

Integrating Energy Performance and Public Space Metrics: A Study from the Perspective of Urban Design

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Abstract

Global warming necessitates energy-efficient urban design. Urban morphology critically impacts both building energy use and public space quality. While prior studies focus on typological parameters (e.g., FAR, density), block-scale energy performance also depends on contextual features like street proportions and public space ratios. This research examines how morphological variations affect energy efficiency and spatial quality by analyzing blocks with identical FAR but differing configurations. Key metrics—alignment ratio, effective street length, and street space density—are evaluated through energy simulations. Results identify specific typologies that simultaneously optimize energy performance and pedestrian experience, demonstrating the potential for integrated low-carbon, human-centric urban design. These findings provide actionable insights for early-stage planning to achieve sustainable built environments.

Keywords: public space; urban form; building energy consumption; performance driven design

Introduction

Global urban populations are projected to reach 68% by 2050, with 2.2 billion additional urban residents concentrated in Asia and Africa (United Nations Habitat, 2022). This urban expansion necessitates increased building construction, resulting in elevated energy consumption and emissions. The built environment currently represents 30% of global final energy use and 26% of energy-related emissions, according to International Energy Agency (IEA, 2022). Despite improvements in energy efficiency per square metre, total building emissions have increased by over 25% since 2000, attributable to a 65% expansion in floor area and growing electricity demand. Building electricity consumption has increased at five times the rate of power sector decarbonisation since 2000 (IEA, 2019). The Paris Agreement (2015) targets – requiring 45% emission reductions by 2030 and net-zero by 2050 – highlight the urgency of urban energy research.

Building energy analysis typically distinguishes operational energy (heating, cooling, lighting) from embodied impacts. According to data from IEA, space cooling demonstrates particular significance, with 2 billion operational air conditioning units globally, 70% of which are residential. Heating accounts for approximately 50% of building energy use worldwide. Effective strategies to reduce operational energy consumption go beyond improving the energy efficiency of heating and cooling systems. They also rely on passive, nature-based, and alternative solutions, including the enhancement of building and district design.

Building energy consumption in urban environments is influenced by multiple factors. Previous research has primarily focused on building-specific elements and parameters, such as the shape coefficient of buildings, envelope materials, and building orientation. However, buildings do not exist in isolation—they are situated within distinct neighborhood contexts, meaning their energy performance is also affected by surrounding environmental conditions. In other words, urban morphological elements equally exert significant influence on building energy consumption patterns. Delmastro et al. (2015) demonstrated that variations in urban form could account for an 11% difference in heating energy use, which increases to 16% when considering solar gain. Similarly, Silva et al. (2017), through a case study of Porto, Portugal, established that urban form could explain up to 78% of the variance in total energy consumption, including heating, cooling, and mobility. The research by Shareef and Altan (2022) demonstrated that a sinuous configuration in urban blocks could reduce building cooling loads by 4.9%.

On the other hand, urban morphological elements constitute essential components of urban design. The control of urban morphology directly and indirectly influences the creation and quality of public spaces, thereby affecting pedestrian experience. Therefore, focusing on urban morphological elements—particularly urban design indicators—can impact urban spatial quality in multiple dimensions and warrants further in-depth research.

Previous studies have explored how urban morphological elements affect building energy consumption across different climate zones, aiming to design low-carbon or even zero-energy urban blocks. However, while pursuing lower energy consumption, the external environments created by certain urban forms are often overlooked.

Crucially, under the same floor area ratio (FAR), different urban forms can produce vastly different qualities of external public spaces. These variations in public space quality profoundly influence urban users, particularly pedestrians, and have implications for spatial equity. Commonly studied urban morphological indicators—such as density, FAR, and building height—fail to fully capture the spatial characteristics of public spaces shaped by urban design.

Urban morphological elements thus exhibit a dual influence, simultaneously shaping both building energy efficiency and the quality of public spaces and pedestrian experiences. While existing research tends to examine these aspects in isolation, practical urban design necessitates an integrated approach that accounts for multiple factors. Unlike studies focusing solely on singular dimensions, this research seeks to bridge energy performance and public space contribution, with particular emphasis on the latter from an urban design—rather than purely technical—perspective.

This study adopts an urban design perspective to identify morphological indicators influencing public space quality, based on a review of urban design guidelines and practices. Three key metrics are proposed: alignment ratio, effective street length, and street space density, to better understand the relationships between building energy performance, public spaces, and urban morphological elements.

Given that total building capacity is typically predetermined in real-world urban design practice, this research conducts a comparative experiment using urban block designs with identical floor area ratios (FAR) but varying public space configurations. By analyzing energy simulation results across different design groups and their corresponding urban design elements, the study explores whether urban design approaches can balance energy efficiency with public space quality, and identifies priority morphological elements.

These findings provide valuable insights for early-stage urban design, encouraging future research to move beyond solely energy-efficient block morphology and equally consider pedestrian experience and public space quality.

Literature Review

Unlike at the building scale, the mechanisms through which block-scale urban form elements influence building energy consumption are markedly more complex. This complexity arises because block morphology not only directly affects a building's passive solar gain and heat dissipation but also indirectly alters energy performance via microclimatic modifications. Consequently, microclimatic impacts must be integral to urban form considerations.

The characterisation and selection of energy-relevant urban form elements vary across studies. Existing research predominantly focuses on four classifications: density measures, geometric measures, land use/cover measures, and typologies (Quan *et al.*, 2021). These categories emerge from systematic syntheses of prior morphological research. While the first three measure types lend themselves to quantitative data analysis, typological approaches better capture urban form complexity. Many studies therefore combine these methods or enhance typologies with context-specific indicators, enabling both relational quantification and practical application for designers.

However, synthesising energy consumption findings for individual factors reveals that most studies preclude direct cross-comparisons of singular morphological variables. Notwithstanding this limitation, our literature review identifies recurrent indicators. Table 1 collates commonly employed metrics for urban form's energy impacts.

Morphological factors in extant research can alternatively be categorised by their descriptive focus:

- Built-environment relations: Floor Area Ratio (FAR), Building Density (BD), Building Coverage Ratio (BCR)
- Non-physical spatial attributes: Open Space Ratio (OSR), obstruction angles, Sky View Factor (SVF)

Whilst both categories influence energy consumption, the second category demonstrably exerts more direct effects on public space quality and pedestrian experience.

Table 1. Morphological indicator choices of some previous research.

Year	Researchers	Location	Indicators
2016	Quan <i>et al.</i> (2016)	Shanghai, China	Building density (BD), building height (BH), floor area ratio (FAR)
2018	Javanroodi <i>et al.</i> (2018)	Tehran, Iran	Building density (BD), height to width ratio (H/W)
2019	Lima <i>et al.</i> (2019)	Maceio, Brazil	Building shape factor (BSF), building height (BH), building density (BD), building orientation (BO)
2021	Mangan <i>et al.</i> (2021)	Istanbul, Turkey	Building typology (BT), height to width ratio (H/W), number of floors (NS), building orientation (BO)
2021	Ahmadian <i>et al.</i> (2021)	London, UK	Plan depth (PD), number of floors (NS), building density (BD)
2021	Zhang and Gao (2021)	Nanjing, China	Floor area ratio (FAR), surface area ratio (SAR), sky view factor (SVF)
2023	Liu <i>et al.</i> (2023)	Jianhu, China	Building density (BD), open space ratio (OSR), shape coefficient (SC), average perimeter-area (PAR)

It is noteworthy that whilst numerous studies examine the impact of urban form at the block scale upon energy consumption, the indicators employed to describe urban form tend to prioritise characteristics of building form, frequently lacking relevant indicators from an urban design perspective. Taking density and floor area ratio (FAR) as examples, utilising merely these two indicator types to describe urban form can yield substantially divergent outcomes owing to variations in building form and layout. These differences manifest not only in the buildings themselves but also influence public space configurations shaped by building forms. Exclusive reliance upon indicators such as open space ratio may inadequately represent actual urban form whilst neglecting pedestrian experience from an urban design standpoint.

Existing urban form descriptors commonly overlook the significance of public space morphology, which holds crucial importance within urban design. Within this context, establishing how public space form influences building energy consumption becomes particularly vital. This proves especially pertinent when the design objective involves creating urban forms that must reconcile energy efficiency with the provision of human-centred, functional public spaces.

Urban design represents a principal methodology for creating and optimising urban public spaces. The urban design process incorporates elements frequently marginalised or entirely disregarded in comprehensive planning and architectural design, including building façade continuity, public space provision, street formation and articulation, alongside street density, amongst others. Consequently, research adopting an urban design perspective can meaningfully address the current knowledge gap regarding how such elements influence energy consumption.

The selection of public space morphological factors may be informed by established street design and urban design guidance. For exemplary high-quality urban spaces, urban design manuals typically furnish explicit directives and design recommendations, regularly incorporating specifications for street space morphology. For instance, the Central Melbourne Design Guide underscores that enhancing both the quantity and quality of public spaces constitutes a central urban design objective. It particularly emphasises that urban development and renewal should privilege walking as the primary transport mode.

At the urban morphology level, this is principally realised through developing laneways and pedestrian connections. The guidelines prescribe that pedestrian connections should not exceed 70 metres separation whilst maintaining minimum 6 metre width. Building volumes ought to align with streets to establish an effective street interface, except where setbacks facilitate plaza creation. The guide promotes appealing colonnades exhibiting height-to-depth ratios of 2:1. Furthermore, street walls should be of reduced height along laneways and streets narrower than 10 metres. Buildings presenting street frontages exceeding 25 metres require subdivision to introduce street façade modulation.

Concerning ground floor levels, the guidelines stipulate that no less than 80% of ground-level frontage facing streets and laneways should comprise entrances or windows, thereby ensuring active frontage. The Central Melbourne Design Guide ultimately defines average urban block length as the mean distance between opposing block sides, measured from laneways and streets.

This integrated approach highlights the necessity of incorporating public space quality considerations within urban design, guaranteeing that energy-efficient, walkable and people-focused spaces receive appropriate priority in urban planning. Correspondingly, the Shanghai Street Design Guidelines (2016) advocate that street spaces should exhibit order, comfort and pleasantness. This is attained through regulating building control lines and alignment ratios, which guarantee a coherent and continuous spatial interface. Through maintaining comprehensive consistency, these guidelines seek to establish foundations for functional spaces that sustain public life and generate walkable urban scales.

Method

To further examine the relationship between urban morphological elements and building energy performance from an urban design perspective, this study employs a set of indicators derived from urban design guidelines that characterise external building spaces. A comparative analysis is subsequently undertaken through a series of simulation experiments, with the overall research methodology and workflow illustrated in Figure 1.

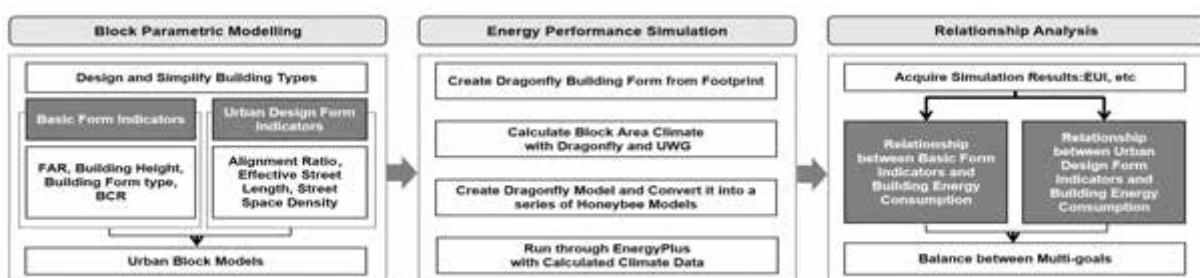


Fig. 1. Workflow of the research process with three stages.

The research comprises three principal stages: block parametric modelling, energy performance simulation, and relationship analysis. The initial stage concentrates on modelling urban forms, which establish the foundation for subsequent energy performance simulations. The results of these simulations then inform the relationship analysis conducted in the final stage.

The primary objective of the first stage involves constructing abstract urban forms and developing their parametric models. A fundamental requirement at this stage ensures all comparative forms maintain identical floor area ratio (FAR) values. This constraint is implemented for three key reasons. Firstly, within practical design processes, urban designers and architects frequently receive explicit, fixed FAR requirements during early planning stages. Secondly, variable control proves essential for isolating effects, with FAR commonly serving as a standard indicator in studies investigating urban form-energy performance relationships. Thirdly, despite FAR uniformity, urban form's inherent complexity permits significant variations in external spatial configurations, rendering these differences crucial components of design decision-making.

To maintain consistent FAR values, this study utilises a typical residential unit as a base model. The unit measures 15 metres in length, with a width of 10.5 metres and height of 3 metres. Through modifications to building heights, typologies and spatial arrangements, six distinct block models exhibiting varying external environmental characteristics are developed, as demonstrated in Figure 2.

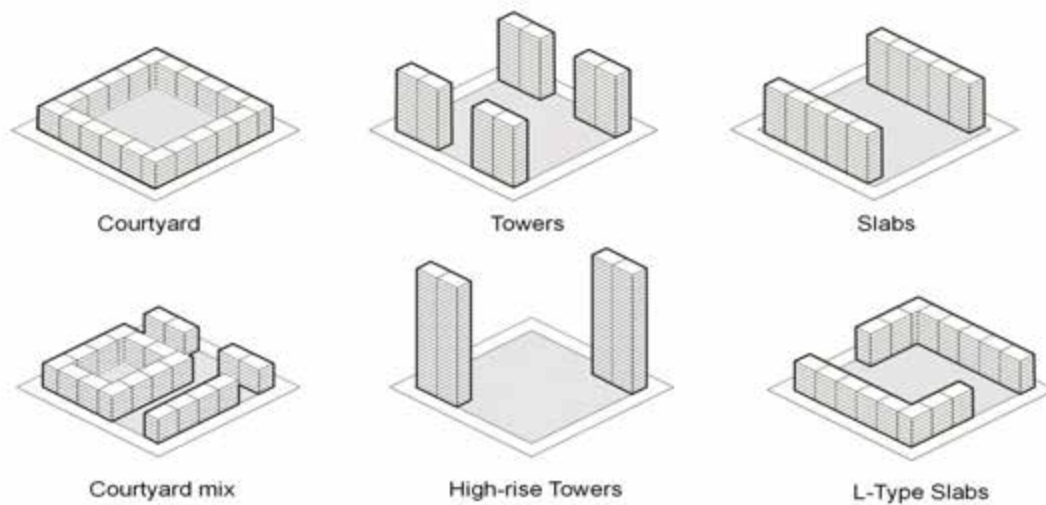


Fig. 2. Residential unit and six block form types.

Situated on identical designated sites, these block models share equivalent FAR values while differing in other fundamental form indicators, summarised in Table 2.

Table 2. Basic form indicators of six types.

No.	Form Type	Site Area	Total Building Area	Building Footprint Area	Number of Floors
C-1	Courtyard	11130.25m ²	18900m ²	3150m ²	6
C-2	Courtyard mix	11130.25m ²	18900m ²	3150m ²	6
T-1	Towers	11130.25m ²	18900m ²	1260m ²	15
T-2	High-rise Towers	11130.25m ²	18900m ²	630m ²	30
S-1	Slabs	11130.25m ²	18900m ²	1575m ²	12
S-2	L-Type Slabs	11130.25m ²	18900m ²	2520m ²	7, 8

Parametric modelling and energy performance simulations are executed based on the defined block forms. While numerous building energy simulation tools exist, determining appropriate methods and tools for block-scale analyses remains crucial. This study implements a workflow centred on Ladybug Tools (Figure 3), operating principally within Rhinoceros and Grasshopper platforms while employing EnergyPlus as the core simulation engine for energy performance analysis.

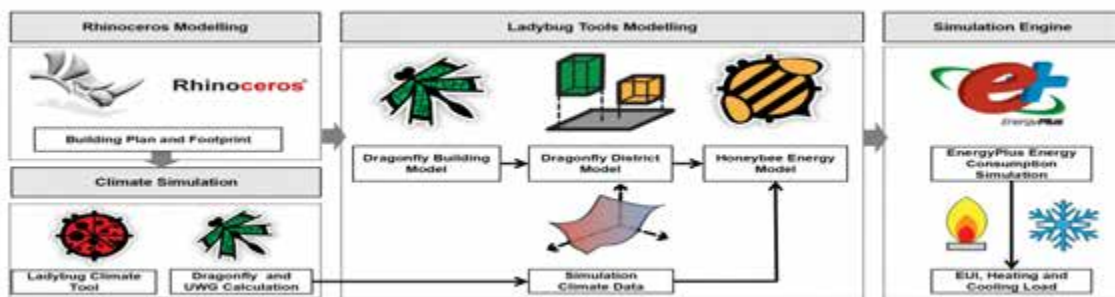


Fig. 3. Energy performance simulation workflow.

Developed by the U.S. Department of Energy, EnergyPlus provides comprehensive simulations of building thermal performance, humidity levels, airflow and lighting conditions. The software incorporates key factors including thermal conduction, air infiltration, solar radiation, lighting and HVAC system performance through its fundamental thermal balance physical model. Unlike simulation engines such as DOE-2 and DeST, EnergyPlus not only ensures thermal balance within rooms but also extends beyond linear time-invariant systems to handle surface convective heat transfer coefficients. Crawley *et al.* (2021) validated EnergyPlus's high precision in building energy consumption simulations through multiple test cases, confirming the reliability of its core algorithms.

To enhance usability, platforms including OpenStudio, DesignBuilder and Ladybug Tools have integrated the EnergyPlus engine within more accessible interfaces. The Grasshopper platform facilitates visual programming through user-friendly plugin tools, with Ladybug Tools serving as a central component. This toolkit comprises four specialised plugins: Ladybug for climate and meteorological analysis with advanced visualisation capabilities; Honeybee for energy performance and daylighting simulations; Butterfly for wind environment analysis; and Dragonfly for urban-scale microclimate and energy performance studies. The current research primarily utilises

Honeybee and Dragonfly for performance simulations.

Compared to alternative EnergyPlus-based tools like OpenStudio and DesignBuilder, Ladybug Tools offers distinct advantages. As a parametric platform, it provides superior comprehensiveness and adjustable flexibility, enabling multi-factor simulation workflows through combined use of its plugins. Consequently, researchers widely employ Ladybug Tools for studies examining solar potential, microclimate, daylighting, energy consumption and their relationships with built morphology. For instance, Rostami *et al.* (2024) applied a Ladybug Tools-UMI integrated workflow to investigate urban canyon solar potential and energy consumption under morphological influences in semi-arid regions. Furthermore, as a Grasshopper plugin, Ladybug Tools demonstrates exceptional usability within established urban design workflows, significantly reducing learning curves while facilitating performance-optimised design operations. These characteristics have led to its widespread adoption in urban morphology-energy consumption research (Feng *et al.*, 2024; Liu *et al.*, 2023; Ibrahim *et al.*, 2021) justifying its selection as the primary simulation tool in this study alongside the EnergyPlus engine.

To account for local urban climate conditions, the study employs Dragonfly's integrated Urban Weather Generator (UWG), validated across multiple cities for effective urban weather data adjustment (Bueno *et al.*, 2013). Using modified climate data, the Honeybee plugin executes EnergyPlus simulations to evaluate block configuration energy performance, generating Energy Use Intensity (EUI) and annual heating/cooling load data. The simulation methodology prioritises result reliability, workflow consistency and parametric form manipulation capacity.

The process utilises Grasshopper's parametric design platform within Rhino to define building site plans, establish volumes through floor height/count parameters, and configure daylighting via window-to-wall ratios (WWR). A Dragonfly model converts into Honeybee models for energy simulations, applying a maximum 0.35 WWR for residential buildings. All block models occupy identical urban contexts to minimise external interference, with Shanghai selected as the experimental location due to its representative ASHRAE 3A (warm and humid) climate classification.

EnergyPlus simulations incorporating Shanghai's climate parameters produce annual EUI data and monthly load outputs. Prior to energy performance comparison, the study defines four urban design form indicators (Table 3) specific to the identified typologies. These indicators focus on building-shaped external spaces, evaluating their capacity to generate sufficient, high-quality public realms.

Table 3. Urban design form indicators.

Indicator	Formula	Connection to high-quality public spaces
Alignment Ratio	$AR = \frac{\text{StreetwallLength}}{\text{Building setbackLineLength}} * 100\%$	High AR helps to create continuous and enclosure street interfaces, thereby promoting pedestrian activity (2011).
Effective Street length	$ESL = \text{StreetwallLength}$	Longer street wall length can enhance the vitality of the street attract more pedestrians to stay (Mehta, 2014).
Effective Street Space	$ESS = \text{ESL} * \text{PedestrianSpaceWidth}$	Higher effective street space provides more spaces for activities (2013).
Street Space Density	$SSD = \frac{\text{Non - UrbanSpaceOccupiedByBuilding}}{\text{SiteArea}} * 100\%$	Higher street space density means more accessible pedestrian spaces for vitality and more pedestrian-friendly environment (Gehl, 2003).

The study examines four key urban design indicators to evaluate block morphology:

Alignment Ratio: This measures the proportion of building street walls aligned with designated setback lines, calculated as the total building street wall length divided by the total setback line length. Urban design guidelines globally emphasise this metric as it quantifies how effectively buildings define street interfaces and contribute to coherent streetscapes.

Effective Street Length: This represents the cumulative length of building façades that actively contribute to high-quality street environments. Streets lacking continuous building interfaces typically fail to generate vibrant public spaces, making this a crucial measure of urban form quality.

Effective Street Space: This indicator calculates the total area of street space bounded by well-defined building interfaces. It measures the spatial extent of streetscapes capable of supporting diverse public activities and pedestrian interactions.

Street Space Density: A novel metric introduced in this research, defined as the ratio of non-building urban space to total site area (illustrated in Figure 4). Higher values indicate more compact, pedestrian-oriented urban configurations where public spaces are efficiently distributed within the block structure. This indicator provides a quantitative measure of urban morphology's capacity to support walkability and public space functionality.

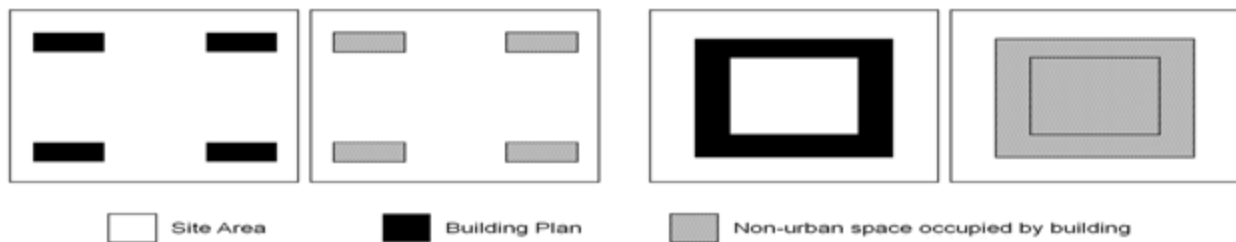


Fig. 4. Definition of street space density.

Table 4 presents the calculated values of these urban design form indicators for each block typology examined in the study. The metrics collectively provide a comprehensive framework for assessing how different urban configurations balance built form with public space quality, particularly in relation to pedestrian experience and spatial usability.

Table 4. Urban design form indicators of six types.

No.	Form Type	Effective Street length	Effective Street Space	Street Space Density	Alignment Ratio
C-1	Courtyard	342m	3820m ²	65.7%	100%
C-2	Courtyard mix	231.5m	3025m ²	65.7%	67.7%
T-1	Towers	120m	1200m ²	11.3%	35.1%
T-2	High-rise Towers	60m	600m ²	5.7%	23.7%

S-1	Slabs	150m	1500m ²	14.2%	43.9%
S-2	L-Type Slabs	261m	2810m ²	65.7%	76.3%

Results and Discussions

The energy performance simulation results for the six urban form types demonstrate notable variations in energy consumption patterns (Table 5). Among the tested configurations, the C-1 type achieves the lowest Energy Use Intensity (EUI), while the T-1 type exhibits the highest consumption. The Tower-type forms generally show poorer energy performance compared to both Courtyard and Slab types. Analysis of cooling and heating loads reveals C-2 as the most thermally balanced configuration, whereas S-1 displays the most significant load fluctuations, likely due to its complex morphological characteristics.

Table 5. Simulation results of six block types.

No.	Form Type	EUI	Cooling Load	Heating Load
C-1	Courtyard	167.591 KW/m ²	52.496 KW/m ²	43.411 KW/m ²
C-2	Courtyard mix	174.148 KW/m ²	53.915 KW/m ²	48.267 KW/m ²
T-1	Towers	182.791 KW/m ²	59.248KW/m ²	50.700 KW/m ²
T-2	High-rise Towers	181.936 KW/m ²	60.094 KW/m ²	49.745 KW/m ²
S-1	Slabs	170.102 KW/m ²	54.854 KW/m ²	42.971 KW/m ²
S-2	L-Type Slabs	170.641 KW/m ²	54.001 KW/m ²	44.555 KW/m ²

The maximum EUI difference between the highest (T-1) and lowest (C-1) performing types is 9%, indicating relatively constrained performance variations under the controlled study conditions. Notably, certain type pairs demonstrate remarkably similar energy performance, including S-1 and S-2 with nearly identical EUI values, and T-1 and T-2 showing comparable consumption patterns. These similarities presumably result from the shared experimental parameters, particularly the fixed Floor Area Ratio (FAR) and standardized environmental conditions.

When evaluating both energy performance and urban design indicators through a comprehensive ranking analysis (Figure 5), the C-1 type emerges as the optimal configuration, excelling in both energy efficiency and public space quality. In contrast, the T-2 type performs poorest overall, with T-1 following closely behind due to its high energy demands and inadequate public space provision. While S-1 and S-2 demonstrate similar energy performance, S-2 shows superior urban design outcomes through better-defined street interfaces and more generous public spaces.

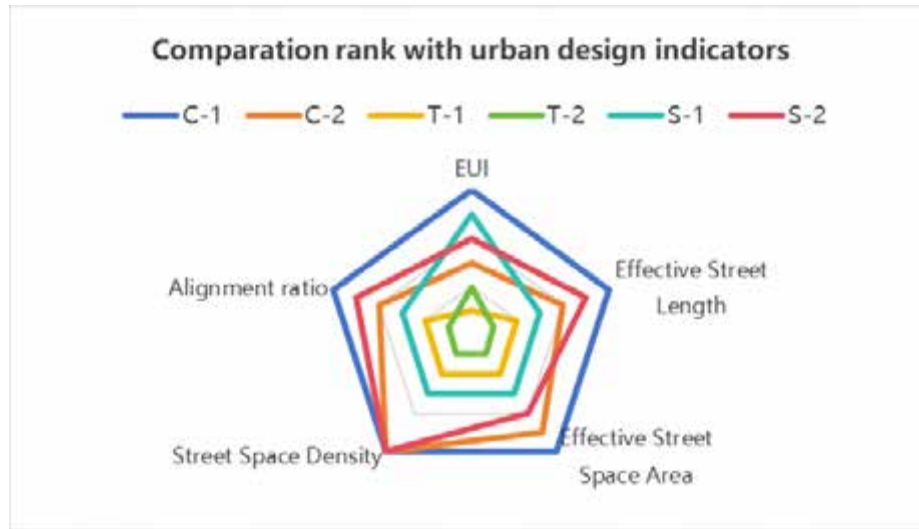


Fig. 5. Comparison rank with urban design indicators.

The comparative analysis reveals that Courtyard-type configurations achieve the best overall balance between energy efficiency and public space quality. Tower types prove least effective across all evaluation metrics, while Slab forms show intermediate performance with potential for further optimization. These findings carry important implications for urban design practice, demonstrating that equivalent FAR conditions can accommodate substantial variations in both energy performance and public space quality across different morphological types.

The study confirms that certain urban form configurations can successfully reconcile energy efficiency with high-quality public spaces, proving this dual optimization is achievable in practice. However, several limitations should be acknowledged, including the simplified morphological representations compared to real urban environments, constrained environmental parameters, focus on relative rather than absolute performance relationships, and exclusive consideration of residential functions. Despite these limitations, the findings provide valuable guidance for early-stage urban design, suggesting designers should prioritize configurations that balance energy performance with public space quality while recognizing these solutions maintain effectiveness across varying FAR conditions. The results substantiate that energy-conscious urban form selection need not compromise public space quality, offering empirical support for more holistic sustainable design approaches. Future research should address the current limitations through expanded typological variety, multifunctional analysis, and real-world validation studies.

Conclusion

Existing research on building energy performance predominantly focuses on architectural characteristics. However, in actual urban and architectural design practice, the preliminary design phase must consider not only building forms but also the configuration of external public spaces shaped by built elements - a fundamental aspect of urban experience. To achieve orderly, comfortable and sustainable urban environments, it becomes imperative to re-examine the urban morphology-energy consumption relationship through an urban design lens.

This study conducted controlled energy simulation experiments across comparative morphological typologies. The results demonstrate that urban form elements and typologies significantly influence building energy performance while exhibiting substantial variation in public space generation capacity. The C-1 typology emerged as optimal, excelling in both energy efficiency and public space provision, whereas T-type forms underperformed across both parameters. Among S-types, while energy consumption remained consistent, urban design indicators showed marked variation. These findings suggest the feasibility of identifying multi-objective

optimised morphological solutions addressable during early-stage urban design. The research provides novel perspectives and indicators to inform future scholarship and practice.

The outcomes offer practical implications for urban designers. During preliminary design phases, prioritising morphological typologies that simultaneously enhance energy performance and public space quality - with minimal FAR dependency - proves achievable. Recommended design approaches include:

When working with predetermined FAR values, designers should favour typologies combining lower energy consumption with high-quality public spaces, as exemplified by Courtyard-type configurations. Where morphological options are constrained, exploring solutions that optimally balance energy and spatial performance within given parameters becomes essential. Crucially, designers should avoid problematic typologies that yield both elevated energy demands and inadequate public space provision.

Future research should investigate larger urban blocks, incorporate diverse programme types, and establish correlations between urban design indicators and energy performance. Addressing these dimensions will facilitate the development of more precise, sustainability-focused urban design guidance. The study demonstrates that energy-conscious urban form selection need not compromise public space quality, providing empirical validation for integrated performance-based design methodologies. Subsequent work should expand typological variety and examine real-world applications to strengthen these findings

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