

Review

A Review of Building Physical Shapes on Heating and Cooling Energy Consumption

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Abstract: The shape of a building profoundly impacts its energy consumption throughout its life and is a critical consideration in early architectural design. Despite its significance, the influence of building shape on heating and air conditioning energy usage remains insufficiently understood. This study systematically analyzes the relationship between building shape and energy consumption, grounded in objective facts about building energy performance from the perspective of architects during the initial design phases. This analysis aids designers in making informed decisions. Key parameters, notably the widely used building shape coefficient, are examined. The relationship between building shape and energy consumption across various global and China's diverse climate zones is synthesized. Current simulation tools and methodologies are assessed to guide future research. Findings reveal a predominant reliance on simulations for comparing energy use across specific building shapes. The academic understanding of the shape–energy relationship remains superficial, complicating standardization. Future research should prioritize extensive, multi-parameter simulations to enhance understanding of building performance, thereby facilitating energy-efficient design.

Keywords: building shape; building energy consumption; architectural design; HVAC



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1. Introduction

1.1. Background

Due to rapid industrialization, urbanization, and modernization, potential energy scarcity is a pervasive challenge globally [1]. Despite the increasing attention on renewable energy sources such as geothermal [2], solar [3], tidal [4], wind [5], and biomass energy [6] in the 21st century, widespread adoption encounters numerous hurdles, while energy conservation and emission reduction remain urgent tasks. The latest report indicates that construction industry has accounted for over 55% of global energy consumption and is responsible for 38% of global carbon emissions, with the trend intensifying [7]. Balancing the increasing demand for energy and building energy consumption is challenging in architecture.

The building shape serves as the physical boundary between indoor and outdoor environments. It is also a fundamental parameter for sustainable architectural design, reflecting the architects' design intent (Figure 1). Hence, building shape influences both the artistic and ecological aspects of a building and its energy performance [8]. Simultaneously, the building envelope affects their thermal performance. Therefore, the design of passive buildings depends on effectively controlling building shape, considering the coupling effects of meteorological parameters such as outdoor air temperature and solar irradiance, as well as architectural planning elements like window-to-wall ratios (WWRs) and building orientations, all of which influence heating and cooling energy consumption [9]. An appropriate building shape is essential for implementing passive measures to reduce

building energy consumption based on local conditions. Thus, optimizing building shape has been a longstanding research focus in building energy conservation [10].

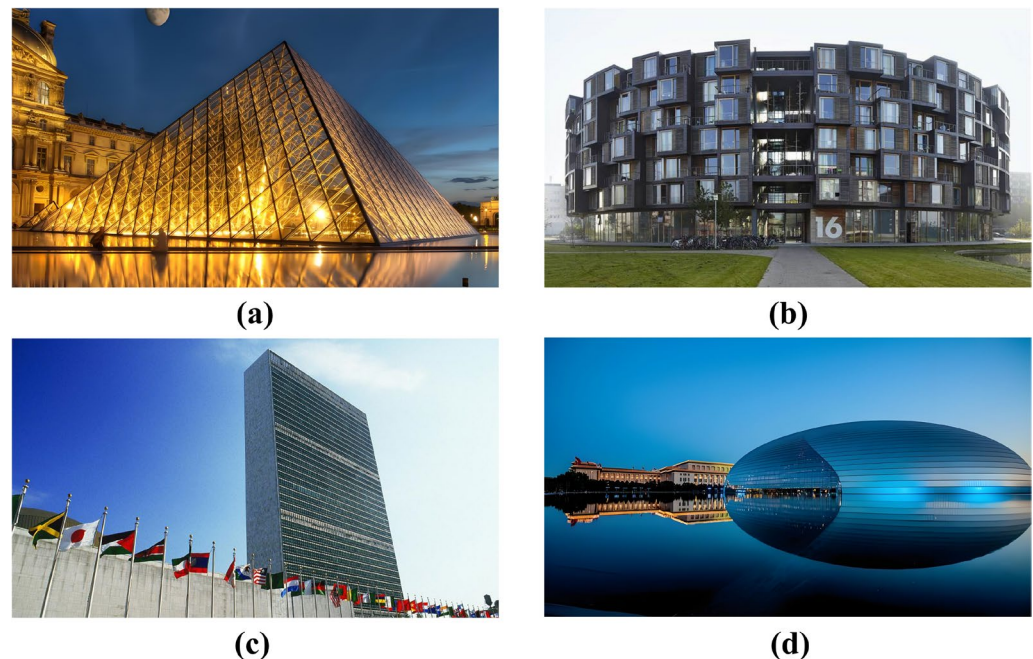


Figure 1. Buildings in different shapes: (a) Glass Pyramid of the Louvre, Paris; (b) Tietgen Student Dormitory, Copenhagen; (c) United Nations Headquarters, New York; (d) National Center for the Performing Arts, Beijing.

The shape coefficient of building (SCB), defined as the ratio of a building's external surface area to its volume, serves as a crucial metric in the design and evaluation of energy-efficient buildings. It is also a key parameter that characterizes the shape of a building and influences its heat consumption index [11]. Generally, the architectural shape determined in the early design stages remains largely unchanged until construction is completed [12]. Accurately predicting energy consumption performance under various building shapes plays an important role in reducing operational energy consumption from the beginning [13]. Driven by this motivation, this paper aims to explore how building physical shapes contribute to reducing building energy consumption.

1.2. Previous Review

It is well understood that numerous interrelated factors affect building energy consumption. Reviews explored the potential reasons, such as retrofit measures [14], decision-making models [15], envelope design, physical and thermal factors, and renewable energy utilization [16]. Determining building shape is a crucial initial step in the architectural design process. Numerous studies have highlighted its significant impact, treating building geometry as a key variable that influences energy consumption, indoor thermal comfort, and environmental design. For instance, one study acknowledged building geometry as a critical variable and explored its impact on various aspects of building performance [17]. Another review focused on the variables of building envelope design for low-energy buildings in tropical climates, covering aspects such as optical, thermal, physical properties, and geometry [18]. Kheiri [19] discussed optimization methods used in the design of energy-efficient building geometry and envelopes. Chen et al. [20] provided a comprehensive review of both internal and external factors influencing the energy efficiency of building designs. Additionally, Roslan and Ismail [21] examined how building shapes affect thermal and energy performances, particularly in high-rise buildings with glass façades. However, the aforementioned reviews do not directly, systematically and comprehensively explore the relationship between building shape and energy consumption.

This paper aims to correlate building shape with energy consumption from an architectural perspective, grounded in a comprehensive understanding of building energy use. The primary focus is on the relationship between building shape—encompassing both physical form and size—and energy consumption. Some scholars assert that energy consumption is primarily influenced by thermal design parameters, not the building shape per se [22]. However, this perspective overlooks the architect's role. Architects typically draft building shapes during the early design stages informed by creativity or artistic vision, often before considering thermal design parameters, which are addressed later to comply with energy efficiency standards. To clarify the relationship between shape and energy consumption, Figure 2 demonstrates the factors influencing building energy consumption, indicating how building shape interacts with weather conditions [23], solar radiation [24], thermal properties of the building envelope [25], building orientation, and other variables, thereby affecting energy usage.

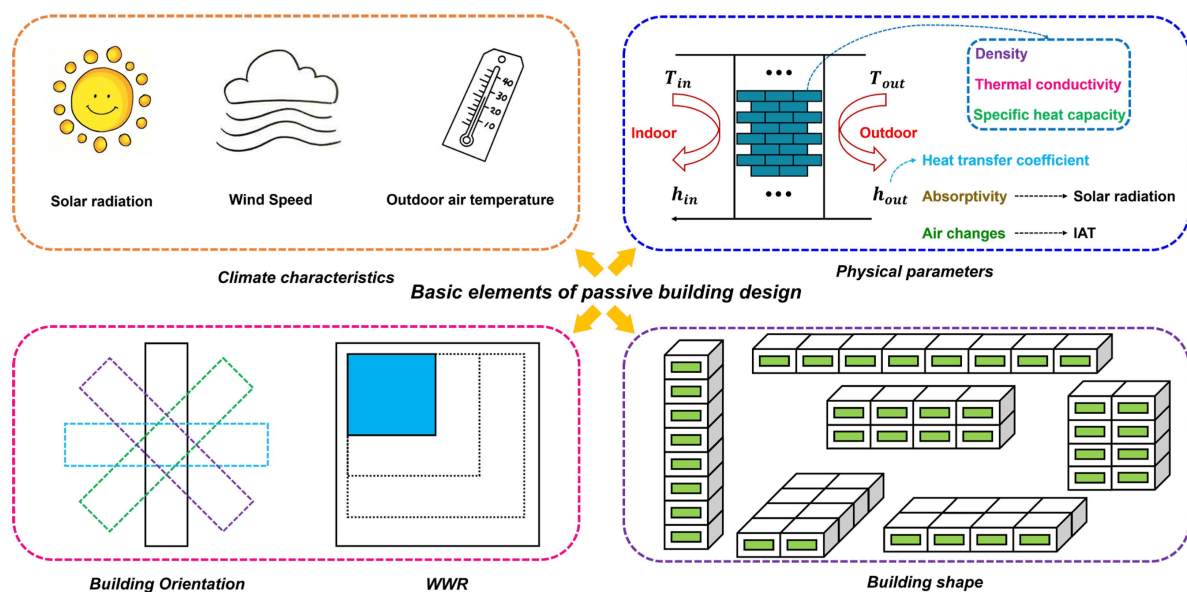


Figure 2. Schematic diagram of factors affecting building energy consumption.

1.3. Research Gap and Overview

The objective of this paper is to provide a comprehensive review of the relationship between building physical shape and heating or cooling energy consumption. First, the paper summarizes characterization methods such as the SCB, compactness, and other relevant indices. Second, it discusses the correlation between building shape and heating or cooling energy consumption across different climates. Researchers commonly utilize commercial software to simulate performance by modeling various geometries. Therefore, the simulation methods are also compared and reviewed. Finally, the paper highlights research and architectural design trends. This paper offers valuable insights into the role of building geometry and enhances the understanding of determinants of building energy consumption.

1.4. Review Methods

This study conducted a thorough literature review using multiple databases, including Google Scholar, Web of Science, Scopus, and CNKI. The search employed keywords such as “building shape” and “building energy consumption”. To ensure a comprehensive analysis, synonyms and alternative keyword combinations were utilized. For “building shape”, the synonyms included “building form”, “building geometry”, and “building topology”, while “building energy consumption” was also searched under terms such as “building heating energy”, “cooling energy”, and “HVAC energy”. The retrieved literature was meticulously

screened based on the relevance to the review theme, eliminating studies with insufficient content relevance. Figure 3 depicts the annual trend in relevant research activities.

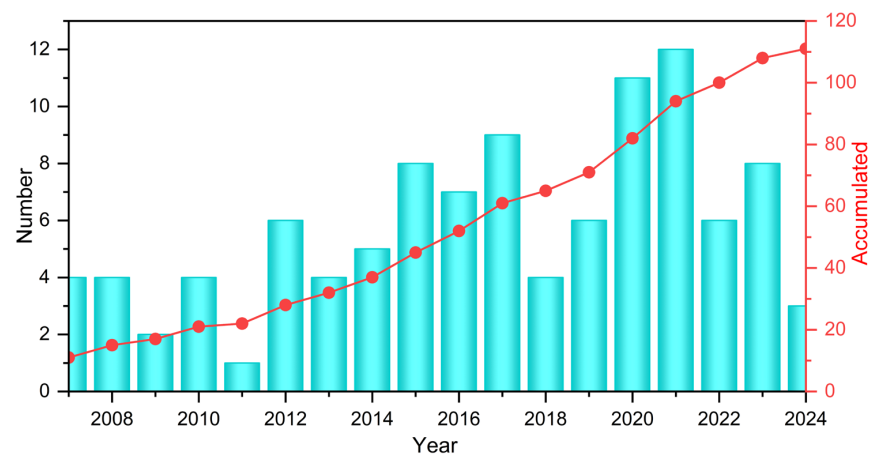


Figure 3. Number of documents published per year.

2. Characterization Methods

Scholars recognize that while building shape can be described using geometric parameters, doing so without constraints can be inefficient. Therefore, it is worthwhile to explore how to characterize building physical shape from the perspective of energy consumption. Currently, the most commonly used metrics are the SCB and compactness.

2.1. SCB

This factor is instrumental in determining thermal performance, influencing both heat gain and heat loss through the building envelope [26]. The regulation of shape factors in building energy standards aims to minimize unnecessary thermal exchange by promoting designs that inherently reduce the surface area exposed to ambient conditions. Figure 4 gives the common building shapes. Equations (1)–(3) illustrate the calculation formula of the SCB. Rectangular, pitched roof, and hexagonal shapes may be the most representative building forms.

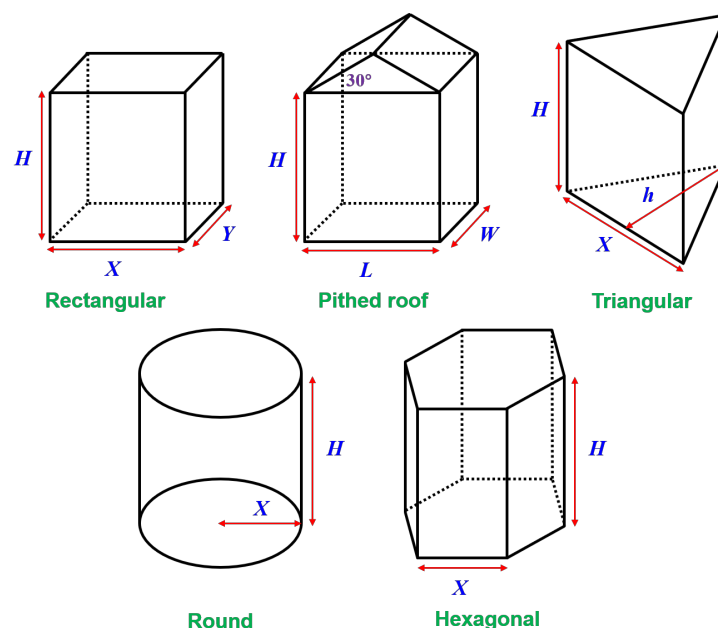


Figure 4. Common building shapes.

For the rectangular plane,

$$SCB = 2\left(\frac{1}{X} + \frac{1}{Y}\right) + \frac{1}{H} \quad (1)$$

For the pitched roof (30°) [27],

$$SCB = \frac{\frac{2}{L} + \frac{2}{W} + \frac{1.15}{H} + \frac{0.29}{L} \frac{W}{H}}{1 + \frac{0.14W}{H}} \quad (2)$$

For the hexagonal plane [28],

$$SCB = \frac{4\sqrt{3}}{3X} + \frac{1}{H} \quad (3)$$

2.2. Compactness

In architectural design, compactness refers to the efficiency of a building's shape in minimizing its surface area relative to its volume, which significantly impacts the building's thermal performance and energy efficiency [10]. Compactness is often quantified through the form factor, a ratio that correlates the external surface area to the volume, serving as a key determinant in the building's heat loss and gain characteristics [29–31].

2.3. Other Indexes

In the long-term practice of building energy conservation, scholars discovered that the SCB has limitations in the architectural design, so they have made improvements or proposed more scientific indicators, as summarized in Table 1. The equivalent shape factor of buildings was proposed to deduct the equivalent surface area concerning the solar heat gain [32]. Lan recommended applying a dimensionless coefficient or the ratio of the surface area to the floor to replace the SCB [33]. Similar to this, Chi et al. proposed the coefficient of building plane energy consumption to explore the relationship between energy consumption and dimensions of the first floor [34], which was similar to the ultimate shape coefficient [35]. Xia considered the effects of solar radiation and indoor and outdoor temperature differences and proposed a thermal shape coefficient for the annual air conditioning conditions [36]. Overall, scholars characterize building shapes from different perspectives, which adds a certain level of scientific validity.

Table 1. Modified SCBs in the existing literature.

Model Name	Calculation Formula	Unit	Data Resource
Modified shape coefficient of building	$S_c = \eta \cdot SCB(\mathcal{G})$	m^2/m^3	(Li et al., 2023b) [37]
Equivalent shape factors of buildings	$S_E = \frac{F - (1+K_y) \times F_{cy}}{V} (\aleph)$	m^2/m^3	(Shi et al., 2019) [32]
Dimensionless coefficient	$S_D = \frac{F}{V^{\frac{2}{3}}}$	1	(Lan, 2014) [33]
Replaced shape coefficient of building	$S_R = \frac{F}{F_1} (\beth)$	m^2/m^3	(Lan, 2014) [33]
Coefficient of building plane energy consumption	$S_P = \frac{a \times 2 + b \times 2}{a \times b} (\beth)$	m^2/m^3	(Chi et al., 2021) [34]
Ultimate shape coefficient	$\lim_{n \rightarrow \infty} \frac{F_0}{V_0} = 2\left(\frac{1}{a} + \frac{1}{b}\right)$	m^2/m^3	(Ding et al., 2002) [35]
Thermal coefficient of buildings	$TSC_{cooling} = \frac{\sum_i \lambda_i A_i}{V} (\wp)$	m^2/m^3	(Xia, 2008) [36]
Shape factor	$C = \sum_{buildings} \frac{A_{ext}}{V^{\frac{2}{3}}} (\varkappa)$	1	(Ratti et al., 2005) [38]
Passive plot ratio	$R = \frac{V_p}{V} (\beth)$	1	(Salat, 2009) [39]
South exposure coefficient	$C_s = \frac{S_{wall}^s}{V} (\mathcal{M})$	m^2/m^3	(Albatici and Passerini, 2011) [40]
Relative compactness	$RC = \frac{(V/A_{ext})_{building}}{(V/A_{ext})_{ref}}$	1	(Ourghi et al., 2007) [41]
Window-to-floor ratio	$WFR = \frac{S_{win}}{S_{wall}}$	1	(Rodrigues et al., 2015) [42]

($\mathcal{G}$) η denotes the correction factor. ($\aleph$) F denotes the external surface area, m^2 ; V denotes the building volume, m^3 ; K_y denotes the equivalent area correction factor; F_{cy} denotes the windows area, m^2 . ($\beth$) F_1 denotes the floor area, m^2 . ($\beth$) a, b denote the side length of the building ground floor, m. ($\wp$) λ denotes the ratio of the comprehensive heat gain coefficient of the building envelopes to the heat transfer coefficient of the exterior wall. ($\varkappa$) A_{ext} denotes the external surface area, m^2 . ($\beth$) V_p denotes the passive zone volume, m^3 . ($\mathcal{M}$) S_{wall}^s denotes the south wall area, m^2 .

3. Correlation Analysis

Throughout the past decade, scholars have approached building shape optimization from various angles. For instance, Camporeale et al. examined shape optimization holistically, analyzing the primary energy consumption in slab and high-rise housing typologies [43]. Wang et al. conducted a numerical simulation to assess the energy-saving impact of different shape parameters, focusing on low latitudes, revealing that the building envelope optimization for high latitudes was not universally applicable to low latitudes [44]. Zhang et al. investigated the building shape optimization of large spaces through obtaining more solar gain [45]. Storz et al. aimed to establish a general method that could generate all potentially feasible building geometries by exploring the relationship between the modular space arrangement system, architectural selection rules, and mathematical geometry generation [46]. Monteiro et al. performed a life cycle assessment of the building shape of a European house [47]. Evidently, these studies affirm that optimizing building shapes is a crucial yet challenging endeavor in the initial phases of conceptual design. Although these works considered many design elements, the specific role of solar radiation remains insufficiently elucidated. Consequently, there exists a research gap in understanding the optimization of building shapes in high-altitude areas abundant in solar radiation resources.

Scholars have extensively explored the relationship between building shape and building energy consumption [48] across various different climatic zones. Moreover, the variations in building energy demand [41,49], power consumption [50], and thermal performance [51] with the building shape were investigated. Interestingly, these studies have identified a discernible correlation between building shape and energy consumption, although this relationship's impact varies across different climate regions [11]. Table 2 gives the related literature under different climate regions.

3.1. Temperature and Cold Climate

In cold regions, the harsh climate makes it essential to study the correlation between building shape and heating energy consumption. These studies cover major cold climate regions worldwide, yet their conclusions vary significantly. For instance, Susorova et al. [52] asserts that building shape significantly impacts energy consumption, while Sekki et al. [53] argue that there is no such correlation. Premrov et al. [54] found that the impact of building shape on energy consumption is related to temperature and solar radiation, suggesting that the effect cannot be generalized. Tiberiu et al. [55] posits that controlling building shape can alter solar irradiation levels. Oral and Yilmaz [56] determine the limit values of the envelope U-value based on building shape. Since most of these studies simulate energy consumption using software, the representativeness and universality of the results are significantly weakened once building shape, envelope, and climate parameters are defined. In summary, the impact of building shape on heating energy consumption in cold regions remains an area worthy of further investigation.

3.2. Tropical or Hot Climate

In tropical and hot regions, where cooling loads are significant due to high temperatures throughout the year, scholars have also provided recommendations regarding building shapes. Barssoum et al. [57] recommended a rectangular shape for Victoria, Canada. Tibermacine and Zemmouri [58] suggested that Algeria should adopt a point or pavilion shape. [59] found that a square shape is more suitable for Sri Lanka, while Pathirana et al. [60] suggested a circular shape for Malaysia. Mohsenzadeh et al. [61] considered Islamic-style architecture, which, although not directly studied in relation to energy consumption, remains noteworthy. Maksoud et al. [62] advised that buildings in Baghdad should have the smallest possible façade area.

3.3. Mediterranean Climate

The Mediterranean climate is characterized by hot, dry summers and warm, wet winters. Mahdavejad et al. [63] suggested that cubic-shaped buildings are suitable for the Tehran region, while Mahjouba and Ghomeishi [64] recommended circular shapes. Giouri et al. [29] recommended rectangular shapes for Greece, whereas Vartholomaos [65] emphasized that low-energy buildings in Greece should have high compactness and a south-facing orientation. Pacheco-Torres et al. [66], after studying residential buildings in Spain, concluded that single-family homes are preferable to multi-family homes. Zerefos et al. [67] found that prismatic buildings in Athens receive less solar radiation.

Table 2. Comparison of the existing literature with respect to different climate zones.

Climate Zone	Research Region	Simulation Software/Measurements	Building Shapes	Comparative Conclusions	Data Resource
Temperature and cold climate	Turkey	Self-programmed	SCB = 1/2, 1/2.5, 1/3, 1/3.5	The limit U values are determined according to building form.	Oral and Yilmaz, 2002 [56]
	Seoul	TRANSYS 16	Cubic	-	Choi et al., 2007 [68]
	France	Not mentioned	Rectangle and cube	Building shape can change the workplace illuminance level	Tiberiu et al., 2011 [55]
	Italy	Self-programmed	Cubic	The south exposure coefficient is introduced	Albatici and Passerini, 2011 [40]
	USA	DesignBuilder	The room width-to-depth ratio	Geometry factors affect energy consumption significantly in hot climates and cold climates.	Susorova et al., 2013 [52]
	Finland	Measurements	SCB: 0.19–0.35 (day care centers), 0.14–0.38 (Schools), and 0.24–0.38 (university buildings)	Energy consumption and the building shape factor do not have any clear connection.	Sekki et al., 2015 [53]
	Ljubljana, Munich, and Helsinki	Self-programmed	Square, rectangle, L shape, T shape, and U shape	The impact of building shape on energy consumption is related to temperature and solar radiation.	Premrov et al., 2016 [54]
	Jubljana	EnergyPlus	5 building shapes with the same volume	Energy consumption decrease with glazing area.	Košir et al., 2016 [69]
	Italy	Self-programmed	Cubic-shaped		Baglivo et al., 2024 [70]
	Yotvata	QUICK II	20 m × 5 m, 10 m × 10 m	A rectangular shape climatically better than A square.	Cicelsky and Meir, 2014 [30]
Tropical or hot climate	Victoria, BC, Canada	OpenStudio and Parametric Analysis Tool	Courtyard, rectangle, T shape, U shape, and L shape	Rectangular-shaped buildings are the most energy-efficient.	Barssoum et al. [57]
	Biskra, Algeria	TRNSYS	Slab, pavilion, U shape, L shape, and courtyard	The most efficiency typology are the slab and pavilion Configurations.	Tibermacine and Zemmouri, 2017 [58]
	Athens and Sevilla	PHPP V8.5	Varied aspect ratio, as well as horizontal and vertical extensions	Building shape has an important influence on the energy behavior of timber-framed buildings located in warm European climate conditions.	Premrov et al., 2018 [71]
	Baghdad	EnergyPlus	Square, rectangle, L shape, U shape, and H shape	Recommendation: shapes with less surface area	Hasan, 2018 [62]
	Katuanyake, Sri Lanka	DesignBuilder	Square, rectangle, and L shape	Lighting electricity: square shape (highest); L shape (lowest).	Pathirana et al., 2019 [59]
	Penang, Malaysia	DesignBuilder	Square, rectangle, triangle, and circle shapes	The most suitable form: circle	Mohsenzadeh et al., 2021 [60]
	United Arab Emirates	Rhinoceros 3D	Islamic patterns	-	Maksoud et al., 2022 [61]

Table 2. Cont.

Climate Zone	Research Region	Simulation Software/Measurements	Building Shapes	Comparative Conclusions	Data Resource
Mediterranean climate	Athens	Self-programmed	Vertical walls and a flat roof instead	Prismatically formed building has lower solar gains.	Zerefos et al., 2012 [67]
	Tehran		Cubic, stair, and pyramid	Recommendation: cubic shape	Mahdavinejad et al., 2012 [63]
	Andalusia, Spain	EnergyPlus	Single-family detached house, semidetached house, and multi dwelling building	Best: single-family	Pacheco-Torres et al., 2015 [66]
	Tehran	DesignBuilder	Square, rectangle, triangle, and circle forms	Best: circular shapes	Mahjouba and Ghomeishi, 2017 [64]
	Thessaloniki, Greece	EnergyPlus	The perimeter urban block, the slab, and the pavilion	Low-energy urban forms' characteristics: high compactness and southern building orientation	Vartholomaios, 2017 [65]
	Greece	DesignBuilder	Change of floor-plan dimensions	Best: square; worst: rectangle	Giouri et al., 2020 [29]

3.4. Chinese Climate Zone

China spans five climatic zones (Figure 5), and it is increasingly recognized within the academic community that energy-saving strategies vary among different types of buildings across these zones [72]. Compared to other countries, China adopt the unique energy-saving strategies [73]. Dr. Lan Bing systematically investigated the differences in building energy-saving standards between China and the United States in his doctoral thesis [33]. Essentially, China posits a correlation between building shape and energy consumption. Although the specific impact patterns remain unclear, energy-saving design standards for public and cold-region buildings emphasize strict control over the SCB to reduce heating demand (Figure 6). While standards allow for final decisions through a balanced judgment approach if limits are exceeded, architects typically adhere to this guideline during the initial design stage. In contrast, the ASHRAE guidelines lack strict restrictions since building shape is not viewed as an essential energy-saving pathway.

The overall design of energy-saving pathways significantly influences architectural design. Inspired by these perspectives, this paper reviews and summarizes related research in China to showcase China's achievements in optimizing passive energy savings through building shape to the international academic community, despite many publications being in Chinese. Moreover, extensive research has been conducted on architectural design parameters, such as the SCB or building shape. It is important to note that China's building energy efficiency design standards impose stringent requirements on the overall heat transfer coefficient of building envelopes. Consequently, existing studies have been conducted with adherence to these standards, and thus, this paper does not delve into specific values for heat transfer coefficients in detail.

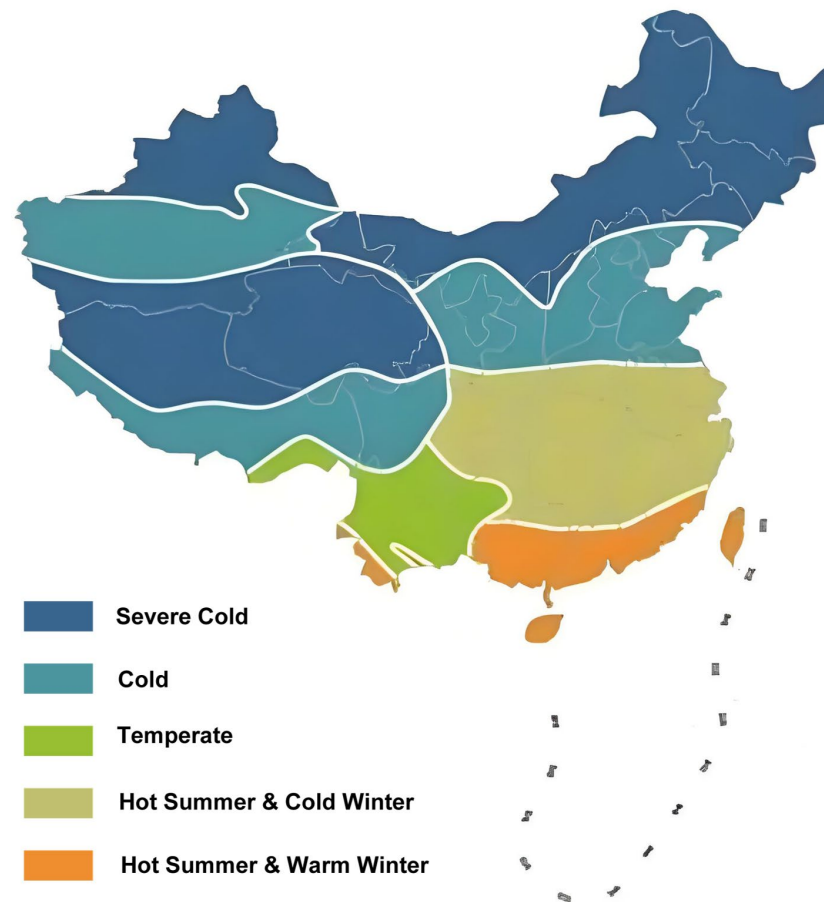


Figure 5. Climate zoning for buildings in China.

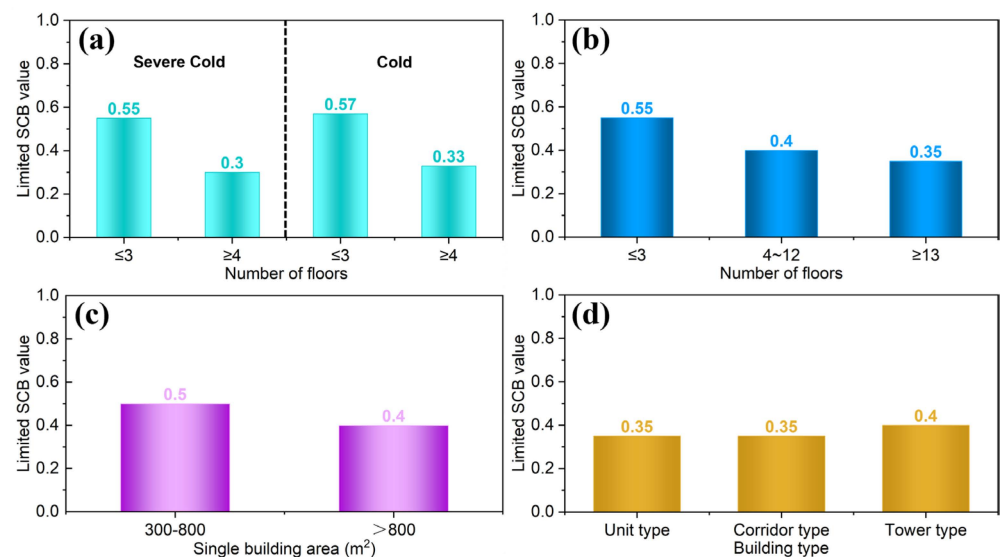


Figure 6. Limited the SCB values in building energy efficiency standards and codes: (a) cold and severe cold regions; (b) hot summer and cold winter regions; (c) hot summer and warm winter regions; (d) hot summer and warm winter regions.

3.4.1. Hot Summer and Cold Winter Regions

In hot summers and cold winters regions, where both heating and cooling loads are significant, research is extensive, as demonstrated in Table 3. For instance, Cao [28] employed DOE-2 software to simulate energy consumption in residential buildings in

Chongqing, representative of such a climate zone. The results showed that a decrease in SCB leads to significant reductions in annual total energy consumption, as well as in heating and cooling energy usage. Notably, the SCB has a more substantial impact on heating consumption than on cooling consumption [74]. Lin et al. [75] selected Shanghai as another representative city and employed DeST-c software to research the influence of the SCB on energy consumption in office buildings. Their findings showed that energy consumption decreases with an increasing SCB and suggested not limiting the system factor in southern regions [76]. Yuan [77], also utilizing DOE-2 software, analyzed the relationship between the SCB and the maximum cooling load in Shanghai, demonstrating a linear increase in maximum cooling load per unit volume with the SCB.

Fu [78] studied a residential building in Nanjing, representative of the hot summer and cold winter zones, using DeST-h software. The results revealed no significant correlation between the SCB and annual heating and cooling energy consumption under intermittent operation mode, leading to a recommendation for a relaxed restriction on the SCB in such residential buildings. Wu [79] investigated the relationship between SCB and building energy consumption in prefabricated buildings in Hefei using EnergyPlus and Design-Builder software. Zang also used EnergyPlus software to study the impact of the SCB on energy consumption in an office building in Wuhan, another typical city in this climate zone, finding that the SCB significantly affects heating load [80]. Quan [81] analyzed the relationship between the SCB and building energy efficiency in residential buildings in Anhui, showing that buildings with an SCB less than 0.4 are more energy-efficient than those with an SCB greater than 0.4. These studies underscore that even within the same climatic zone, the impact of the SCB on energy consumption can vary significantly among different regions or types of buildings.

Moreover, Figure 7 illustrates a comprehensive comparison of the SCB variations documented in the literature, highlighting the diversity in SCB values across different studies. This variability underscores that the conclusions drawn from these studies are primarily qualitative and challenging to compare directly.

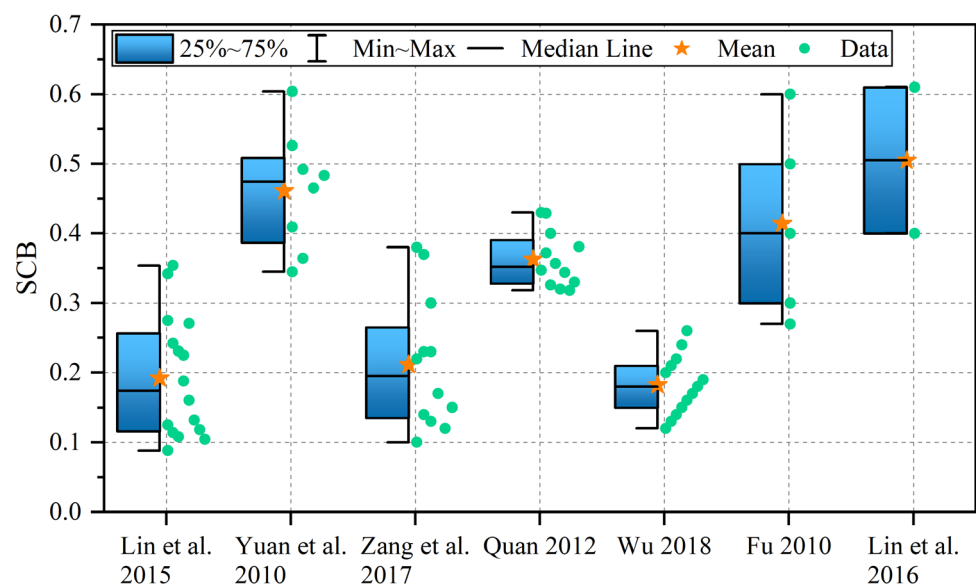


Figure 7. The SCBs in references of hot summer and cold winter regions [75–81].

To advance the field, future research should focus on standardizing the SCB measurements, which would facilitate more precise and meaningful cross-study comparisons. Such standardization could significantly improve the reliability of research outcomes and foster the development of universally applicable conclusions in building shape optimization and energy efficiency.

Table 3. Correlations in hot summer and cold winter regions.

Building Categories	Research Cities	Simulation Software/Measurements	Building Shapes	Correlation	Data Resource
Residential buildings	Shanghai	DesT-c	Tower type; slab type	H (+) C (+)	Lin et al., 2015 [75]
Residential building	Shanghai	eQUEST	Rectangle	H (*) C (−) TEC (−)	Lin et al., 2016 [76]
Residential buildings	Nanjing	DesT-c	Rectangle	Non-energy-saving design: H (+) and C (+); energy-saving design: H (*) and C (*)	Fu, 2010 [78]
Residential buildings	Huaibei, Hefei	DesT	Rectangle	—	Quan, 2012 [81]
Residential buildings	Chongqing	DOE-2	“Y” type “+” type	H (+) C (+) TEC (+)	Cao, 2007 [28]
Residential building	Hangzhou	TRANSYS	Rectangle	Length–width ratio < 1.0: EUI (−); Length–width ratio < 1.0: EUI (+)	Lu et al., 2017 [82]
Public buildings	Shanghai	DOE-2	Rectangle	C (+)	Yuan et al., 2010 [77]
Public buildings	Hefei	EnergyPlus	Cube, regular hexagon, cylinder, conicalness, and frustum	EUI (*)	Wu, 2018 [79]
Public buildings	Wuhan	EnergyPlus	Rectangle	H (+) C (+) TEC (+)	Zang et al., 2017 [80]
Public buildings	Hangzhou	DesignBuilder	U shape	—	Ying and Li, 2020 [83]
Public buildings	Hangzhou; Shanghai	EnergyPlus	U shape	—	Ying et al., 2023 [84]
Public buildings	Nanjing	Measurements	Point type; slab type and the mix type	—	Yang and Wang, 2022 [85]

Note: EUI—energy use intensity; H—heating; C—cooling; TEC—total energy consumption; +—positive correlation; ——negative correlation; *—uncorrelated or unobvious.

3.4.2. Hot Summer and Warm Winter Regions

In hot summer and warm winter regions, specific climate conditions necessitate less stringent insulation during winter, thus reducing the demands on the SCB [86]. Table 4 compares the main studies. Sun et al. demonstrated that in these regions, a larger SCB at a given WWR (window-to-wall ratio) in hotel buildings correlates with higher energy consumption [87]. Wang et al. [88] noted that the SCB has a minimal impact on large office buildings in these climatic conditions. Zhu observed that the SCB also exerts minimal influence on the air conditioning energy consumption of residential buildings in Shenzhen, a typical example of hot summer and warm winter regions [89]. Deng et al. employed DesignBuilder software to simulate the energy consumptions of four different architectural shapes—point, slab, block, and comb—of library buildings across China’s major climatic zones. The findings indicated significant disparities in energy consumption among the same architectural shapes in different climatic zones, with the SCB proving to be a critical parameter for energy reduction in severely cold regions [90]. Feng et al. employed BECS software to examine the heating and cooling energy consumption patterns of a resi-

dential building at various SCBs, indicating that reducing the SCB yields greater energy conservation benefits [91].

Table 4. Correlations in hot summer and warm winter regions.

Building Categories	Research Cities	Simulation Software	Building Shapes	Correlation	Data Resource
Public buildings	Shenzhen	Dest	Rectangle	EUI (+)	[87]
Public buildings	Shenzhen	eQuest	Rectangle	EUI (*)	[88]
Residential buildings	Shenzhen	DOE-2	Rectangle	C (*)	[89]
Public buildings	Guangzhou	DesignBuilder	Point, block, comb, and slab	TEC (*)	[90]
Residential building	Not mentioned	BECS	Rectangle	H (+)	[91]
				C (+)	
				TEC (+)	

Note: EUI—energy use intensity; H—heating; C—cooling; TEC—total energy consumption; +—positive correlation; *—uncorrelated or unobvious).

3.4.3. Cold and Severe Cold Regions

China's building energy efficiency standards impose stringent restrictions on the SCB for buildings in severely cold or cold regions, where extensive research has been conducted. Table 5 compares the major studies from China, along with a selection of studies from other countries. Shandong, representative of a cold region, was the focus of a study by Xue et al. who used DesignBuilder software to perform a sensitivity analysis of the main factors affecting energy consumption in high-rise buildings. They pointed that designs should prioritize minimizing the SCB, recommending a range of 0.221 to 0.236 [92]. Zhang used DesignBuilder software to examine the quantitative relationship between architectural body design parameters—plan shape, length, width, and height—and the energy consumption of residential buildings in Tianjin. The results indicated that there is no consistent ratio between energy consumption and the SCB in residential buildings in cold regions [93]. Ren et al. also explored the relationship between the SCB and energy consumption in Tianjin, finding that while the two are not directly proportional, optimizing the SCB can still be beneficial [94]. Liu et al. employed DesignBuilder to study the correlation between the layout of high-rise office buildings in Beijing and their energy consumption, highlighting that the SCB's impact is primarily through the loads formed by the building envelope [95]. Huang et al. analyzed the impact of building plan shape on the air conditioning cooling load in Xuzhou, finding no inherent link between cooling load and the SCB [96]. Xie argued that in northern cold regions, architectural design should first identify the critical point of energy consumption variation before appropriately increasing related dimensions [97]. Zhao et al. explored the relationship between the SCB and building dimensions in various types of university library buildings in Changchun, a severely cold region, but did not provide details on changes in energy consumption [98]. Gao et al. conducted a Morris sensitivity analysis to examine the impact of the SCB on load and the sensitivity of its influencing parameters in Beijing, revealing a clear positive correlation between the SCB and heating energy consumption when single factors vary, while the relationship becomes less apparent under the influence of multiple factors [99].

3.4.4. Summary and Comparison

In various climatic zones, scholarly comparative studies demonstrate that heat transfer, induced by temperature differentials, escalates with the increased external surface area of buildings. Most research focuses on building exteriors as key heat-loss components. Consequently, academic consensus recommends reducing the external surface area to minimize heat loss and reduce energy consumption when the building volume is fixed [32]. This principle has been codified as a mandatory clause in China's building regulations [74], thereby influencing the building shape factor right from the conceptual design stage. On the other hand, the relationship between building shape and energy consumption differs

significantly across China's various climatic zones; even within a single climatic zone, buildings of different shapes may exhibit diametrically opposed outcomes. This complexity underscores the imperative for region-specific and shape-specific approaches to building design and energy optimization.

From our comprehensive review of the studies mentioned, it is clear that even among the same building types, such as residential or public buildings, scholars often arrive at different conclusions, and at times, these conclusions can be entirely opposing. In contrast, research findings in China tend to exhibit greater uniformity compared to climate zones in other countries. This uniformity can largely be attributed to the similarities in research paradigms among Chinese scholars. Moreover, most simulation studies conducted by Chinese researchers operate under the premise of meeting stringent energy-saving design standards, particularly concerning thermal design parameters like the heat transfer coefficient of exterior walls. This leads to higher comparability of findings and a greater consistency of patterns than those observed in studies from other regions.

However, despite these advantages, formulating a unified pattern for inclusion in the conclusions remains a significant challenge. Therefore, this paper also recommends that future research on building shapes adopt a unified research paradigm or standardized reference buildings. This approach could enhance the comparability of findings and help in establishing more consistent conclusions across different studies.

Table 5. Correlations in cold and severe cold regions.

Building Categories	Research Cities	Simulation Software	Building Shapes	Correlation	Data Resource
High-rise residential buildings	Qingdao	DesignBuilder	Rectangle	EUI (+)	Xue and Xiang, 2021 [92]
Residential buildings	Tianjin	DesignBuilder	Rectangle; square; circle; triangle	H (*); C (*); TEC (*)	Zhang et al., 2017 [93]
Not mentioned	Tianjin	DesignBuilder	Rectangle, serrated shape, I shape, zigzag, ellipse, circle, and square	TEC(*)	Ren et al., 2015 [94]
High-Rise office buildings	Beijing	DesignBuilder	Polygonal line plane; dot shape plane; linear plane; plane with a big atrium	H (+); C (*)	Liu et al., 2015 [95]
Not mentioned	Xuzhou	Not mentioned	Rectangle; square; circle	C (*)	Wei et al., 2010 [96]
Residential buildings	Not mentioned	Not mentioned	Rectangle; Y shape; U shape; + shape; L shape	H (+)	Xie, 2018 [97]
Office buildings	Beijing	Simlab	Rectangle; square; U shape; + shape; L shape	H (+);C (*); TEC (*)	Gao and Zhu, 2020 [99]
Residential buildings	Harbin	Open studio EnergyPlus	Line shape L shape	TEC (+)	Leng and Xiao, 2020 [100]
Residential buildings	Ghardaia	Self-programmed	Rectangle	—	Bekkouche et al., 2013 [101]
Not mentioned	Malaysia	Autodesk Ecotect	Rectangle; U shape; L shape; T shape; ellipse; circle; courtyard; square	C (—)	Rashdi and Embi, 2016 [102]
School buildings	Auckland	Measurement	57 sample schools	H (+)	Su, 2016 [103]
Office buildings	Shenyang	Dest	S roundness, square, and rectangle	H (—)	Feng et al., 2016 [104]
Residential buildings	Western Sichuan	Energyplus	Rectangle	IAT (+)	Ren et al., 2023 [105]
Office buildings	Harbin	Energyplus	Slab-type and point-type	TEC (+)	Leng et al., 2020 [106]
School buildings	Harbin, Beijing	DesignBuilder	Point, slab, block, and comb	TEC (*)	Deng et al., 2020b [90]
School buildings	Jinan	NSGA-II algorithm	U shape	—	[107]
Library buildings	Beijing	DesignBuilder	Point, block, bomb, and slab	TEC (+)	[90]

Note: EUI—energy use intensity; H—heating; C—cooling; TEC—total energy consumption; IAT—indoor air temperature; +—positive correlation; ——negative correlation; *—uncorrelated or unobvious.

4. Simulation Techniques or Methodologies

When addressing building shape optimization, most scholars employed the mathematical algorithms to construct models using a “Black box” approach [17].

4.1. Traditional Machine Learning Models

4.1.1. Artificial Neural Networks

Artificial Neural Networks (ANNs) are sophisticated computational models inspired by the structure and functioning of biological neural networks [108–111]. They are designed to process complex information and tasks by dynamically adjusting their connection structures and weights. Figure 8 illustrates a typical structure of an ANN, which comprises an input layer, hidden layers, and an output layer. In building shape optimization, the output layer commonly includes metrics such as heating energy consumption, cooling energy consumption, and energy consumption per unit area. The input layer can vary based on the specific parameters being analyzed.

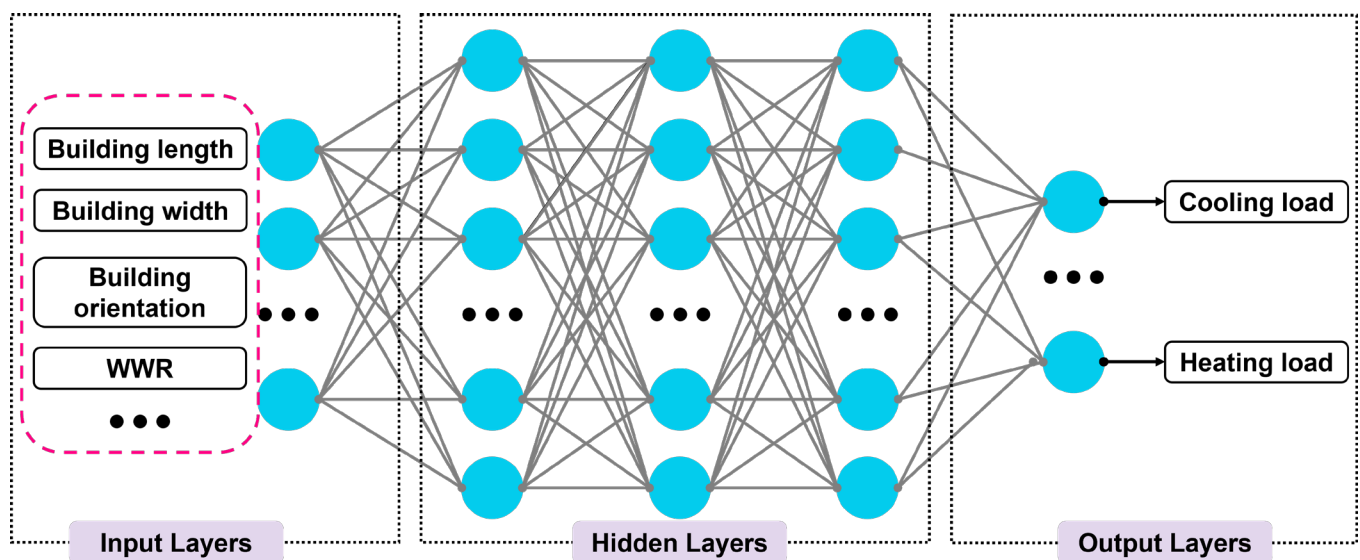


Figure 8. The typical ANN architecture for building energy consumption prediction.

4.1.2. Regression Models

Regression models are widely utilized in machine learning for predicting and elucidating the relationships between variables [112,113]. Regression models are particularly favored due to their simplicity, ease of use, and efficiency, leading to their extensive applications in the building energy efficiency field. Table 6 summarizes studies related to building shapes and their influences on energy consumption.

Table 6. Summary of building energy consumption prediction using regression models.

Author	Formula	Parameters Related to Building Shape
Hygh et al., 2012 [114]	$y(x_1, x_2, \dots, x_n) = \beta_0 + \sum_{j=1}^n \beta_j x_j$	Aspect ratio, number of stories, and depth
Catalina et al., 2008 [115]	$y = \alpha_1 + \sum_{i=1}^5 \beta_i X_i^2 + \sum_{i=1}^5 \gamma_i X_i + \sum_{i=1}^4 \delta_i X_i X_{i+1} + \sum_{i=1}^3 \varepsilon_i X_i X_{i+2} + \sum_{i=1}^2 \zeta_i X_i X_{i+3} + \sum_{i=1}^1 \sigma_i X_i X_{i+4}$	Shape factor
Korolija et al., 2013 [116]	$y(x_1, x_2) = a + b \cdot x_1 + c \cdot x_1 + d \cdot x_1^2 + e \cdot x_1 \cdot x_2 + f \cdot x_2^2$	Building type and glazing ratio
Asadi et al., 2015 [117]	$y = \sum_{i=1}^n \beta_i x_i$	Building shape

Presently, the most commonly employed model is the multiple regression model, which provides researchers with the flexibility to select the regression formula that best aligns with their data. Frequently, researchers base their model selection on the R^2 value, which indicates the proportion of variance that the model explains. However, the application of regression models is limited by several underlying assumptions, including linearity, normality of errors, and independence. Additionally, linear regression often struggles to adequately capture nonlinear relationships.

Consequently, while regression models offer valuable insights into the analysis of building shapes and their associated energy consumption, researchers must remain vigilant regarding the limitations inherent in these models. Exploring alternatives or augmentations to traditional regression techniques, such as incorporating nonlinear models or leveraging machine learning approaches, may yield more robust and insightful findings in future research.

4.2. Deep Learning Model

ANNs with more than three hidden layers are classified as deep learning models, which represent a more advanced category of neural networks with enhanced capabilities. Table 7 summarizes various studies that have utilized ANNs for optimizing building shapes. Overall, ANNs excel at capturing and learning complex nonlinear relationships and have the capacity for adaptive learning. This adaptability allows them to model intricate patterns that may elude simpler methodologies. However, it is essential to recognize that ANNs operate as black-box models, meaning their internal workings and decision-making processes are often not transparent to users. Additionally, ANNs necessitate a substantial amount of labeled training data; a lack of sufficient data can lead to overfitting (where the model learns the noise rather than the signal) or underfitting (where the model is too simplistic to accurately represent the underlying trends).

Table 7. Summary of building energy consumption prediction using the ANN method.

Author	Dataset Source	Type of the ANN	Input Variables	Output Variables
Li et al., 2019 [118]	EnergyPlus simulations	Back propagation neural network	Length, width, WWR, storey height, storey number, and room number	Cooling energy and heating energy
Pittarello et al., 2021 [119]	EnergyPlus simulations	Deep feedforward artificial neural networks	Length, number of stories, azimuth, and window area fraction	Heating energy demand and cooling energy demand
Askar et al., 2023 [120]	AutoCAD MEP 24.2	Multi-layer perceptron and radial basis function	Relative compactness	Cooling load and heating load
Samardzioska et al., 2021 [121]	58 real-designed buildings	General regression neural network	Shape factor and areas of the envelope component	Total energy consumption
Elbeltagi and Wefki, 2021 [122]	Software simulations	Back propagation neural network	Length, depth, and height	Predicted energy use intensity

In summary, while ANNs present powerful capabilities for modeling complex relationships in building shape optimization, researchers must be mindful of their limitations. Ensuring adequate and high-quality training data is essential to effectively leverage ANNs' full potential and mitigate issues such as overfitting and underfitting. Careful consideration of these factors can significantly enhance the robustness and reliability of ANN applications in the field of building energy efficiency.

4.3. Optimization Algorithms

4.3.1. Genetic Algorithms

Genetic algorithms (GAs) are among the most extensively utilized optimization techniques in architectural design. Wang et al. [123], for example, applied a multi-objective GA to optimize green building designs, focusing on the aspect ratio and orientation of a fixed-area rectangular building. Similarly, Jin et al. [124] leveraged GAs to optimize irregular building shapes with the aim of minimizing thermal loads. Touloupaki et al. [125] also implemented GAs for the parametric optimization of irregular building forms, targeting energy consumption reduction. Furthermore, Chi et al. [126] combined a multi-objective GA with digital genetic maps to enhance the performance of university dormitory buildings, whereas Li et al. [127] utilized a multi-objective GA to optimize daylighting and geometric dimensions in underground office settings.

GAs are noted for their robust global search capabilities and reduced susceptibility to local optima entrapment. Nonetheless, they are computationally intensive and sensitive to the selection of parameters such as population size and mutation rates. Their precision in building shape optimization is sometimes questioned. In contrast, Feng et al. [9] explored an improved manta ray foraging optimization algorithm for optimizing residential building shapes. This innovative bionic swarm algorithm excels in optimization and rapid convergence but necessitates a basic understanding of mathematics from its users.

Consequently, genetic algorithms and innovative methods like the manta ray foraging optimization algorithm are valuable tools in architectural optimization. However, researchers must carefully evaluate their applicability and limitations in specific contexts, particularly regarding building shape optimization.

4.3.2. Taguchi Method

Recent studies have increasingly applied the Taguchi Method to optimize architectural building shapes. Developed by Japanese engineer Genichi Taguchi, this statistical method enhances process optimization in manufacturing by determining the most effective combinations of factors through orthogonal experiments and analyzing signal-to-noise ratios.

For instance, Zahraee et al. [128] utilized the Taguchi Method to optimize materials for windows, ceilings, and walls in a two-storey Malaysian building, aiming to reduce energy consumption effectively. Similarly, Hwang et al. [129] employed the Taguchi variance method to streamline decision-making processes across various building design parameters, including building shape. Lin et al. [130] introduced a triple optimization approach to refine building shape designs and enclosure attributes while factoring in thermal and visual comfort and energy efficiency.

The Taguchi Method's primary strength lies in its ability to enhance quality and cut costs by minimizing the experimental trials necessary. Nonetheless, its application might be constrained in contexts requiring exceptionally fine precision, as it may not fully capture the intricacies of highly complex systems. Consequently, while the Taguchi Method offers substantial benefits for optimizing architectural forms, assessing its suitability for specific scenarios remains essential.

4.4. Summary

Other methodologies, such as principal component analysis [131], self-programmed calculation model [132], and even platforms like Google Earth [133,134], are also utilized to building shape optimization. While these mathematical methods enable the extraction of specific rules from the data, they often require substantial datasets. Although these approaches yield key findings, they may not fully elucidate the underlying physical mechanisms. Therefore, employing traditional methods for mechanistic analysis rooted in physical principles becomes essential for a comprehensive understanding.

5. Discussion and Future Directions

5.1. The Importance of Experimental Validation

Simulation techniques play a critical role in the field of building energy efficiency [135]. As most scholars have not independently simulated energy consumption based on building shapes as a specific research focus, the methods reviewed in this paper reflect only the mainstream approaches relevant to shape research.

A systematic literature review reveals that simulation methods can be categorized into two primary types. The first category pertains to the simulation of building energy consumption, which was discussed earlier in the manuscript. This area predominantly utilizes energy consumption simulation software tools such as Energy+ [129], DeST [136], DOE-2 [137], and DesignBuilder [138]. While these commercial software tools are grounded in algorithms based on physical principles [139], users generally only need to input parameters, leading to a superficial understanding of the core mechanics behind energy consumption simulation. This effectively renders these tools as “black box” models.

Conversely, some researchers opt for custom programming to manually calculate building energy consumption [140]. These custom programs are considered “white box” models due to their transparency, but they may encounter limitations in accuracy, calculation speed, and visualization when compared to commercial software. In conclusion, while both approaches operate on the principle of energy conservation, they each carry distinct advantages and disadvantages.

Both commercial software and energy consumption simulations calculate each individual case sequentially. When attempting to discern patterns through numerous computational cases, this method proves to be inefficient. As a solution, scholars have proposed the utilization of data-driven methods [141] and mathematical techniques. Emerging tools such as deep learning and machine learning have become increasingly popular in this context. For instance, artificial neural networks represent typical machine learning tools; however, once the number of hidden layers exceeds three, these networks transition into deep learning. Additionally, many multiple regression models also fit within the broader category of machine learning.

Furthermore, optimization methods like genetic algorithms and their improved variants are frequently applied to shape optimization with the goal of minimizing building energy consumption. While these methods demonstrate excellent computational efficiency, their reliability is heavily contingent on the scale and quality of the underlying data. If the energy consumption simulation data lacks sufficient accuracy, the robustness of the results may be compromised.

To address these challenges, this paper proposes a framework that integrates actual measurement data with machine learning algorithms. This integration aims to enhance the reliability and applicability of simulation results, ultimately leading to more effective and precise energy conservation strategies in building design.

5.2. The Limitations of the SCB

During both heating and air conditioning periods, buildings experience distinct load compositions that significantly influence energy consumption patterns. When in heating mode, the external surfaces of a building play a crucial role in absorbing solar radiation to mitigate indoor heating loads, effectively acting as heat-gaining components. This phenomenon underscores the importance of utilizing solar energy, particularly for passive buildings that aim to reduce heating energy consumption through natural means.

However, the established shape coefficient of building (SCB) tends to focus solely on the geometric parameters of a building, primarily reflecting heat transfer mechanisms driven by temperature differences across the building's envelope. This narrow focus fails to account for critical factors such as solar radiation, building orientation, and the radiative properties of envelope materials, all of which have substantial impacts on energy consumption. For example, in regions like Tibet and the western high-altitude areas of Sichuan, where solar energy is plentiful, the intense solar radiation and extended daylight

hours can effectively mitigate heating demands. In such contexts, adhering to the current SCB limitations may not support the optimum harnessing of solar energy, ultimately contributing to higher energy consumption.

Furthermore, regardless of the method used to characterize the SCB or other relevant indices, a common limitation is the ambiguity surrounding the physical meanings of these metrics. The current methodologies for determining these indices do not incorporate energy consumption variables into their formulations, making it challenging to understand how different design choices will influence energy performance.

To address these issues, it is essential to revise the definition and calculation of the SCB and related indices to include considerations for energy consumption, solar radiation, and the thermal properties of the building materials. Doing so would provide a more holistic view of how building design impacts energy efficiency, particularly in regions with varying climatic conditions. This approach would not only enhance the effectiveness of energy optimization strategies but also support a more comprehensive understanding of the interactions between building form, environmental factors, and energy consumption. Ultimately, this evolution in the understanding of the SCB could promote more sustainable architectural practices tailored to harness solar energy and improve overall energy performance.

5.3. The Correlation Between Building Shape and Design

Compared to other critical parameters in architectural design, the SCB not only embodies the architect's intent but also tends to remain relatively static from the initial design stages through to the operational stage of the building. This consistency results in certain challenges, particularly in the design and implementation of heating and air conditioning systems, which are developed based on a predetermined SCB.

The current definition of the SCB fails to capture the essential contradictions that exist in building energy consumption. This limitation can pose constraints on designers during the initial conceptual design phase, particularly as they strive to comply with regulatory energy efficiency limits. It can also impede the ability to modify heating, ventilation, and air conditioning (HVAC) systems later on, creating barriers to the effective promotion of architectural diversity.

To address these challenges, it is essential to explore the possibility of relaxing SCB-related restrictions in a context-sensitive manner. Different regions have unique climatic conditions and regulatory frameworks that can significantly influence building energy performance. By allowing for greater flexibility in SCB definitions and applications, designers can experiment with more diversified architectural designs that align better with regional energy consumption patterns and aesthetic objectives.

Encouraging this kind of adaptability in architectural design can foster innovation while preserving energy efficiency. It is important for regulatory bodies to consider these factors to support a broader range of architectural expressions and to enhance the overall sustainability of the built environment. By doing so, designers can create buildings that not only meet energy performance standards but also enrich the architectural landscape.

6. Practical Implications and Recommendations

Drawing from an in-depth analysis of the interplay between building shape and energy consumption, architects are advised to consider the following practical recommendations during the early design phase:

- Severely cold and cold regions: adopting a cylindrical building shape is beneficial for enhancing thermal performance;
- Temperate regions: the impact of building shape on energy consumption is minimal, allowing for greater design flexibility without stringent shape constraints;
- High-altitude regions: given the prevalence of solar radiation and the significance of heat load, architects are encouraged to explore diverse building shapes to optimize energy efficiency [142].

Estimating building energy consumption with the SCB remains advisable as it provides a valuable metric for preliminary assessments. Additionally, integrating advanced artificial intelligence methods for early energy consumption estimation is recommended. By adhering to these recommendations, architects can make informed design decisions that promote energy efficiency and sustainability in their projects.

7. Conclusions

This paper focused on optimizing building design parameters, specifically targeting the coupling relationship between building shape and energy consumption. The objective is to elucidate the impact mechanisms of building shape on energy consumption for environmental regulation. A systematic review of the methods used to characterize building shape, the mechanisms through which shape influences energy consumption, and the simulation techniques was conducted. Additionally, the paper explores the challenges and development trends in shape decision-making during the early stages of building design. The research conclusions are as follows:

- (1) The building shape coefficient, although widely used for characterizing shape, has clear limitations due to its lack of precise physical significance. Future research should focus on further optimizing the shape coefficient;
- (2) Rectangular, squared, L-shaped, and U-shaped buildings are the most common forms studied. Future research should emphasize continuous simulation of shape parameters and irregular shapes;
- (3) Existing simulation software, while capable of quantifying impacts, is inefficient due to the need for case-by-case analysis. Future efforts should consider large-scale, multi-parameter computer simulations;
- (4) The impact of building shape on energy consumption across different climate zones remains insufficiently understood;
- (5) Preliminary results reveal that building shape significantly impacts heating energy consumption in cold regions. In tropical regions, building shape plays a crucial role in cooling energy consumption. However, in temperate regions, the influence of building form on both heating and cooling energy consumption appears to be less significant.

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