimize user-centric designs	improves functional efficiency and user satisfaction in built environments	Autodesk Forma
	Space Utilization Optimization	optimizes interior layouts based on occupancy data	increases spatial efficiency and reduces operational costs	Density.io AI
Historical preservation	Virtual Reconstruction of Heritage Sites	reconstructs historical sites using AI-driven 3D modelling	facilitates accurate digital preservation and restoration planning	RealityCapture AI

of AI applications in architecture, including examples of tools, the specific work performed, and an assessment of their effectiveness.

Discussion

Integrating AI in architectural design has demonstrated significant potential to revolutionise the field. This study has explored various dimensions of AI applications, including generative design, optimisation, and predictive analytics. The findings suggest that AI can enhance architectural practices' creativity, efficiency, and sustainability. AI-driven generative design tools have shown the ability to produce innovative and diverse design solutions that might not be conceived through traditional methods. These tools leverage algorithms to explore a vast design space, offering architects many options. This fosters creativity and allows for exploring unconventional design forms and structures. The case studies reviewed in this paper highlight successful implementations where AI has contributed to groundbreaking architectural projects. AI optimisation applications have proven effective in streamlining various aspects of the design process.

The findings from this study highlight a typology of AI applications in architectural design, categorizing their contributions into conceptual design, performance optimization, and sustainability enhancement. At the conceptual level, AI-driven generative and parametric design tools have proven instrumental in producing diverse and innovative design solutions. These tools allow architects to explore vast design spaces, fostering creativity while reducing manual effort. At the performance optimization level, AI applications, such as structural analysis and energy simulations, demonstrated significant improvements in efficiency and precision. The experimental results revealed a marked reduction in design iterations, material waste, and energy consumption, underscoring AI's potential to optimize critical aspects of the design and construction process. At the sustainability level, integrating predictive analytics and simulation models facilitated the selection of environmentally friendly materials and the achievement of green building standards, effectively reducing carbon footprints. AI algorithms can process large datasets and perform complex calculations at a speed and accuracy unattainable by human designers alone. This leads to more efficient use of materials, cost savings, and reduced project timelines. Integrating AI in BIM further exemplifies how AI can enhance coordination and collaboration among different stakeholders in a project. Presented levels of AI applications collectively illustrate how AI transitions from enhancing creativity to ensuring technical precision and promoting environmental stewardship in architectural design.

Adopting AI in architectural design introduces significant benefits, such as enhanced automation, improved precision, and rapid optimization. However, AI's hasty and unregulated application also poses substantial risks that must be carefully considered. AI algorithms often rely on historical data and existing patterns, which can lead to the replication of safe solutions and hinder the creation of unique, innovative designs. Over-reliance on AI tools risks diminishing the creative role of architects, reducing their ability to think outside the box and limiting human ingenuity in favour of algorithm-driven recommendations. Additionally, many AI models, particularly neural networks, operate as black boxes, making it difficult to trace how a design decision was reached. This lack of explainability raises concerns about error detection and accountability, particularly when errors go unnoticed until later stages, potentially leading to costly rework or safety compromises.

Despite these advancements, the reliance on high-quality data, the need for specialized expertise, and ethical considerations regarding decision-making accountability remain key challenges to address. The hasty application of AI in architectural design brings potential risks. The quality of AI outputs depends heavily on the data used to train the models. Biased, incomplete, or low-quality datasets can result in flawed or unsafe designs that fail to meet user requirements or safety standards. AI tools may also struggle to comply with local building codes, zoning laws, or regulations, increasing the risk of non-compliant designs and potential legal and financial repercussions (Alkfairy et al. 2024). Moreover, questions about accountability arise during design failures: determining whether responsibility lies with the architect, software provider, or AI developer remains a legal and ethical challenge. Another notable risk is AI's inability to capture subtle cultural, historical, or social nuances, often integral to architectural projects. Overlooking these factors can result in designs that lack cultural resonance or fail to align with user expectations. Furthermore, the high costs of implementing AI and the need for specialized skills can act as barriers to adoption, particularly for smaller firms. Ethical concerns, such as job displacement and the potential erosion of human judgment in decision-making, further complicate AI's integration into architectural workflows. While AI holds transformative potential for architectural design, its limitations and associated risks must not be ignored. Achieving a balanced, human-AI collaborative approach with clear regulatory frameworks, accountability measures, and robust ethical standards will ensure that AI enhances architectural innovation while minimizing its challenges.

Sustainability is a critical concern in contemporary architecture, and AI has shown promise in addressing this challenge. Predictive analytics powered by AI can assess the environmental impact of design choices, optimise energy consumption, and suggest sustainable materials. The study's findings indicate that AI can play a pivotal role in achieving green building standards and reducing the carbon footprint of construction projects. Despite the promising potential, integrating AI in architectural design is challenging. One significant concern is the reliance on high-quality data for AI algorithms to function effectively. Inaccurate or incomplete data can lead to suboptimal design outcomes. Additionally, architects need to acquire new skills to work effectively with AI tools, which may require substantial training and adaptation.

Conclusion

The transformative integration of AI in architectural design holds immense potential to reshape the industry. AI can contribute to more innovative, cost-effective, and environmentally friendly architectural solutions by enhancing creativity, improving efficiency, and promoting sustainability. However, addressing the challenges related to data quality, skill acquisition, and ethical implications is essential to realise these benefits fully. Future research should focus on developing robust AI frameworks that seamlessly integrate with existing architectural practices and creating educational programs to equip architects with the necessary skills to leverage AI technologies effectively.

While AI enables multi-criteria analysis to evaluate and optimize various project aspects – such as cost, energy efficiency, aesthetics, and environmental impact – its introduction into such a complex and nuanced process is not without difficulties. One of the primary challenges lies in the complexity and ambiguity of architectural criteria. Architecture encompasses technical, aesthetic, social, and environmental dimensions, many of which are difficult to quantify or define as clear inputs for AI systems. Non-measurable values, such as subjective aesthetics or the project's impact on the local community, remain challenging for AI to interpret, as concepts like "beauty" or "harmony with the environment" are inherently subjective and influenced by cultural context.

Another major challenge is the quality of input data. Architectural data is often incomplete, inaccurate, or unstructured, which poses significant obstacles for AI algorithms that rely on high-quality data to deliver reliable results. Furthermore, AI must address conflicting criteria within the design process – for instance, achieving low construction costs may conflict with goals of high energy efficiency, aesthetic appeal, or sustainability. Without clearly defined priorities, AI may favour one criterion, such as cost minimization, while neglecting others that are equally important, such as environmental considerations (Kurcjusz 2024).

Additional challenges stem from the limited adaptation of AI algorithms to the unique requirements of architecture.

Elements such as a building's impact on the surrounding landscape, spatial relationships, or compliance with historic preservation regulations are difficult for standard AI models to capture. For example, an algorithm optimized to reduce material costs may fail to consider aesthetic requirements or cultural heritage constraints.

In conclusion, while AI presents exciting opportunities for the future of architectural design, a balanced approach that considers both the advantages and the challenges is crucial for its successful implementation. The ongoing collaboration between AI experts and architects will be key to unlocking the full potential of AI in this field.

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Streszczenie

Transformacyjna integracja sztucznej inteligencji w projektowaniu architektonicznym

Wprowadzenie sztucznej inteligencji (Artificial Intelligence – AI) do projektowania architektonicznego zmienia tradycyjne praktyki. W artykule przedstawiono typologiczne zastosowania AI w architekturze, koncentrując się na jej wkładzie w projektowanie koncepcyjne, optymalizację wydajności oraz zrównoważony rozwój, podkreślając jej transformacyjny wpływ na procesy w sektorze architektury, inżynierii i budownictwa (AEC).

Celem autorek pracy było sklasyfikowanie i analiza hierarchicznych zastosowań AI w projektowaniu architektonicznym. Głównym zamierzeniem – ocena roli AI w rozwijaniu kreatywności, zwiększaniu efektywności i wspieraniu praktyk zrównoważonego rozwoju. Metodologicznie badanie oparto na kompleksowym przeglądzie klasyfikacji typologicznych, walidacji eksperymentalnych oraz analizach studiów przypadków. Synteza wyników z najnowszej literatury przedmiotu i rzeczywistych implementacji pozwala na ocenę potencjału i ograniczeń AI na różnych etapach projektowania architektonicznego.

Wyniki badania wskazują na hierarchię typologiczną zastosowań AI w projektowaniu architektonicznym, ukazując jej wielowymiarowy wkład. W projektowaniu koncepcyjnym narzędzia generatywne napędzane AI umożliwiają architektom eksplorację rozległych przestrzeni projektowych, pozwalając na tworzenie innowacyjnych i różnorodnych rozwiązań. W zakresie optymalizacji wydajności AI wykazuje znaczną poprawę efektywności poprzez redukcję czasu iteracji projektowych, minimalizację marnotrawstwa materiałów oraz poprawę efektywności energetycznej dzięki zaawansowanym symulacjom. W dziedzinie zrównoważonego rozwoju analityka predykcyjna AI wspiera podejmowanie świadomych decyzji dotyczących wyboru materiałów oraz zgodności ze standardami ekologicznymi, przyczyniając się do uzyskania certyfikatów zielonego budownictwa. Mimo tych postępów wyzwaniami pozostają zależność od wysokiej jakości danych, kwestie etyczne związane z odpowiedzialnością za decyzje oraz potrzeba specjalistycznych kompetencji. Na podstawie otrzymanych wyników można stwierdzić, że AI wzmacnia kreatywność, precyzję i zrównoważony rozwój w architekturze, ale jej skuteczna integracja wymaga współpracy człowieka i AI, wspieranej przez solidne ramy etyczne oraz rozwój kompetencji.

Słowa kluczowe: sztuczna inteligencja, algorytmy, parametryka, współczesne projektowanie architektoniczne