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Chapter 9

Parametric Approaches for Energy-Efficient Urban morphologies

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Introduction

Background and Context

The rising demand for sustainable urban development in response to the twin challenges of climate change and rapid urbanization has intensified the imperative for energy-efficient urban environments (Umoh et al., 2024). As rural populations increasingly migrate to cities, the resulting urban growth places additional pressure on housing, infrastructure, and employment opportunities. This urban expansion is accompanied by a surge in energy demand, largely influenced by heightened population activity (Aidaoui et al., 2024; Menai et al., 2024). In this context, Urban morphology, defined by elements such as building layout, density, orientation, and spatial configuration, plays a pivotal role in shaping environmental performance. It affects solar exposure, airflow, shading, and heat retention, with empirical studies showing that urban heat islands can elevate energy demand by 10% to 35%, depending on urban density and form (Salvati et al., 2015). To address these challenges, cities are increasingly embracing strategies that minimize energy consumption. In Algeria, this vision is reflected in the Taka Nadhifa program, a clean energy initiative launched within the framework of the strategic energy partnership with the European Union. This program aims to rationalize energy use, particularly in the energy-intensive construction sector (Maiza, 2010; Salah-Salah & Harbi, 2023).

Conventional urban planning approaches, typically grounded in static, typology-based models, often lack the adaptability required to dynamically respond to environmental performance metrics (Bruno et al., 2011). Consequently, many urban morphologies are developed without fully leveraging their potential to reduce energy consumption or enhance thermal comfort (Ebaid & Helim, 2024). In response, urban designers and planners are more and more adopting parametric design methodologies to model, simulate, and optimize urban form (Umoh et al., 2024). Urban energy modelling plays a crucial role in this process, offering a data-driven framework to assess solar potential and inform design decisions that foster more energy-efficient urban configurations (Harbi et al., 2024)

Parametric design utilizes algorithmic tools that enable the dynamic manipulation of spatial and morphological variables. These tools allow for the rapid generation and evaluation of multiple design iterations based on performance criteria such as energy use intensity, solar access, and microclimatic behavior (Pektas, 2023). When integrated with advanced simulation platforms, such as EnergyPlus, Ladybug, or computational fluid dynamics (CFD), parametric approaches can reveal the environmental consequences of design choices across scales (Ibrahim et al., 2021; Salvati et al., 2015). This performance-driven, data-informed design process is particularly impactful during early-stage planning, where strategic decisions regarding form and layout have long-term implications (Doelling & Nasrollahi, 2013; Farouk et al., 2019).

In climate-sensitive regions, especially hot-arid and Mediterranean zones, where energy demand for cooling is high and passive design strategies are essential, parametric tools provide critical insights. They enable the reconfiguration of urban form to improve solar control, thermal comfort, and energy efficiency (Aboulfaraj et al., 2024; Eshraghi et al., 2024; Ibrahim et al., 2022). As a result, parametric approaches are gaining traction not only in academic research but also in professional design practice and urban policymaking.

Yet, despite the growing interest and evident potential, the integration of parametric methods into mainstream urban planning remains fragmented. There is a lack of comprehensive frameworks to systematically evaluate the

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effectiveness, scalability, and contextual applicability of different parametric techniques. Most existing studies are highly context-specific, limiting their generalizability across diverse climatic conditions and urban scales (Robinson, 2011; Zhang et al., 2024). This underscores the need for a consolidated understanding of how parametric approaches can be more holistically adopted to inform energy-efficient urban morphologies worldwide.

Based on these studies, "How can parametric design methodologies be systematically integrated into early-stage urban planning to optimize energy-efficient urban morphologies across diverse climatic and spatial contexts?"

Objectives and Hypotheses

This paper aims to conduct a systematic review of the state-of-the-art parametric approaches applied in urban morphology design to enhance energy efficiency. It seeks to categorize and evaluate the performance of various computational methods and tools based on their effectiveness, scalability, and applicability in different design contexts. Furthermore, the study identifies the key morphological parameters that most significantly influence energy performance, with a particular focus on hot-arid and Mediterranean climates. By synthesizing current research trends and identifying existing gaps, the paper contributes to advancing the development of integrated parametric workflows for optimizing energy-efficient urban forms.

Hypotheses:

- H1: Among morphological parameters, building orientation, height-to-width ratios, and street layout exert the strongest influence on energy performance in specific climates.

- H2: Integrated frameworks using multi-objective optimization techniques are more effective than single-objective or manual parametric approaches in identifying energy-efficient urban configurations.

Materials and Methods

This study employs a mixed-method approach combining bibliometric analysis and systematic literature review (SLR) to critically examine the development, applications, and performance of parametric design approaches for enhancing energy efficiency in urban morphologies. The dual-method strategy ensures both quantitative insight into the research landscape and qualitative depth in content analysis, enabling a robust and comprehensive evaluation of the topic.

Research Design

The methodology was designed to answer the following research questions:

- What are the dominant parametric approaches and tools used to optimize energy performance in urban morphology?
- Which morphological parameters are most frequently studied and found to be impactful in different climatic contexts?
- What are the emerging research trends, gaps, and future directions in the application of parametric design for energy-efficient urban planning?

To address these questions, the study followed a three-phase workflow:

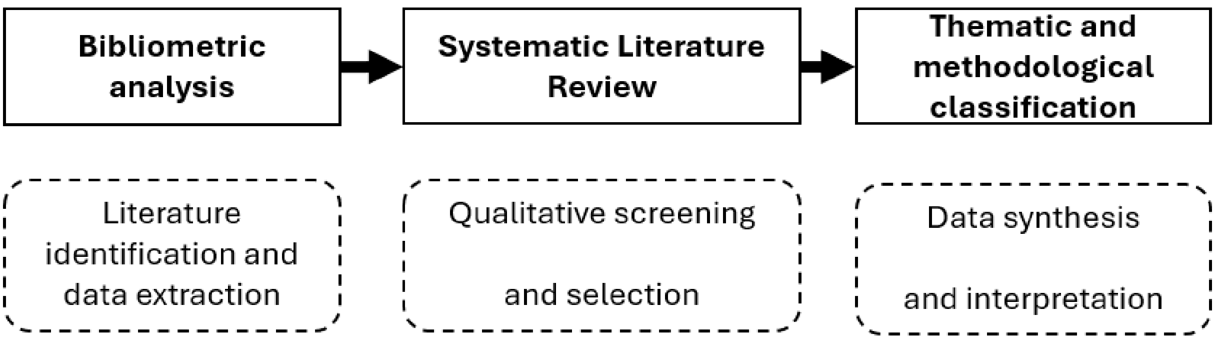

Figure 1. three-phase workflow of the research methodology.

bibliometric analysis

A bibliometric analysis was conducted to map the intellectual structure, thematic evolution, and research trends within the domain of parametric approaches for energy-efficient urban morphology. The Dimensions AI database was selected for its broad multidisciplinary coverage and integration of citation analytics across scholarly outputs in architecture, urban planning, and environmental sciences. The search strategy employed Boolean logic using the following keyword combination: ("parametric design") AND ("urban morphology" OR "urban form") AND ("energy efficiency" OR "energy performance"). The query was restricted to English-language publications, including papers published between 2016 and 2024. After de-duplication and abstract-based relevance screening, a refined dataset of 561 documents was selected for in-depth bibliometric mapping. VOSviewer software was used to construct and visualize bibliometric networks, including co-authorship relationships, offering insights into the structure and collaboration dynamics of the field.

Systematic literature review

A systematic Literature Review (SLR) was conducted in accordance with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. The review focused specifically on peer-reviewed studies that applied parametric tools for urban-scale energy efficiency analysis. Inclusion criteria encompassed studies utilizing frameworks; those applied at the urban or neighbourhood scale rather than limited to single-building analyses; studies incorporating energy performance metrics such as energy use intensity (EUI), solar access, and thermal comfort; and case studies situated in hot-arid or Mediterranean climates. Exclusion criteria eliminated studies focused exclusively on material, structural, or facade optimization without addressing urban morphological configurations and studies conducted at the building scale without extrapolation to broader urban or neighbourhood contexts. From the 561 documents identified through bibliometric filtering, 68 met the criteria for full-text analysis. Each article was systematically reviewed and classified according to its methodological approach, including generative algorithms, rule-based modelling, machine learning, or multi-objective optimization; the tools and software utilization, the morphological parameters assessed, and the key performance indicators measured.

Results

The Bibliometric Analysis

This chart highlights the growing academic interest in energy-efficient morphology and parametric urban design over the past decade, showing a clear and steady rise in publications from 2016, peaking in 2024. This trend reflects the increasing recognition of parametric approaches as essential tools in sustainable urban planning.

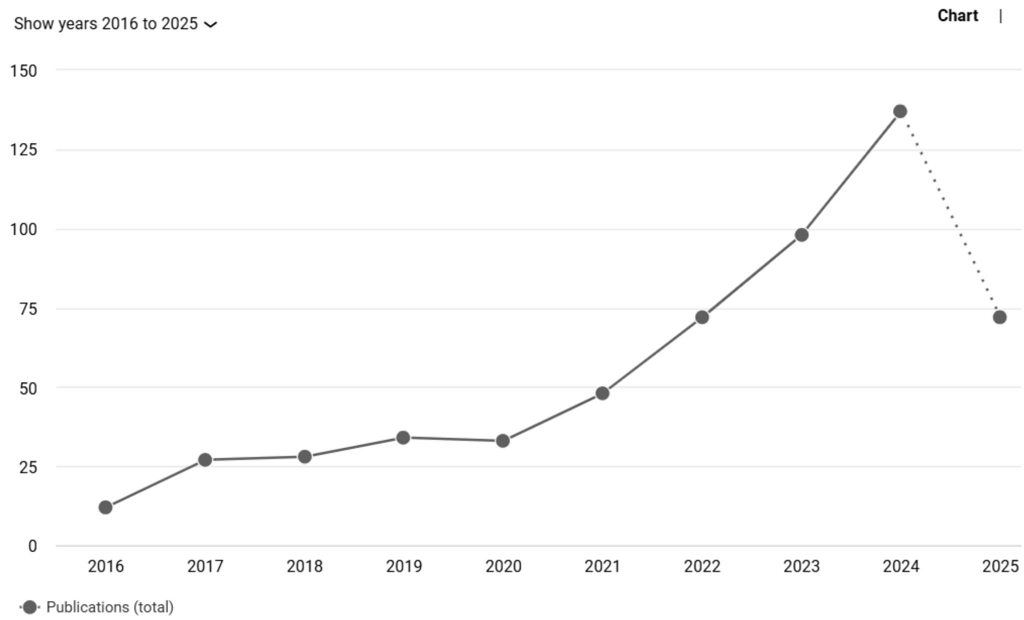

Figure 2. Annual Growth of Publications on Parametric Approaches for Energy-Efficient Urban Morphologies (2016–2025). Source: Dimensions Database: (https://www.dimensions.ai).

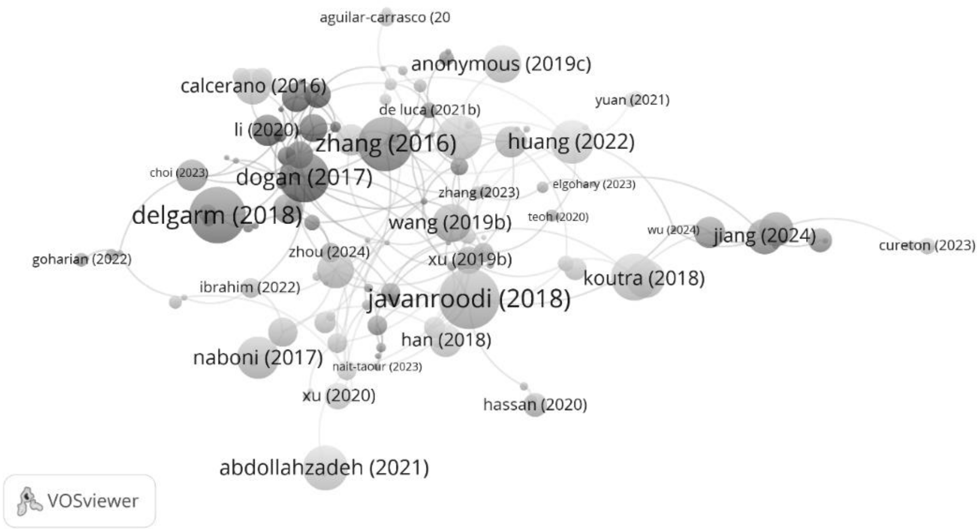

Figure 3. Co-authorship Network Visualization of Key Researchers.

This VOSviewer author co-citation map reveals key contributors and collaborative clusters in the field of parametric urban design for energy efficiency. Central figures like Zhang (2016), Delgarm (2018), Dogan (2017), and Javahroodi (2018) form dense nodes, indicating strong citation influence and thematic connectivity. The presence of multiple clusters, each represented by distinct colors, reflects diverse methodological approaches and research focuses. Emerging researchers such as Jiang (2024) and Goharian (2022) suggest a growing and evolving field, while the interlinked network underscores increasing interdisciplinary collaboration.

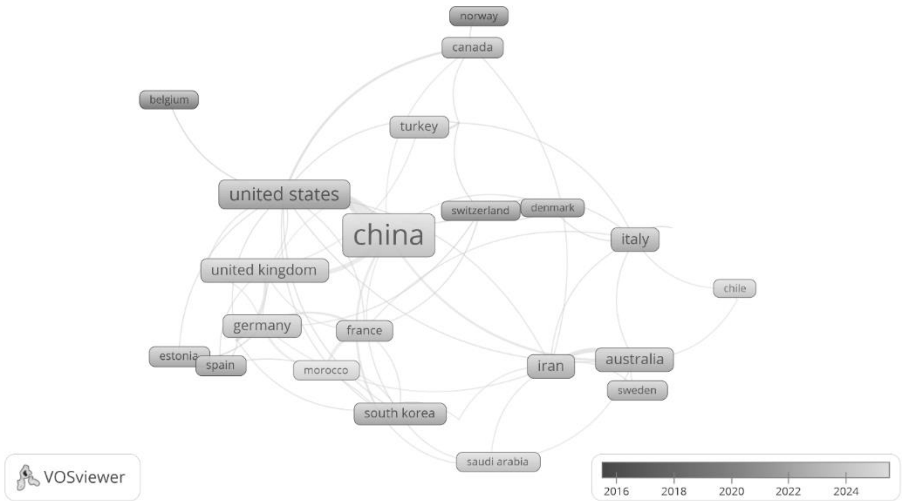

Figure 4. A network visualization mode bibliometric map based on co-authorship nations.

The co-authorship network map generated using VOSviewer provides a comprehensive overview of the international research collaboration landscape in the field of parametric design and urban energy efficiency from 2016 to 2024. China appears as the most central and influential contributor, demonstrating both high publication output and strong international collaboration ties, particularly with the United States, the United Kingdom, Iran, and Australia. This centrality highlights China's pivotal role in advancing research on energy-efficient urban morphologies through parametric approaches. The United States, United Kingdom, Germany, and Iran also emerge as key players with dense interconnections, indicating active and sustained participation in the field.

The color gradient, which reflects the average publication year, reveals temporal trends in research engagement. Countries such as Belgium and Norway, indicate earlier involvement around 2016–2018, while countries like Morocco, Chile, and Saudi Arabia, suggest more recent entry into the field. This temporal dynamic underscore a growing global interest, particularly from regions that face climatic challenges well-suited for parametric energy optimization strategies, such as hot-arid and Mediterranean climates.

Emerging contributors, including Morocco and Chile represent a rising research interest, likely driven by the practical need for climate-responsive urban planning. The network illustrates a shift from a traditionally

Eurocentric and North American research dominance toward a more geographically diversified engagement. Overall, the map reflects the increasing globalization of research efforts in parametric urban design, emphasizing the value of interdisciplinary and cross-regional collaboration to address energy efficiency challenges in urban environments.

The Systematic Review

Design Parameters and Their Influence on Urban Energy Efficiency

Building Design Parameters

Energy usage is greatly influenced by **building morphology**, which includes elements like building height, form, and orientation. Energy usage intensity (EUI) can be significantly decreased by improving these characteristics, according to studies. For example, a study conducted in Hangzhou, China, showed that Energy Use Intensity can be decreased by up to 7.73% by improving morphological characteristics such aspect ratio, floor area ratio, and orientation (Feng et al., 2024). Similarly, it has been discovered that larger floor area ratios and compact building forms lower heating energy consumption in temperate-humid climates (Kocagil, 2021; Mangan et al., 2021). Furthermore, building geometry and orientation markedly influence environmental performance metrics, including solar gain, daylight availability, and wind behavior. A study in Tehran highlighted that optimized building orientation can lead to a 41.3% to 61.1% reduction in solar radiation variation compared to traditional configurations (Mavahebi Tabatabai et al., 2025).

Other important factors in building design are **the type of plan and the height of the building**. For instance, it has been demonstrated that square plans and pavilion-style structures outperform rectangular and slab-type buildings in terms of energy efficiency in temperate-humid climates (Mangan et al., 2021). Furthermore, it has been discovered that taller structures with lower height-to-width (H/W) ratios have superior sun access and energy consumption (Ibrahim et al., 2021; Kocagil, 2021)

The building envelope, including factors such as opacity, transparency, and solar control systems, also plays a significant role in energy consumption. Studies have shown that optimizing these parameters can lead to further reductions in energy use. For example, in Istanbul, the integration of building envelope optimization and solar control systems was found to improve energy performance by up to 19% (Kocagil, 2021).

Urban Form Parameters

Urban density and layout are key parameters in urban form optimization. Higher urban densities have been shown to reduce energy consumption by promoting more efficient use of land and infrastructure. For example, in hot arid climates, compact and medium-density urban forms have been found to perform better in terms of thermal comfort and energy efficiency (Ibrahim et al., 2021). Similarly, in severe cold regions, higher building densities have been found to reduce energy consumption by improving insulation and reducing heat loss (Wang et al., 2024). A study in Switzerland demonstrated that parametric modelling can help balance built density with solar potential and daylighting performance (Peronato, 2014). **Street width and orientation** are also important parameters in urban form optimization. Narrower streets in hot climates can reduce urban overheating by providing shade and promoting natural ventilation (Ibrahim, Kershaw, Shepherd, & Coley, 2021; Wai et al., 2024). A study in Kayseri, Turkey, found that canyon geometry parameters, such as aspect ratio and length-to-height ratio, significantly influence microclimatic conditions and energy consumption (Toren & Sharmin, 2024).

Green spaces and public areas play also a crucial role in urban microclimates and energy consumption. Studies have shown that strategically located green spaces can reduce urban overheating and improve outdoor thermal comfort (Ibrahim et al., 2021; Wai et al., 2024). Additionally, public spaces with optimized layouts and orientations can enhance solar access and reduce the need for artificial lighting (Kocagil, 2021; Mangan et al., 2021).

Key Methods for Enhancing Energy Efficiency in Urban Morphologies

These are the most recognized and widely adopted parametric approaches in energy-efficient urban design. These methods are at the core of how designers simulate and optimize urban morphology to reduce energy consumption:

Parametric Energy Simulation Method

The parametric energy simulation method integrates algorithmic modelling tools—such as Grasshopper (a plugin for Rhinoceros 3D)—with advanced environmental simulation engines like Ladybug and Honeybee. These tools import local weather data and generate interactive visual outputs, allowing designers to assess environmental performance metrics from the earliest design stages (Sadeghipour Roudsari & Pak, 2013). This integration enables comprehensive analysis of energy efficiency and climate responsiveness across various urban and architectural configurations (Delmas et al., 2018).

Typical applications of the parametric energy simulation method include the analysis of solar gains based on building geometry, orientation, and spatial layout; the simulation of annual or seasonal energy consumption while accounting for both morphological and climatic variables; and the evaluation of thermal comfort at multiple spatial scales—ranging from individual buildings to entire neighbourhoods, by incorporating factors such as solar exposure, natural ventilation, and interior temperature dynamics (Wai et al., 2024; Wang et al., 2024). A major strength of this method lies in its capacity for real-time performance feedback on flexible parametric geometries. This facilitates iterative design refinement and supports informed, energy-conscious decision-making from the conceptual phase onward. Ultimately, it fosters a more responsive and sustainable approach to urban design (Aboulfaraj et al., 2024).

Multi-Objective Optimization Method

This method involves the use of evolutionary algorithms such as Galapagos (single-objective) A genetic algorithm that optimizes single-objective problems, demonstrating effectiveness in architectural design by finding feasible solutions and outperforming other tools in specific scenarios (Cubukcuoglu et al., 2019). and Octopus (multi-objective) a multi-objective optimization tool that extends the capabilities of Grasshopper, enabling the simultaneous consideration of various design criteria, thus providing a more comprehensive solution set (Meraihi et al., 2021). These plug-ins are integrated within Grasshopper, to simultaneously optimize several design criteria. It is particularly effective for exploring trade-offs between conflicting objectives in complex urban environments (Bruno et al., 2011). The applications of this method include finding a balance between built density, solar access, building orientation, and form factor (Ibrahim et al., 2022). Rather than identifying a single "best" solution, this method generates a range of optimal solutions based on Pareto efficiency (Li et al., 2024), offering designers a set of well-balanced alternatives. While the advantages of this approach lie in its ability to deliver intelligent design options that account for conflicting constraints while preserving creative control over urban form (Showkatbakhsh & Makki, 2022) . In urban contexts—where goals such as maximizing sunlight exposure, increasing density, minimizing energy use, and complying with land-use regulations often conflict—multi-objective optimization provides a robust framework (Sicuaio et al., 2024). It supports the development of scenarios that reconcile morphological, environmental, and regulatory priorities, making it especially valuable in urban planning and development studies.

Genetic Modelling Method

The genetic modelling method is based on the use of genetic algorithms to automatically generate a wide range of urban or architectural form variants. Genetic algorithms (GAs) mimic evolutionary processes, utilizing selection, mutation, and recombination to evolve solutions to optimization problems (Hsu, 2009). Each variant is evaluated from the outset using predefined energy performance criteria, such as energy use intensity (EUI) or solar gain. This approach enables the rapid and systematic exploration of complex morphological configurations by manipulating parameters such as building height, orientation, and spacing. By simulating and comparing these alternatives, the method identifies the most energy-efficient solutions. One of its main advantages is the direct integration of sustainability objectives into the generative process, making it a powerful tool for optimizing urban form in the early design stages (Boyukliyski et al., 2022; Sohail, 2023).

Comparative Analysis of Different Methods:

Table 1. comparative analysis of different methods.

Method	Key Parameters	Energy Reduction Achieved
Simulation Tools	Building height, street width, green spaces, public areas	Significant reductions in heating and cooling energy consumption (Wai et al., 2024) (Ibrahim et al., 2021) (wang et al., 2024)
Multi-Objective Optimization	Building orientation, layout, spacing, typology	Up to 27.8% reduction in heat emissions (Qiu et al., 2023) (Li et al., 2024)
Genetic Algorithm	Aspect ratio, floor area ratio, orientation, number of floors	Up to 7.73% reduction in EUI (Feng et al., 2024) (Boyukliyski et al., 2022)

Integration with Artificial Intelligence and Machine Learning

While generative design methods are already well established (Elshanshoury et al., 2023), the integration of more advanced machine learning (ML) techniques presents a promising trajectory. Deep learning models trained on large datasets of urban configurations and environmental performance metrics could enable predictive modeling, pattern recognition, and adaptive form generation beyond traditional simulation limits (Eshraghi et al., 2024),. These models have the potential to automate and accelerate design-space exploration, offering real-time feedback without extensive computational overhead.

Recent studies have begun to demonstrate the transformative potential of ML and artificial intelligence (AI) in parametric design workflows. For instance, Lu et al. (2022) employed a Generative Adversarial Network (GAN) to predict the environmental performance of urban blocks based on simulation results, significantly improving the speed and efficiency of the optimization process. Similarly, Huang et al. (2024) applied ML techniques to assess and refine the impact of urban morphology on photovoltaic system performance, enhancing solar energy efficacy in urban environments.

Discussion

The results from both the bibliometric analysis and the systematic literature review offer compelling evidence that parametric approaches are becoming pivotal in optimizing urban morphology for improved energy efficiency. The upward trend in scholarly publications from 2016 to 2024, particularly the peak observed in 2024, underscores the growing recognition of these computational methods within sustainable urban planning. The bibliometric insights also reveal a geographically expanding research network, with China, the United States, and the United Kingdom emerging as central contributors, while countries from hot-arid and Mediterranean regions like Saudi Arabia are increasingly engaging with parametric tools to address their specific climatic challenges.

The systematic review further demonstrates how parametric methodologies, particularly parametric energy simulation, multi-objective optimization, and genetic modelling, enable the exploration of complex design spaces. These methods allow for performance-driven decision-making in the early stages of urban form generation. For instance, the integration of tools such as Grasshopper, Ladybug, and EnergyPlus facilitates high-resolution simulations that assess solar gain, energy consumption, and thermal comfort across varying spatial and climatic contexts.

Each method reviewed offers distinct advantages in optimizing urban form for energy efficiency. Parametric energy simulation enables real-time feedback and interactive visualization, supporting iterative refinement based on environmental performance. Multi-objective optimization tools like Galapagos and Octopus facilitate the balancing of competing goals through Pareto-optimal solutions. Genetic algorithms automate the exploration of diverse morphological variants, proving especially effective in early design stages. Building on these established generative approaches, the integration of advanced machine learning (ML) techniques presents a compelling future direction, with the potential to further enhance predictive capabilities and design efficiency.

Crucially, the findings highlight key morphological parameters—such as building height, plan typology, orientation, street width, and urban density—as influential drivers of energy performance. These elements are not only frequently studied but have also shown measurable impacts across diverse climate zones.

In sum, parametric design methods are reshaping the discourse on urban energy performance by enabling a data-rich, iterative, and performance-based approach to planning. As cities worldwide confront the dual challenges of climate change and urbanization, these methods offer a promising pathway toward more adaptive, efficient, and context-responsive urban environments.

Conclusion

This study has examined the transformative potential of parametric design approaches in advancing energy-efficient urban morphologies, particularly in the face of accelerating urbanization and climate-related challenges. Through a systematic review of existing methodologies, tools, and applications, it becomes evident that the convergence of parametric modelling, environmental simulation, and optimization techniques offers a powerful framework for performance-driven urban design. These approaches enable the dynamic manipulation of urban form based on real-time environmental feedback, allowing designers to explore a wide range of solutions that balance solar access, thermal comfort, and energy use.

While tools such as genetic algorithms, multi-objective optimization, and simulation-integrated parametric platforms are increasingly being adopted, their application remains largely fragmented and context-specific. The integration of advanced machine learning techniques further extends the potential of generative design by automating complex design-space explorations and enhancing predictive capabilities. However, despite significant progress, the widespread adoption of these methods in mainstream urban planning is still limited by the lack of standardized frameworks and generalized models.

To fully realize the benefits of parametric design for sustainable urban development, future research must focus on developing adaptable, scalable methodologies that are sensitive to climatic diversity and urban complexity. This calls for interdisciplinary collaboration between urban designers, environmental engineers, and data scientists, as well as greater integration of these tools into planning policies and education. Ultimately, a performance-driven, data-informed design paradigm holds the key to creating more resilient, livable, and energy-efficient cities.

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Conflict of Interests

The author(s) declare(s) no conflict of interest.

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