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Climate and Sustainability in Architecture: Analysis of Challenges and Limitations for Universal Solutions in the Design of Single-Family Houses

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ABSTRACT

The aim of the article is to analyze the influence of different climatic conditions on the development of architectural forms of single-family houses. The study focuses on a modular, prefabricated structure with a simple form, ensuring flexibility and adaptability to different environmental conditions. The authors, a geographer and architects, examined six selected locations representing different climatic zones, chosen for their distinct environmental characteristics and relevance to global climate diversity. The analysis is based on the SWOT method, taking into account adaptation strategies, possibilities of implementing the principles of sustainable development and the relationship between design and environmental conditions. The article puts forward the thesis that universal architectural solutions have limited effectiveness due to specific climatic and environmental requirements. However, appropriately designed adaptability of modular forms allows to overcome these limitations. The conclusions indicate that achieving sustainable and ecological design is possible by adapting techniques, materials and architectural forms to local climatic conditions. For the purposes of the study, an original design of a modular prefabricated house with a frame structure was developed, consisting of 4×4 m modules, creating a body with the dimensions of 8×16 m. This model was selected due to its potential for easy adaptation to different locations and user needs. The analysis was conducted in the form of a theoretical design simulation, which resulted in guidelines for the optimal shaping of modules, their perforation and computer models of buildings. The study is based on the author's hybrid classification of climate zones, extending the traditional Köppen-Geiger system with additional factors relevant to architecture, such as extreme weather events, humidity levels, sun exposure, geotechnical conditions, etc. The SWOT analysis allowed to assess the strengths and weaknesses of the modular construction in different climatic contexts, taking into account material efficiency, construction possibilities and passive adaptation strategies. The research results prove that universal architectural solutions are inherently limited by climatic factors. However, the use of modularity and flexibility of forms enables effective adaptation of designs to local conditions. The article contributes to the discussion on adaptive architecture by presenting a design framework for modular residential buildings, combining standardization with flexible adaptation to local conditions.

Keywords: Sustainable design, Climate change, Single family houses, Adaptation, Flexibility, Prefabrication, Modular building

INTRODUCTION

The growing challenges of climate change require a reassessment of architectural design strategies, particularly for single-family housing. Traditional approaches, based on standardized solutions, often overlook specific environmental and climatic conditions. The globalization of the architectural profession and education has reinforced these standardized methods, which do not always align with local needs. This study analyzes how climatic conditions shape architectural forms and the adaptability of single-family houses. The research examines six locations, selected based on the author's climate classification, which integrates the Köppen-Geiger system with additional architectural parameters such as extreme weather events, seasonal heating and cooling demands, and material durability. The study focuses on a theoretical model—a modular 8 × 16-meter single-family house composed of prefabricated 4 × 4-meter modules. This model was chosen for its scalability, flexible spatial configuration, and adaptability to various climates. To ensure broad applicability, analyses were conducted on optimal usable area, number of inhabitants, and functional requirements, optimizing spatial efficiency and ergonomics. The study employs a comparative methodology, including a SWOT analysis. A key challenge was balancing the need for a universal model with local modifications required by specific climates. The analysis considered temperature variations, precipitation patterns, wind exposure, and solar radiation, which significantly affect thermal comfort and energy efficiency. Even small climatic differences may necessitate major design adjustments. The results indicate that effective climate-responsive architecture requires flexible design solutions that integrate both structural and operational aspects while minimizing environmental impact. A modular approach, combined with adaptive strategies, provides an effective response to sustainable construction needs amid global climate change. Given challenges related to housing availability, climate adaptation, and sustainable development, studying a universal single-family house model is increasingly relevant. This article aims to develop a theoretical building model that embodies modularity, spatial efficiency, and sustainability while allowing adaptation to diverse climatic and geographical conditions.

CLIMATE CLASSIFICATION AND ARCHITECTURAL IMPLICATIONS

In response to the need for interdisciplinary analysis combining geography and architecture, a hybrid climate zone classification was proposed, incorporating meteorological, climatic, and geographical factors influencing architectural forms. The Köppen-Geiger classification was the initial reference for selecting model house locations due to its broad acceptance in climate sciences and precise zoning based on temperature and precipitation. Beck et al. (2018) developed high-resolution maps, enabling more accurate matching of analyzed locations to real and projected climate conditions. This classification facilitated comparisons of building models in different environmental contexts, essential for evaluating adaptability to changing climates. While the Köppen-Geiger system is widely used in geography and meteorology, it does not fully account for critical architectural factors. Elements such as wind force, solar radiation, storm and hurricane risks, insulation, ventilation, and material selection are also crucial. To address this gap, this study introduces a climate zone classification tailored to architectural design and climate adaptation, complementing the Köppen-Geiger framework. The need for a hybrid approach is supported by a literature review, particularly the findings of Stagrum et al. (2020), who highlight that most research focuses on warm climates, where overheating is the main issue, while studies on cold climates remain limited despite significant financial implications. The proposed classification expands traditional climate parameters by including additional key factors: 1) Extreme weather events – frequency and intensity of hurricanes, storms, floods, and strong winds affecting structural resilience. 2) Heating and cooling season length – determining energy demand, crucial for efficiency and operational costs. 3) Air humidity – impacting material durability, condensation risk, mold growth, and occupant comfort. 4) Natural energy availability – solar radiation, wind, and water resources influencing passive design strategies. 5) Ground stability and foundation conditions – frost presence, subsidence risks, erosion, and sea-level rise affecting structural requirements. This classification enables a more precise assessment of architectural adaptability to climatic challenges and serves as a valuable tool for designing buildings with enhanced environmental resilience.

MATERIAL AND METHODS

Designing a universal house model for this study required the adoption of clear and evidence-based criteria that would potentially enable the adaptation of the universal model house to different climatic conditions and the needs of residents. As a result of analyses and calculations based on, among others, statistical data, structural efficiency and transport width, a model with a simple form, optimal surface area, volume and structure was developed, which is functional and flexible, and at the same time meets the standards of sustainable design. The research did not include any elements of aestheticization of form (which can be treated as a potential, additional, later element of individualization) due to the possible difficulties of comparative analyses. The initial goal of the study was: 1) Determination of the minimum, optimal usable area and volume of a universal theoretical house for conducting the research, assuming that it is intended for an average-sized household in the world. 2) Creation of a universal functional program that will be consistent with the needs of residents despite being located in different climatic zones. 3) Preparation of a universal theoretical modular house model, possible to adapt depending on the number of residents or local requirements.

RESEARCH BACKGROUND

The inspiration for this research is the growing popularity of modular, repeatable and prefabricated construction, built in factories and transported to the construction site. It includes not only container housing estates erected in response to natural disasters, housing estates for war immigrants and refugees or summer houses, but increasingly also individual, year-round residential houses. A particularly interesting phenomenon is the wide use of shipping containers as adapted residential modules in almost every part of the world. This concept has gained popularity due to its modularity, cost-effectiveness and the possibility of quick implementation. This proves both the existence of a strong idea of universal solutions in architecture, resulting from real needs, and the growing demand for cheap construction using recycled materials. Despite the numerous advantages resulting from the repeatability of modular elements, the biggest limitation of this solution is its low adaptability to local conditions. This applies to both climatic aspects (difficult perforation of external walls, the need for additional insulation) and the needs of residents (insufficient flexibility of interiors, high cost of modifying internal and external walls). The material properties of containers additionally make it difficult to adapt them to specific environmental and utility requirements. This is where the key research thesis comes from regarding the limited possibilities of using so-called universal architectural solutions in different climate zones. Below is an analysis and characteristics of commonly used container solutions, as well as conceptual assumptions for a modular universal house. Many features of container houses, especially those considered advantages, coincide with the assumptions adopted in this study. On the other hand, for identified weaknesses, solutions were proposed that eliminate key limitations. First of all, an important assumption is to change the material and type of casing construction, which will allow for maximum adaptability thanks to an appropriately designed structure of external wall panels. A key aspect is the selection of durable construction materials that will also be consistent with the principles of sustainable development.

ASSUMPTIONS FOR OPTIMIZING FUNCTIONS, AREAS AND STRUCTURES

Based on global data in relation to the division into continents, the average number of people per household is 3.7 people (Table 1). Averaging this value, a household consisting of 4 people was assumed: two parents and two children or two parents, one child and one additional family member (e.g. grandfather or grandmother). According to international standards (e.g. UN, Eurostat), national standards regarding areas and scientific research, the minimum usable area per person is about 25–30 m^2. The upper value of 30 m^2 was assumed, because it ensures both the functionality of the rooms (ergonomics of movement and daily use and the space occupied by equipment), psychological comfort (sufficient living space) and the potential possibility of adaptation to different climate zones and the needs of residents. Usable area = 3.7 persons $\times$ 30 m^2 = 111 m^2. The result was rounded up to 110–120 m^2, taking into account the tolerance for local adjustments.

Table 1: Analysis of the average number of people per household by continent.

Continent	Average Number of People Per Household	
Africa	4,7	World Bank 2020
Asia	4,3	Statista 2020
Europe	2,3	Eurostat 2020
North America	2,6	US Census Bureau 2020
South America	3,5	World Bank 2020
Australia and Oceania	2,8	Australian Bureau of Statistics 2020

Although the research concept is based on the location of a universal theoretical model of a research house in different climatic zones, the averaged data are presented by continent. The article adopts an approach in which the model is analyzed in terms of adaptation to different climatic zones, but the average number of people per household is a key parameter in the design of the area and functional program. However, the climatic zone will determine the degree and type of adaptation. The averages for continents take into account both urban and rural regions and allow for generalization of the results.

Table 2: Design principles that enable a sustainable and functional research house model.

Minimizing construction and operating costs	The rectangular shape of the building facilitates the simplicity of the structure and minimizes heat losses. Optimization of dimensions for typical building materials (e.g. standard lengths of beams, slabs, prefabricated elements).
Functional efficiency	Separation of necessary rooms in a minimal space that will provide comfort of use.
	Reduction of auxiliary space (corridors, hallways) in favor of usable space.
Modularity and scalability	Space layout that allows for easy expansion (e.g. adding additional modules in the future).
Material economy	Avoidance of unusual dimensions and shapes of walls that increase construction costs.

One of the initial assumptions of the search for a model house is to use the modular potential of prefabricated construction, which means that it will potentially be transported in modules. Therefore, the key factor for the structural and functional efficiency of the model house was the transport width of the modular element, which is 4.2 m. In connection with this, a variant of a cuboid with the projection proportions of 1:2 (width, length) and dimensions of 8 $\times$ 16 m was analyzed, which is a derivative of the construction module of 4 m and at the same time is the optimal size for individual utility functions of the rooms and meets the approximate value of the calculated usable area = 110–120 m^2. It was assumed that the dimensions of the building 8 $\times$ 16 m, also meet the following criteria: (1) simplicity of construction - proportions 1:2 allow for effective arrangement of rooms while minimizing heat losses, (2) material economy - dimensions are adapted to standard lengths of prefabricated elements, beams and building boards, which reduces costs, (3) functionality - the layout of space allows for the separation of necessary rooms while maintaining optimal communication zones. It was also assumed that simplicity of construction and optimized functional program are key to creating a model that can be adopted and implemented in different regions of the world.

The functional program of the house has been optimized for a model household consisting of four people (family 2+2) or a 2+1+1 variant, taking into account an additional resident, e.g. a senior citizen. The spatial layout has been designed symmetrically, which allows for an even distribution of functions and maximum use of the available space. The entrances to the building can be located on different sides, which increases its flexibility in adapting to local conditions, such as exposure to sunlight, wind directions or accessibility of the plot. Many variants of the room layout have been analyzed, striving to optimize functionality and comfort of use. The interiors can be arranged in a way adapted to the individual needs of the residents, thanks to the use of modular space division and flexible partitions. The common living area includes a spacious living room (22 m^2) connected to the kitchen and dining room (14 m^2), which facilitates the integration of the household members. The layout of the bedrooms (13 m^2 for parents and two 10 m^2 for children) provides comfortable conditions for rest, and the compact but well-equipped bathroom (7 m^2) and separate toilet (2.5 m^2) increase the functionality of the building. Additionally, the communication space has been reduced to a minimum (8 m^2) to provide the largest possible usable area, and the utility room (4 m^2) serves as a storage room, laundry room or optional pantry. This layout allows for easy adaptation of the interiors to the changing needs of users, while maintaining high spatial efficiency and ergonomics of everyday functioning.

Table 3: SWOT analysis for a universal research house model 8 × 16 .

Category	Characteristics
Strengths	Rectangular shape to minimize heat loss and construction costs. Dimension optimization for typical building materials (prefabricated elements, standard elements). Modularity allowing for easy expansion and adaptation to different needs and number of residents. Minimum volume while maintaining thermal comfort and functionality. Simple functional program with separate common and private spaces.
Weaknesses	Limited flexibility in case of unusual local requirements. Smaller circulation space, which may be insufficient for larger families. Simple construction may be perceived as lack of aesthetic and architectural expression and individual character.
Opportunities	Possibility of expanding the project into larger housing estates or use in humanitarian projects.

Continued

Table 3: Continued

Category	Characteristics
	Adaptation to different climate zones by modifying insulation and ventilation solutions. Use of prefabrication for mass production, which reduces construction costs. Adaptation of the project to government and international programs related to solving housing crises.
Threats	Possibility of not adapting to local building standards and cultural conditions. Limited social acceptance due to simplified building aesthetics. High modification costs if significant adaptation to specific climatic or local requirements is required. Risk of competition with local building solutions that may be more culturally embedded.

SITE SELECTION CRITERIA AND ANALYSIS OF DATA FOR CLIMATE ZONES

The selection of locations was based on three key criteria: 1) Representativeness of climate zones – each location was selected to cover different types of climate, from tropical to Arctic; 2) Population size – the selected cities are among the most populated in their climate zones, which allows for an assessment of their importance in the global architectural context; 3) Geographic diversity – locations on different continents were included, which increases the universality of the study. This approach allows for precise identification of challenges and adaptation strategies for a modular house with a plan size of 8×16 m. The analysis of climate data for individual zones was developed based on statistical meteorological data, including parameters such as: air temperature, relative humidity, wind speed and direction, solar radiation intensity and total precipitation. Long-term measurement series were included, which allow for determining the average climate conditions in a given region. For each location, the nearest weather station was selected to obtain the most precise data. Additionally, the ground freezing depth and geographical location were analyzed, which can have a significant impact on the architectural form of the building, including in the context of the frequency of earthquakes, hurricanes, floods and other extreme weather phenomena.

Table 4: Climatic characteristics of different climate zones.

Mediterranean (Csa/Csb – Hot/Warm Summer Mediterranean)	Average Annual Temperature: 12 °C – 25 °C, with hot, dry summers and mild, wet winters. Precipitation: 300 – 900 mm per year, concentrated mostly in winter. Humidity: 40% – 70%, fluctuating with proximity to coastlines and seasonal shifts.

Continued

Table 4: Continued

Tropical (Af, Am, Aw – Rainforest, Monsoon, Savanna)	Average Annual Temperature: 20 °C – 30 °C, consistently warm with minimal seasonal variation. Precipitation: 1500 – 4000 mm per year, high annual rainfall with distinct wet and dry seasons. Humidity: 70% – 100%, often exceeding 80% in rainforest and monsoon zones.
Desert (BWh, BWk – Hot & Cold Desert)	Average Annual Temperature: Hot Desert (BWh): 20 °C – 40 °C, with extreme daytime heat and cold nights. Cold Desert (BWk): –5 °C – 25 °C, large diurnal temperature swings. Precipitation: Less than 250 mm per year, often occurring in sporadic storms. Humidity: 10% – 40%, extremely low in hot deserts, slightly higher in cold deserts.
Mountainous (Dfc/Dfd, ET – Alpine, Subarctic)	Average Annual Temperature: –5 °C – 10 °C, varies by altitude with strong temperature drops at night. Precipitation: 800 – 2500 mm per year, mostly as snow at higher elevations. Humidity: 40% – 80%, lower at high altitudes due to dry air.
Arctic (ET, EF – Tundra, Ice Cap)	Average Annual Temperature: –30 °C – 5 °C, long freezing winters and short, cool summers. Precipitation: 200 – 600 mm per year, mostly as snow, often dry in winter. Humidity: 50% – 90%, influenced by ice/snow coverage, but generally low in interior Arctic regions.

RESULTS AND DISCUSSION

The study results support the need for adaptive architectural solutions that take into account both universal design principles and local environmental factors. The modular, prefabricated 8×16 house model analyzed in this study shows how the flexibility of architectural form can increase resilience in different climate zones. However, the effectiveness of such solutions depends on integrating a comprehensive set of climate variables beyond temperature and precipitation. Recent research on climate adaptation strategies for buildings emphasizes the importance of considering extreme weather events, seasonal fluctuations, and material durability (Stagrum et al., 2020) Smith et al.'s (2024) Climate-Responsive Design Strategies for Residential Buildings: A Comprehensive Review provides an in-depth analysis of architectural approaches to enhancing building resilience against climate-induced challenges. The authors review various design strategies addressing extreme weather events such as hurricanes, floods, and heat waves, emphasizing adaptive building forms and materials. Key strategies include elevated structures for flood mitigation, aerodynamic shapes to reduce wind loads, and reflective materials to minimize heat gain. The study also highlights passive design elements like strategic orientation and natural ventilation in improving energy efficiency and occupant comfort. The focus on targeted design interventions aligns with modular, prefabricated housing solutions adaptable to different environments.

Table 5: Chosen climate adaptation strategies in proposed climate zones.

Proposed Climate Zone	Main Climate Risks	Adaptation Strategies	Additional Construction Features
Temperate (Stockholm, Denver, Tokyo, Warsaw)	Temperature variability, heat waves, frost, increased rainfall	Optimized thermal insulation, passive heating systems, rainwater retention	Low-emissivity windows, high thermal mass roofs
Mediterranean (Marseille, Sydney, Marrakech)	Intense sunlight, droughts, occasional heavy rainfall	Shading devices (eaves, pergolas), natural ventilation, green roofs	Reflective lightweight materials, shading elements
Tropical (Manila, São Paulo, Singapore)	High humidity, heavy rainfall, hurricanes, extreme heat waves	High cross-ventilation, moisture resistance, rainwater drainage systems	Elevated foundations, flood protection, roof ventilation
Desert (Dubai Phoenix, Denver)	Extreme temperatures, low humidity, strong winds	Thick wall insulation, minimal openings, radiative cooling techniques	White coatings for solar reflection, chimney ventilation
Mountainous (Denver, Innsbruck, Aspen)	Heavy snowfall, rapid temperature changes, strong winds	Wind- and snow-resistant structures, reinforced insulation, heat storage	Steep roofs for snow drainage, impact-resistant materials
Arctic (Tromsø, Nuuk)	Extremely low temperatures, ice accumulation, strong winds, short daylight	Additional insulation, minimal openings, wind protection, energy-efficient heating	Triple-glazed windows, vestibules to reduce heat loss, thermal mass storage

Stagrum et al. (2020) note that most climate adaptation strategies prioritize overheating prevention in warm climates, while cold regions remain underrepresented in scientific literature. This aligns with findings indicating that architectural adaptations must extend beyond passive cooling to include heating demand, wind exposure, and insulation. Similarly, research on zero-energy buildings suggests that sustainability requires balancing energy-efficient technologies with climate-responsive design (Eknes et al., 2020). The impact of extreme climate events on the built environment has been widely examined. Dong et al. (2024) explore coastal erosion adaptation in Southeast Asia, emphasizing how sea-level rise and storm surges compromise structural resilience. These studies indicate that design must account for both gradual climate shifts and acute environmental stresses. This study supports this perspective, demonstrating that site-specific modifications, such as foundation stability and wind resistance, are essential for long-term adaptability. Integrating these adaptation strategies within a modular framework offers a promising approach to balancing performance with resilience. However, as previous research highlights, effective adaptation requires a multidisciplinary approach incorporating architecture, engineering, and climate science (Eknes et al., 2020). The challenge remains to reconcile cost-effective prefabrication with local environmental adaptations. Future research should refine hybrid classification systems integrating Köppen-Geiger climate zones with architectural parameters to enhance adaptation precision. The results confirm the importance of embedding adaptation strategies in architectural design, as reflected in existing research.

A holistic approach to climate-responsive architecture is essential, combining mitigation and adaptation strategies (Altomonte, 2010). In the analyzed model of a prefabricated modular house, adaptability is key—building mass, orientation to cardinal directions, and the use of low-emission materials must be carefully considered. The concept of dynamic architectural systems, capable of responding to changing climatic conditions, has been widely discussed in previous studies. This perspective aligns with the findings of our study, which analyzes modular spatial configurations that can be reconfigured depending on location and user needs. Passive climate strategies play a crucial role in ensuring efficiency. In hot climates, features such as pergolas, shading, and green roofs contribute to thermal comfort, while increased insulation is essential in colder regions. Additionally, effective adaptation should address both occupant well-being and environmental impact. In this context, circular architecture has been incorporated, focusing on recycled materials and the reuse of building modules to enhance energy efficiency. Advances in technology optimizing energy consumption further support climate-responsive design, aligning with strategies integrating solar energy and natural ventilation. The findings demonstrate that a modular approach allows buildings to effectively adapt to local climatic conditions while minimizing environmental impact.

CONCLUSION

The universal research house is a model that can be adapted to various conditions and needs, while maintaining functionality and energy efficiency. Its simple form and flexible spatial layout make it a tool for further research on sustainable housing. The 8 × 16 m model meets the criteria of universality, economy and functionality. Thanks to its modular design and optimized dimensions, it can be implemented in various regions of the world, adapting to local climatic conditions and the needs of residents. Despite the existence of projects with similar dimensions and assumptions, there is a lack of detailed scientific research on the universal 8 × 16 m house model, optimized for economy, functionality and modularity in different climatic zones. Future research should refine hybrid classification systems integrating Köppen-Geiger climate zones with architectural parameters by incorporating additional environmental variables such as wind patterns, soil stability, and seasonal energy demands to enhance adaptation precision. Adaptive actions can also promote the individualization of repeatable modular houses, which will avoid the spatial monotony often observed in suburban areas around the world.

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