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# VARIABLE HOUSEHOLD DESIGN AND ADAPTABILITY TO THE BUILT ENVIRONMENT: AN ANALYSIS OF IMPROVING THE ECO EFFICIENCY OF RESIDENTIAL DESIGNS

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***Abstract:*** *This study scrutinizes the enhancement of eco-efficiency in residential design through the lenses of variable house type design and the adaptability of the built environment. It delves into the favourable ramifications of variable house type design on resource and energy utilization, delineates the pivotal role of built environment adaptability in environmental preservation and resource optimization, and expounds on the combined impacts of variable house type design and built environment adaptability. The analysis reveals that variable house type design can mitigate resource wastage, optimize indoor space utilization, curtail energy consumption, and enhance energy efficiency through flexible spatial layout and multifunctionality. Moreover, the concept of built environment adaptability underscores the harmonious integration of buildings with their surroundings, leading to reduced natural resource consumption and fostering sustainable development via green building practices and ecological landscape design. The synergy between these two approaches optimizes eco-efficiency based on the specific environmental context of the building, a benefit that traditional methods cannot achieve. Variable house design offers greater spatial flexibility and potential for adaptability to the built environment, thereby encouraging the use of more environmentally friendly and energy-efficient building materials. Solar and wind energy, especially, can reduce their consumption rate and increase the range of available energy. Together, variable house type design and building environmental adaptability have a comprehensive impact on improving the eco-efficiency of residential design and provide important ideas and directions for future residential design.*

***Keywords:*** *Variable House Types, Built Environment Adaptability, Improvement, Residential Design, Eco-Efficiency, Energy Consumption*

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## 1. Introduction

Conventional residential design suffers from several problems related to eco-efficiency. Traditional residential design, due to spatial utilization issues, often results in insufficient lighting, poor ventilation, and inadequate insulation after the completion of housing construction. The oversight in considering environmental characteristics during material selection leads to resource and energy wastage, along with environmental degradation, undermining sustainability (Song et al., 2024; Umoh et al., 2024). Furthermore, extensive development and construction activities disrupt the natural landscape and disrupt the equilibrium of the surrounding ecosystem, resulting in diminished biodiversity and degradation of the ecological environment. Traditional housing design exhibits limited adaptability to accommodate residents' needs and environmental fluctuations, rendering it insufficiently sustainable to confront forthcoming environmental shifts and challenges. As depicted in Figure 1, illustrating the correlation between global carbon dioxide emissions and the progression of urbanization from 1800 to 2020, carbon dioxide emissions demonstrate an escalating trend over time alongside the rapid pace of urban expansion. Consequently, the imperative to enhance housing eco-efficiency becomes increasingly urgent (Bauer et al., 2009; Raith & Estaji, 2020).

Carbon dioxide is an important greenhouse gas that benefits the Earth's ecosystems in maintaining circle in ecosystem, but excessive emissions of carbon dioxide can have negative impacts on the environment and human health particularly in climate change and biodiversity (Feng et al., 2024). The adaptability inherent in variable house type design enables accommodation of diverse resident needs and evolving family structures, thereby facilitating personalized living spaces and minimizing waste in residential design. Furthermore, when coupled with flexible layout design and architectural and environmental adaptability, this approach mitigates energy wastage, enhances building energy utilization efficiency, integrates the building's energy system with the surrounding environment, and diminishes environmental impact. The resultant outcome is a building that progressively approaches a zero-energy design. A zero-energy building employs efficient building design, technology, and renewable energy systems to attain a net-zero energy consumption state. Such structures are capable of generating renewable energy that offsets their energy consumption, thereby achieving energy self-sufficiency or net-zero energy consumption (Wilberforce et al., 2023).

In traditional building design, houses need to be designed according to engineering and environmental characteristics. For example, residential buildings in hot areas need to consider their ventilation characteristics and materials such as lightweight timber are usually used. However, timber has a short lifespan, and human swarming requires large amounts of timber, leading to a reduction in the number of trees in the area, soil erosion, and damage to the environment (Attiya et al., 2024). Therefore, it is essential to explore the impact of improving the eco-efficiency of residential design in terms of both variable house design and adaptation to the built environment. This will help to improve the ecological problems in existing residential design and promote the residential sector towards more sustainable development. By exploring new design concepts and methods, it is possible to harmonize residential design with the natural environment, improve energy efficiency, reduce resource waste, protect the ecological environment, and at the same time, provide residents with a more comfortable, healthy, and sustainable living environment (Oktarini, 2018; Wang et al., 2024).

Using case studies and field research, this paper examines how variable house design and adaptation to the built environment affect and improve the eco-efficiency of homes through data collection and analysis method

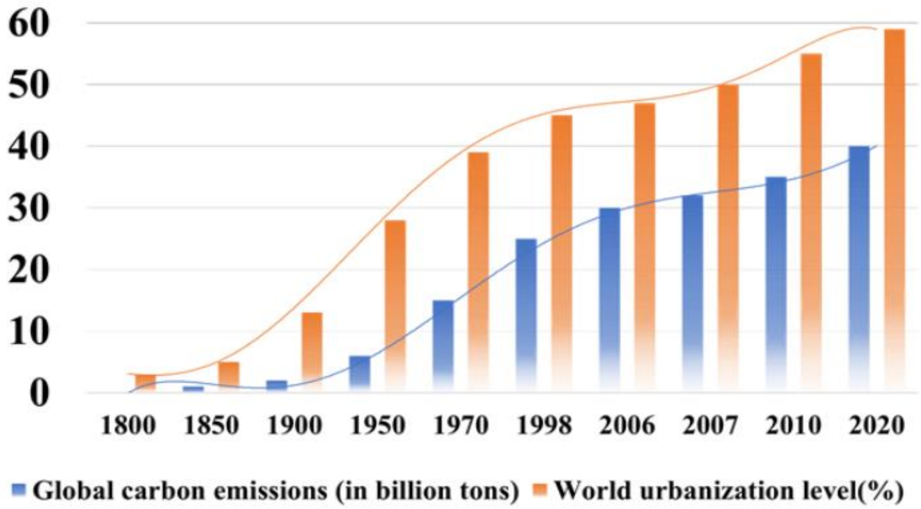


*Figure 1: World carbon dioxide emissions and level of urbanization (Bauer et al., 2009; Raith & Estaji, 2020)*

## 2. Concepts and Principles of Variable Household Design

### 2.1 Concepts and Advantages of Variable House Design

Variable house type design refers to a design concept that is flexible and adjustable in terms of building structure and spatial layout. The principle is that by using movable or adjustable partitions, furniture, walls, and other elements, the layout and function of the living space can be adjusted and changed according to the needs and lifestyles of the residents. The advantages of this design concept are reflected in the following aspects (Carrasco et al., 2018; Tarashkar et al., 2024; Y. Wang et al., 2019)

Flexibility and Diversity: Variable house design can meet the individual needs of different residents, making it easy to adapt residential space to different family structures, lifestyles, and phases. Through flexible design, occupants can re-plan and re-utilize the space according to actual needs, thus better utilizing the versatility and flexibility of the space.

Improvement of Space Utilization Efficiency: Variable house type design has the capacity to optimize spatial utilization and mitigate inefficiencies inherent in conventional fixed layouts. By offering flexible adjustments to spatial function and layout without necessitating alterations to the building structure, it enhances space utilization efficiency and diminishes construction costs (Long, Huang, & Zhang, 2006).

Adapting to Family Changes: As family structures evolve and members undergo changes, the rigid design inherent in traditional fixed house types fails to adequately adapt to residents' evolving needs. Variable house type design, on the other hand, offers flexibility to accommodate shifting family dynamics, thereby better aligning with residents' individual requirements and prolonging the building's service life.

Enhanced Comfort and Adaptability: Variable floor plan design provides a more personalized and comfortable living environment, enabling occupants to adjust the space to their needs and better adapt to changes in the living environment and community.

In sum, variable house type design furnishes residents with augmented flexibility, diversity, and personalized living spaces, underscoring its versatility, variety, and adaptability. This approach enhances the efficiency and comfort of building utilization, representing an innovative concept of profound significance in the realm of residential design.

### 2.2 Types of Variable Household Design

In Figure 2 (Tan, 2013; Tang, 2010), the change in global building area from 1996 to 2012 is shown, from which it can be seen that urban buildings and public buildings increased from 1996 to 2012, while rural buildings decreased, and urban residential buildings did not have much change in house type due to the limitation of topography, which could not contribute to the enhancement of eco-efficiency. For variable house type design, there are various types, which can be categorized into several different types mainly based on their variability and scope of application. The following are some common types of variable house type design.

Adjustable Interior Space: This form of variable house design facilitates adaptable living spaces through movable walls, partitions, furniture, and other elements. Residents have the autonomy to alter the layout and function of interior spaces based on their preferences. For instance, they can partition a room into two separate spaces or merge multiple smaller rooms into a larger area, thereby enabling versatile space utilization.

Variable Exterior Design: This type of variable house design mainly refers to the variability of the building's exterior. Through the use of adjustable external components, façade materials, etc., the appearance of the building can be adjusted according to the needs and environmental changes to adapt to different climatic conditions, seasonal changes, or the personalized preferences of the occupants (Y. Wang et al., 2019; Yang, L. & Yang, Y., 2019).

Intelligent Home Design: The development of intelligent home technology has made variable house design more convenient to realize. Through intelligent control systems, such as adjustable lighting, temperature, ventilation, etc., residents can intelligently adjust the entire living environment according to their needs, thus realizing flexible living space design.

Modular Design: Modular design involves partitioning building space into discrete modules that can be interchanged and arranged according to requirements, thereby facilitating a flexible house-type design. This approach finds widespread application in residential constructions, enabling the combination of various modules to align with residents' needs and family structures, thereby achieving a customized spatial layout.

Adjustable Functional Areas: This type of variable house design refers to the setting up of multi-functional areas inside the building, which can be flexibly divided and adjusted according to needs. For example, a space can be used as both a living room and quickly transformed into a studio or bedroom to meet different functional needs (Song et al., 2024; Umoh et al., 2024).

These types of variable house designs can meet the needs of different residents, improve the efficiency of building use, reduce unnecessary resource consumption, and thus achieve a more flexible, diverse, and personalized living space design.

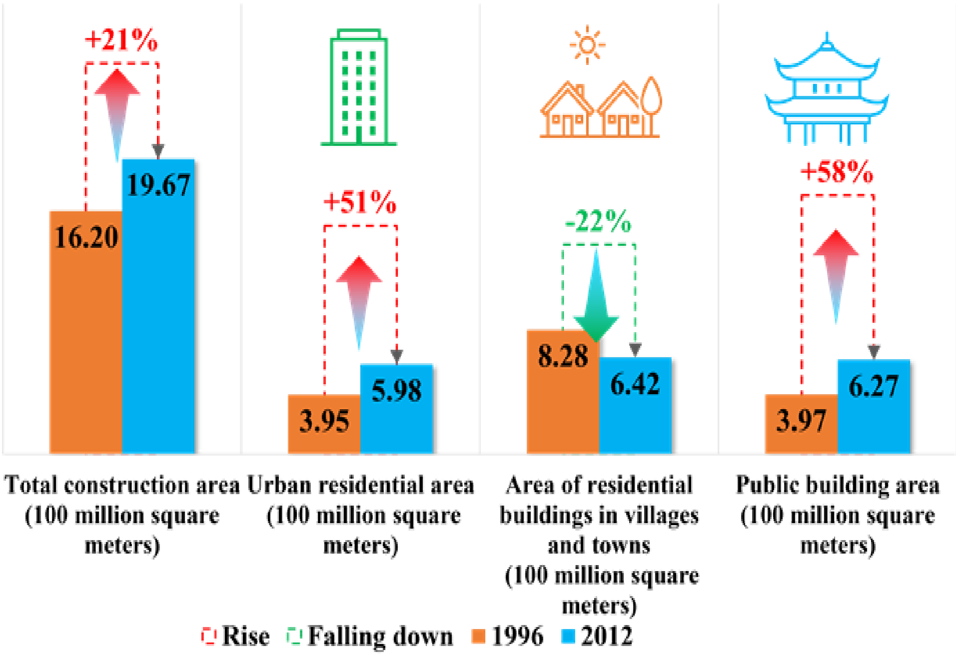


*Figure 2: Changes in floor space from 1996 to 2012 (Tan,2013; Tang, 2010)*

## 3. Built Environment Adaptation and Eco-Efficiency

### 3.1 The Concept of Adaptability to the Built Environment

The adaptability of the built environment aims to create a spatial environment that is efficient in the use of resources and energy, energy-saving and environmentally sustainable, architecturally flexible, and harmoniously coexisting with its surroundings, and to provide a healthy and comfortable living environment for human beings. Adaptive design maximizes the life cycle of buildings by studying their coping strategies during different life cycles, as well as component, spatial, environmental, and climatic adaptations. Adaptive design emphasizes the interaction between buildings and the environment, minimizes the impact on the environment, and reduces irreversible damage to the Earth's ecology.

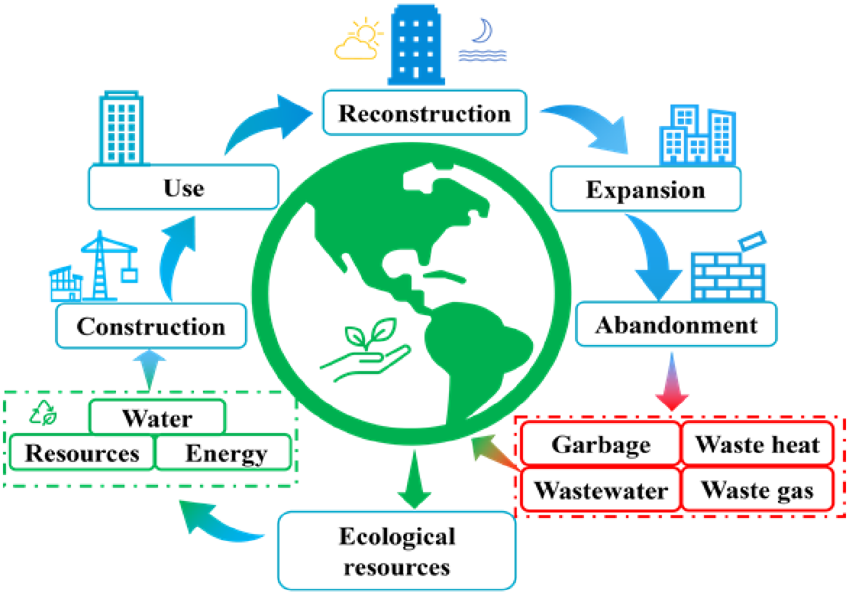


*Figure 3: Impact of the built environment on the Earth's ecology*

### 3.2 The Impact of Built Environment Adaptation on Eco-Efficiency

The influencing factors of the eco-building system are demonstrated in Figure 4 (Song et al., 2024; Umoh et al., 2024). It is evident from the figure that the eco-building system is impacted by factors such as land saving and outdoor environment, resource utilization, water utilization, material resources, indoor environmental quality, and operation and management. Because of the differences in function and application of different building types, they are affected in different ways. Residential buildings, in terms of function, are influenced by the occupants' daily lives, family activities, aesthetics, etc., and have greater functional flexibility and require better privacy than other types of buildings. In the use scenario of residential buildings, there are a series of basic forms of change: removal and addition of components, moving and replacing, and categorizing them according to the different behaviours of the occupants. Other uses of space, such as medical, commercial, office, and educational buildings, are more dynamically influenced. The library, for example, is traditionally a space for storing books or for quiet study, but due to a variety of factors such as user needs and social and technological influences, it has evolved into a wider range of scenarios of use: meeting, working and socializing, as well as the components that are added to satisfy these functions: cafeterias, conversation and discussion forums, computer labs, and so on. The use of scenario simulation allows for the prediction of such dynamic influences and the gathering of information on the causes of change in different building types. Scenario planning for different building types will better prepare the building for an unpredictable future, with specific scenarios adapted to the nuances of the users' needs, thus enabling extended adaptation to possible behaviours. Therefore, when designing for adaptability, it is not only necessary to consider the functional needs of the current building type but also to generalize the influencing factors to establish a certain degree of adaptive predictability. This integrated design concept makes buildings more environmentally friendly and energy efficient and helps to improve the quality of life for occupants (Moraes et al., 2019; X. Wang et al., 2019).

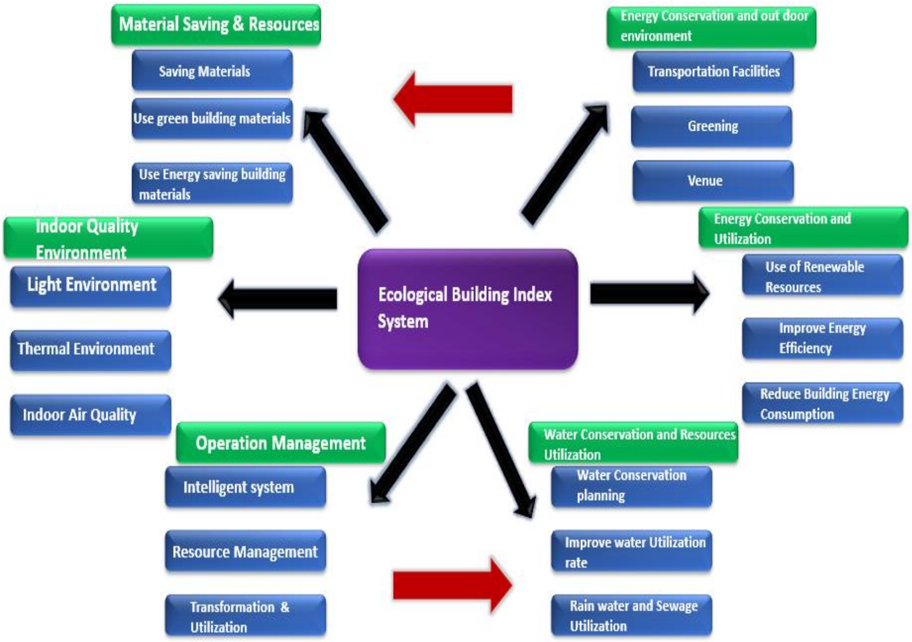


*Figure 4: Relationship map of building ecological indicators*

### 3.3 The Relationship Between Variable House Design and Adaptation to the Built Environment

Variable house design is closely linked to the adaptability of the built environment, with both playing a synergistic role in enhancing the eco-efficiency of residential design. Functionality is a critical factor that directly influences user satisfaction during a building's usage. The constant repetition of changes in a given space is mainly reflected in changes in spatial qualities that may reduce the user experience and longevity. The active participation of users is essential for adaptive retrofitting and adaptive design in the early stages of a program. Professionals, such as medical staff, are more aware of the conveniences and inconveniences in the use of a space, which helps designers to consider market needs broadly. Buildings cannot be physically modelled and change over time, so it is important to focus on getting feedback from existing buildings and making improvements. Post-occupancy evaluations and other performance monitoring techniques are becoming more common, but obtaining feedback from using the building is still uncommon. Adaptive design can guide users, but it also requires a more open approach to understanding buildings and an awareness of the complexity and importance of multi-participation. This flexibility and increased efficiency in resource utilization are common focuses of both built environment adaptability and variable house design. As illustrated in Figure 5 (Song et al., 2024; Umoh et al., 2024), which shows the percentage of various land uses on Earth, only 15.3% of the available land is green space. A substantial portion of land is dedicated to housing and infrastructure, highlighting the urgent need to change house type designs to improve the suitability of the built environment.

Secondly, variable household design can adapt to changes in family structure and the individual needs of residents, while built environment adaptability improves the adaptability and flexibility of buildings through such means as intelligent control systems and sustainable building materials, enabling them to better adapt to changes in environmental conditions and thus maintain a comfortable indoor environment. At the same time, built environment adaptability also helps to improve the coordination between buildings and the natural environment through ecological landscape planning and greening design to better integrate the buildings with the surrounding environment and reduce the impact on the ecosystem.

Therefore, variable house type design and built environment adaptability have a complementary relationship in improving the eco-efficiency of residential design.

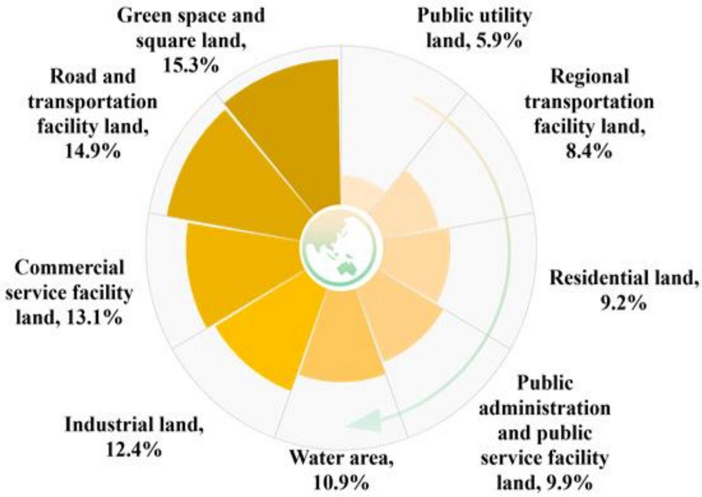


*Figure 5: Percentage of different types of planned sites*

## 4. Impact of Variable Household Design on Eco-efficiency

### 4.1 Impact of Variable Household Design on Energy Use

#### 4.1.1 Energy-Efficient Design and Sustainable Energy

Variable house design has a significant impact on energy use, especially in terms of energy-efficient design and sustainable energy use. Variable house type design helps optimize the energy efficiency of buildings through rational spatial layout and flexible functional design. The interior layout can be flexibly adjusted according to different household needs and seasonal changes, enabling the building to better utilize natural lighting and ventilation and reduce energy consumption for lighting, air conditioning, and heating. This flexibility can effectively reduce the building's energy demand and improve energy utilization efficiency. In Table 1, the conversion rates of various common types of the sun are given, and it can be seen that the conversion rates of all energy sources available to humans are relatively high, especially wind kinetic energy, rain potential energy, etc., and how to utilize these energy sources is crucial to improving eco-efficiency (Song et al., 2024; Umoh et al., 2024).

Variable house designs also promote the use of sustainable energy. The use of renewable energy contributes to the energy-saving effect of buildings and reduces dependence on traditional energy sources. In Table 2, the scientists' view on the proportion of solar energy in the future energy sources is given. With the depletion of resources, renewable energy sources such as solar and wind will gradually replace other energy sources, which guides the direction of variable house design.

*Table 1: Solar Energy Conversion Rates for Several Common Energy Types*

| Type of Energy | Solar Value Conversion Rate (sej/J) |
|---|---|
| Sunlight | 1 |
| Wind-Powered Energy | $1.50 \times 10^3$ |
| Tidal Energy | $1.70 \times 10^3$ |
| Rain Potential | $1.00 \times 10^3$ |
| Rainwater Chemical Energy | $1.80 \times 10^3$ |
| Wave Energy | $3.00 \times 10^3$ |
| River Water Chemical Energy | $4.10 \times 10^3$ |
| Soil Loss Energy | $1.70 \times 10^3$ |

*Table 2: Projected Share of Solar Power in Energy Sources*

| Percentage of Energy Mix | 2030 | 2050 | 2100 |
|---|---|---|---|
| Renewable Energy | About 38% | About 52% | About 86% |
| Solar Energy | About 14% | About 28% | About 67% |
| Solar Power | About 10% | About 24% | About 64% |

### 4.1.2 Efficient Use of Materials and Water Resources

Variable house design has a significant impact on resource utilization, particularly in terms of efficient use of materials and water resources. First, variable house design reduces the need for building materials through flexible layout and space utilization. The heat capacity per unit volume of common materials is given in Table 3, and the use of these traditional materials can effectively maintain the loss of energy within the house type, but at the same time, the recyclable utilization of such materials should be increased. Compared with the traditional fixed house type design, the variable house type can be flexibly adjusted according to different needs, avoiding the waste of resources due to the disposal of old materials and the reacquisition of new materials during house re-layout and remodelling. This helps to reduce the consumption of limited natural resources while lowering the demand for energy and water. In Figure 6, the process of an urban water recycling and treatment system is illustrated, whereby water resources in a house can be rationed and utilized more accurately through intelligent systems and equipment. Variable house design facilitates the efficient use of resources by reducing the demand for building materials and water resources. This design concept helps to reduce the consumption of natural resources and the impact of construction activities on the environment, making an important contribution to improving the eco-efficiency of residential design.

*Table 3: Specific Heat Capacity Per Unit Volume of Each Material*

| Makings | Heat Capacity Per Unit Volume (kJ/m³•K) |
|---|---|
| (of clothes) Classifier for the number of washes | $4.18 \times 10^3$ |
| Steel (Chemistry) | $3.96 \times 10^3$ |
| Numbness | $1.74 \times 10^3$ |
| Brick | $1.68 \times 10^3$ |
| Concrete (stone) | $1.48 \times 10^3$ |
| Foam insulation | $0.064 \times 10^3$ |
| Atmosphere | 1.34 |

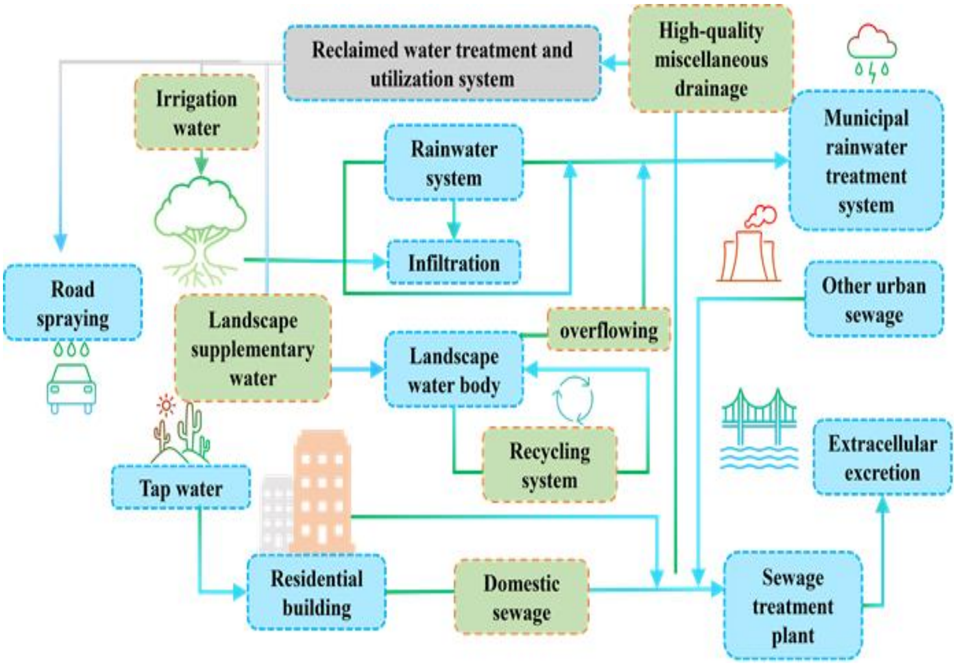


*Figure 6: Construction and Domestic Water Treatment*

### 4.2 Impact of Variable Household Design on Environmental Protection

Variable house design plays an important role in environmental protection, of which waste reduction and recycling are key aspects. The majority use of energy is designed for environment comfort and maintenance. This includes heating, cooling, lighting, and other building equipment. In addition, the building production process covers the energy required for the manufacture of building materials and construction. According to relevant studies, the building itself contains 10-30% of the energy of its entire life cycle, while the energy consumption during the use phase of the building occupies 70-90%, which includes the energy required for maintenance, repair, renovation, renewal, and regeneration. In addition, the demolition process includes the energy required during the construction and material handling phases.

Variable house type design encourages versatility of use and sharing of space, thus extending the life of the building. Variable house types allow for the dismantling and reuse of existing materials when making spatial adjustments, thereby reducing the need for new materials. This helps to reduce the negative environmental impact of discarded materials and promotes the recycling of resources.

## 5. Impact of Built Environment Adaptation on Eco-Efficiency

### 5.1 Impact of Adaptation of the Built Environment on Energy Use

#### 5.1.1. Intelligent Control Systems and the Passivhaus Concept

Building environmental adaptability has a significant impact on energy utilization, especially in combination with intelligent control systems and the Passivhaus concept.

First of all, through the intelligent control system, the building can realize the intelligent management of energy, automatically adjusting the lighting, heating, ventilation, and other systems according to the different needs of use to minimize the consumption of energy. This intelligent system can make precise energy allocations according to the actual demand, avoiding excessive use of energy and improving the efficiency of energy utilization. In Fig. 7, a schematic diagram of the energy flow of the building system is shown, and it can be seen that in maintaining the normal service function of the building system and not destroying the ecology of the system, the energy is made to flow more to the parts that are beneficial to human beings, to achieve more ideal ecological benefits (Song et al., 2024; Umoh et al., 2024).

Passivhaus is a widely recognized architectural design concept that aims to create an efficient, low-energy built environment. His core objective is to achieve energy self-sufficiency in buildings, reduce dependence on conventional energy sources, reduce greenhouse gas emissions, and improve the environmental friendliness of buildings.

The Passivhaus concept underscores the mitigation of energy consumption and the enhancement of building energy efficiency by optimizing structural and detailing design. Employing highly effective insulation materials, refined window design, and the eradication of thermal bridges, Passivhaus structures can optimize natural energy utilization and diminish dependence on artificial energy sources, consequently curbing overall energy consumption.

Intelligent control systems for building environments entail the utilization of sophisticated sensors, monitoring apparatus, and automation technology to oversee and adjust environmental variables (e.g., temperature, humidity, light, etc.) within a structure. These systems hold the potential to markedly enhance the energy efficiency, comfort, and safety of buildings, thereby mitigating energy consumption and operational expenditures while augmenting the ecological sustainability of architectural structures. Particularly evident in expansive commercial complexes, office edifices, and industrial facilities, the pervasive adoption of such intelligent control systems has emerged as a prevailing trend (Huda et al., 2024).

Particularly for solar or wind energy-related intelligent systems, the generation of solar and wind energy is predicted through the use of meteorological data and prediction models. Intelligent systems can dynamically adjust building energy use strategies, such as adjusting the operating status of equipment such as lighting, air conditioning, and heating to maximize the use of renewable energy. By collecting, analysing, and mining a large amount of building energy data, intelligent systems can continuously optimize building energy management strategies to improve energy efficiency and reduce energy waste.

Building Environmental Adaptability enables buildings to better adapt to their surroundings and user needs, maximize the use of natural resources, and reduce dependence on artificial energy sources through the integration of intelligent control systems and the Passivhaus concept. The benefits of this environmental adaptability help to improve the building's energy efficiency and reduce energy waste, thus making an important contribution to improving the eco-efficiency of residential design

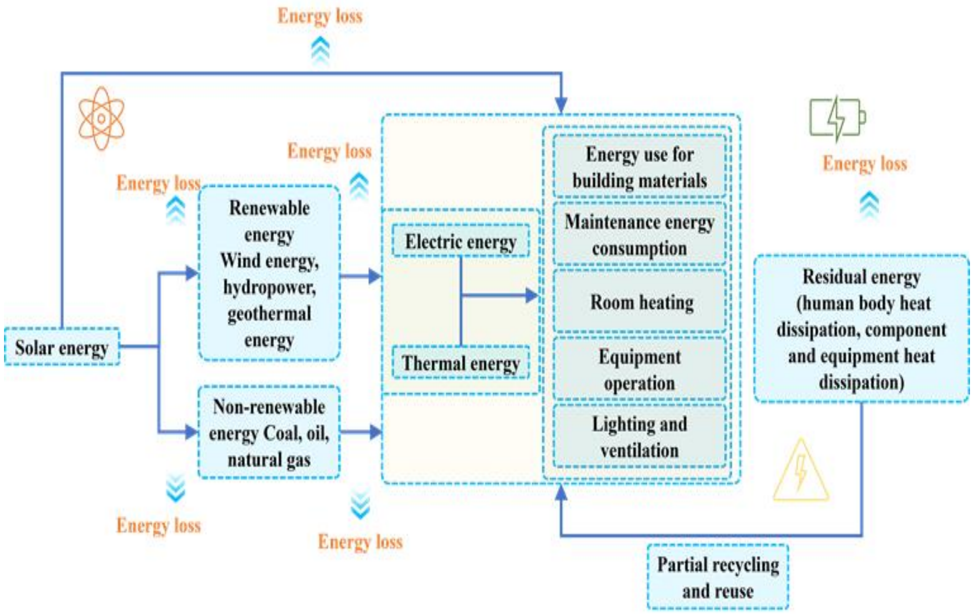


*Figure 7: Schematic diagram of building energy transfer*

#### 5.1.2 Environmentally Friendly Materials and Recycled Designs

Built environment adaptability significantly influences resource utilization by incorporating environmentally friendly materials and recycled design principles (Omole et al., 2024). The building's lifecycle, spanning approximately 30 to 300 years, serves as the cornerstone of its entirety, allowing for adaptive design control both during initial construction and eventual demolition phases. The building envelope system, comprising walls, windows, balconies, roofs, and floors, directly interacts with and responds to external environmental factors and technological advancements, necessitating replacement roughly every 20 years.

At the spatial level, which directly impacts users, the replacement cycle typically ranges from 3 to 30 years, contingent upon changes in service content and objectives. Meanwhile, the equipment pipeline, crucial for indoor comfort, constitutes an indispensable aspect of spatial quality enhancement, with a replacement cycle typically falling between 7 to 15 years owing to frequent usage and rapid technological advancements.

Consequently, the adoption of environmentally friendly materials diminishes reliance on non-renewable resources, fosters natural resource conservation, and curtails resource exploitation and consumption.

### 5.2 Impact of Adaptation of the Built Environment on Environmental Protection

Built environment adaptation has a positive impact on environmental protection by combining green building and ecological landscape design. Ecological landscape design protects and improves the ecosystem through rational planning of green space, vegetation, and water bodies (Liu et al., 2023). The adaptability of the built environment integrates the natural environment into the architectural design, which helps to reduce the urban heat island effect, improve air quality, and enhance the quality of life. In addition, ecological landscape design helps protect wildlife and promote biodiversity and ecological balance.

Built environment adaptability plays a crucial role in environmental preservation by promoting green building practices and ecological landscape design. This design approach facilitates the reduction of energy consumption and greenhouse gas emissions, enhances the urban ecological landscape, safeguards biodiversity, and actively contributes to advancing the eco-efficiency of residential design.

*Table 4: Assessment of Wind Energy Resources at Different Building Heights*

| Wind Energy Resource | Within 30 meters | Within 10 m height | Within 30 meters |
|---|---|---|---|
| Estimation | Wind Energy Density | Average Wind Speed | Average Wind Speed |
| Available | 240~320 | 5.1 to 5.6 | 6.0~6.5 |
| Richer | 320~400 | 5.6~6.0 | 6.5~7.0 |
| Enrichment | >400 | >6.0 | >7.0 |

### 5.3 Impact of Variable Household Design and Built Environment Adaptation Together on Improving the Eco-efficiency of Residential Designs

Variable house design and building environmental adaptations can have a synergistic effect when they work together to further improve the eco-efficiency of residential design. In Figure 8, which gives the pyramid structure of sustainable ecosystems for building capital, it can be seen that building construction adaptation relies on sustainable ecosystems and natural capital and also influences this eco-efficiency, and the two are in an interactive relationship.

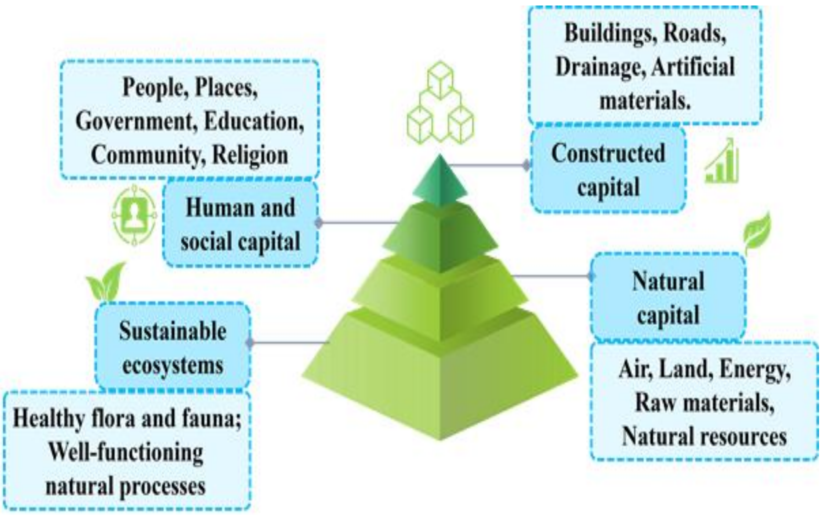


*Figure 8: Pyramid structure of sustainable ecosystems*

Variable house design allows for greater flexibility and diversity of dwellings that can be adapted to different family structures and lifestyles (Engvall et al., 2014). For example, variable house design can work with built environment adaptability to reduce energy consumption by optimizing lighting and ventilation and reducing reliance on artificial lighting and air-conditioning systems.

The amalgamated impact of variable house type design and building environmental adaptability offers a dual benefit: it provides flexibility and comfort to occupants while concurrently minimizing the building's energy consumption and environmental footprint, thereby enhancing the eco-efficiency of residential design. This integrated design paradigm not only fosters environmentally friendly and energy-efficient buildings but also contributes to the overall quality of life for occupants.

## 6. Results and Discussion

In this paper, the importance of variable house design and built environment adaptability in improving the eco-efficiency of residential design is explored. By analysing the impact of these two design concepts on resource use, energy use, and environmental protection, it is found that they work together to provide a comprehensive guarantee for improving the eco-efficiency of residential design.

### 6.1 Flexible and Functional Layouts

Variable house design provides buildings with flexible, functional layouts that can adapt to changing needs and uses over time. This adaptability reduces the waste of resources and lowers energy consumption by ensuring that space is utilized efficiently and effectively. For example, spaces can be designed to serve multiple purposes throughout the day, such as a home office that transforms into a guest bedroom. This reduces the need for additional square footage, which in turn reduces the materials and energy required for construction and maintenance.

The concept of variable house design extends beyond mere floor plan adjustments; it encompasses the ability to modify structural and mechanical systems to better align with occupants' needs. For instance, modular construction techniques allow for sections of a house to be added or removed with minimal disruption, ensuring that the building can grow or shrink in response to the inhabitants' circumstances. This not only extends the life of the building but also enhances its eco-efficiency by minimizing the need for new construction and the associated environmental costs.

### 6.2 Adaptive Design for the Built Environment

Adaptive design for the built environment minimizes the consumption of natural resources and promotes sustainable development through green building and ecological landscape design. By integrating buildings with their natural surroundings, the use of energy and materials can be optimized. For example, positioning buildings to take advantage of natural light and ventilation reduces the need for artificial lighting and mechanical cooling systems, thereby lowering energy consumption. Additionally, the use of locally sourced, sustainable materials in construction reduces the carbon footprint associated with transportation and manufacturing.

Moreover, adaptive design often includes the incorporation of green roofs, rainwater harvesting systems, and other sustainable features that help manage stormwater runoff, reduce heat island effects, and support local biodiversity. These elements not only improve the environmental performance of individual buildings but also contribute to the resilience and sustainability of the larger urban ecosystem.

### 6.3. Renewable Energy Integration

A comparative analysis of the sustainable design of solar, wind, and thermal energy in the design of variable house types reveals significant potential for improving eco-efficiency. Variable house designs can be tailored to maximize the capture and utilization of renewable energy sources. For instance, roofs can be oriented and angled to optimize solar panel efficiency, while building forms can be shaped to funnel wind towards turbines. Thermal energy can be harnessed through the strategic placement of thermal mass and the use of passive solar heating techniques.

These design strategies not only increase the energy conversion rate but also enhance the overall sustainability of residential buildings. By reducing reliance on non-renewable energy sources, these designs contribute to a decrease in greenhouse gas emissions and help mitigate the impacts of climate change. Furthermore, the integration of renewable energy systems can provide occupants with greater energy independence and protection against rising energy costs.

### 6.4 Synergistic Effects of Integrated Design

When variable house design and built environment adaptability work together, they bring a comprehensive impact on improving the eco-efficiency of residential design. This integrated design concept is conducive to reducing the consumption of natural resources and improving the energy utilization efficiency of buildings while enhancing the living environment and promoting the practice of sustainable development.

For example, a building designed with both adaptable spaces and integrated renewable energy systems can respond dynamically to seasonal changes and varying occupancy patterns. During the summer months, shading devices and natural ventilation can reduce cooling loads, while in the winter, the building can be reconfigured to maximize solar gain and minimize heat loss. This level of adaptability not only improves comfort and reduces energy consumption but also extends the lifespan of the building by allowing it to evolve in response to changing environmental conditions and user needs.

### 6.5 Dynamic Design Solutions for Diverse Needs

The combined effect of variable house type design and building environmental adaptability provides important ideas and directions for future residential design. Particularly for building eco-efficiency, the theory can provide dynamic design solutions for different types of buildings with different spatial requirements. For the same building, different adaptations can be provided according to different house types.

This approach allows for a more personalized and responsive residential architecture, where homes can be tailored to meet the specific needs and preferences of their occupants. For example, a family with young children might require open, connected spaces for play and supervision, while a household with older adults might prioritize accessibility and ease of movement. By incorporating adaptability into the initial design, these varying needs can be accommodated without the need for extensive renovations or new construction.

### 6.6 Contribution to Sustainable Development

The concept of designing to meet different usage requirements by changing the house type has been widely considered. At the same time, it contributes important concepts and practices to the sustainable development of the building industry. By promoting the use of adaptable, eco-efficient designs, architects and builders can help reduce the environmental impact of residential construction and support the transition to a more sustainable built environment.

Furthermore, the adoption of these design principles can lead to broader changes in the construction industry, encouraging the development and use of new materials and technologies that support sustainability. For instance, the demand for flexible, modular building components could drive innovation in prefabrication and off-site construction techniques, which have been shown to reduce waste and improve efficiency compared to traditional building methods.

It is hoped that the discussion in this paper will draw more attention to eco-architectural design, promote the integration and practice of more environmentally friendly and energy-saving concepts, and make efforts to build a more sustainable future society. The combined strategies of variable house design and built environment adaptability offer a roadmap for creating residential spaces that are not only more efficient and sustainable but also more liveable and adaptable to the changing needs of their occupants.

As we look to the future, it is clear that the challenges of climate change, resource depletion, and urbanization will require innovative and holistic approaches to residential design. By embracing the principles outlined in this paper, we can move towards a more sustainable and resilient built environment that supports both human well-being and ecological health.

## 7. Research Limitations and Future Research Directions

### 7.1 Research Limitations

The eco-efficiency of buildings is the result of the joint action of many parties, which needs to be analysed synergistically. Currently, there is little sample data on the impact of variable house types on the environmental suitability and eco-efficiency of buildings, which makes it difficult to conduct in-depth research. At the same time, there is a lack of long-term shared research mechanisms to monitor the long-term energy consumption of buildings under different usage conditions.

One significant limitation is the heterogeneity of the existing data. Variations in climate, cultural preferences, building materials, and energy systems across different regions make it challenging to draw universal conclusions from case studies. Additionally, the rapid pace of technological advancements in building materials and energy systems means that data can quickly become outdated. As a result, research findings might not be applicable to future projects that utilize more advanced technologies.

Moreover, the complexity of tracking and quantifying the multifaceted benefits of eco-efficient designs presents another challenge. For example, while energy consumption can be relatively straightforward to measure, assessing the impact on occupants' health and well-being, biodiversity, and broader ecosystem services is more complex and often requires interdisciplinary collaboration. This lack of comprehensive and long-term data hinders the ability to fully understand the potential of variable house designs and adaptive environments to enhance eco-efficiency.

### 7.2 Future Research Direction

It is highly encouraged to share data collected and case studies of particularly long-term projects of eco-efficient buildings. However, researchers and stakeholders need to keep in mind that feasibility analysis builds on consideration of multiple factors, which requires interdisciplinary approaches and proficiency. Establishing long-term monitoring projects to gather data on the performance of variable house designs and adaptive built environments. These studies should track energy consumption, resource use, and environmental impacts over several years to provide a comprehensive understanding of their benefits and challenges.

Encouraging collaboration between architects, engineers, environmental scientists, and social scientists to develop holistic approaches to studying eco-efficiency. This interdisciplinary effort can help address the complexity of eco-efficient design and ensure that all relevant factors are considered. Developing global platforms for sharing data and case studies on eco-efficient buildings. These platforms should facilitate the exchange of information across different climatic and cultural contexts, helping to identify universal principles and region-specific adaptations.

Utilizing advanced simulation and modelling tools to predict the performance of eco-efficient designs under various conditions. These tools can help bridge the gap between short-term experimental data and long-term real-world performance, providing valuable insights into the potential impacts of different design strategies. Incorporating comprehensive lifecycle analyses to evaluate the environmental impacts of buildings from construction through operation to demolition. This approach will help identify the most effective strategies for minimizing resource use and maximizing eco-efficiency throughout the building’s lifespan.

Exploring the integration of emerging technologies, such as smart home systems, renewable energy technologies, and advanced materials, into variable house designs. Research should examine how these technologies can enhance the adaptability and eco-efficiency of residential buildings.

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