International Journal of Design & Nature and Ecodynamics
Vol. 19, No. 5, October, 2024, pp. 1527-1539
Journal homepage: http://iieta.org/journals/ijdne

# Natural Design Procedures for Enhancing Energy Efficiency in Buildings

Abdulsalam Alshboul[1*], Diana Alatrash[2]

[1] The University of Jordan, Amman 11942, Jordan
[2] Masters Engineering Consultants, Amman 11942, Jordan

Corresponding Author Email: alshboul@ju.edu.jo



https://doi.org/10.18280/ijdne.190507

**Received:** 10 July 2024
**Revised:** 31 July 2024
**Accepted:** 15 August 2024
**Available online:** 29 October 2024

***Keywords:***
*allometry, living organism, shape factor, final energy demand, climate, thermal design, building envelope, Jordan*

**ABSTRACT**

Cooling and heating of buildings account for a significant part of global energy consumption, with the expanding need to decrease energy demands, developing new energy-efficient innovations and technologies is essential. Sustainability has gained mainstream attention in the recent decade as a response to the global quest for environmentally responsible buildings. This study focuses on the shape factor as an initial part of the design, during which a biophysical framework is developed to facilitate access to pertinent analogies. It offers a structured blueprint of heat regulation mechanisms to aid in discovering and selecting appropriate methods from the extensive natural database. A range of morphological configurations was identified to illustrate a technique that assesses the influence of form on the energy efficiency of buildings. The climate and environment of Al Mafraq-Jordan are taken as a case study to explore the effects of shape factors on the energy performance of buildings. The study analyzed the outcomes to determine how the form of a building affects its energy performance. Additionally, the research established a number of shape parameters that might be useful in figuring out how a building's form and primary energy loads relate to each other, including lighting, heating, and cooling. The design tools are crucial in the initial design phase, encompassing the investigation model, evaluation of selected analogies, and abstract exploration channels. In this phase, different organisms with unique adaptation strategies are examined, as they provide insight into the abstraction of their methodologies. The final results showed that the more compact the external envelope is, the more energy-efficient the building will be. The main recommendation was to explore more geometric shapes further compared with a base compact shape, which is the sphere regardless of the diameter, as this will help include such results in the development of building codes for design practices in Jordan.

## 1. INTRODUCTION

In the construction industry, there is a rising need to reduce energy consumption in buildings. To address this issue, the development of energy-efficient technologies and services is becoming more crucial. One approach is to draw inspiration from nature, which employs strategies to regulate body temperature within narrow ranges using physiological, morphological, and behavioral methods. Some organisms achieve this through their skin, while others rely on their built structures. The key components that contribute to reducing heat loss are the medium's morphology, assembly, and structure, which can be applied analogously in buildings.

Inspired by nature's strategies, where form generation is driven by maximal performance with minimal resources through local material property variation, there is huge potential for innovative thermal solutions, especially at the conceptual phase, where exposure to relevant biological examples is involved [1]. Biomimetics is a rapidly growing discipline in engineering and an emerging design field in architecture. Solutions are obtained by emulating strategies, mechanisms, and principles observed in nature.

Due to the interdisciplinary nature of this field, designers often face difficulties throughout the design process, where biophysical information is not easily accessible.

The current research combines both disciplines; to summarize, the main objective of this research is to develop guidelines related to the relationship between geometric form and energy consumption and thermal performance, based on the analysis of the relationship between surface area and volume of natural organisms existing in nature.

The challenging issue facing the thermal design of buildings in Jordan is ignoring the shape factor represented by the concept of surface-to-volume ratio as a basic parameter in thermal calculations of buildings; the thermal insulation code of practice in Jordan ignores this fact [2]. The procedure of thermal design calculations considers the external building area, but the problem resides in the fact that the procedure adopted does not categorize the factor of external area as a function of climate zone and the objective of searching for the minimum external surface area aimed to minimize energy consumption and at the same time not sacrificing the intended functional design. This work is an initiator to establish and define this missing phase in the thermal design procedure, the concept has grown from the explorations of organisms' adaptation to the harsh climate in terms of energy intakes, and many studies found in the literature have addressed this issue, which is explored in the following section.

## 2. LITERATURE REVIEW

Analogy inspired many scientists in different disciplines to develop applications and theories for human use, examples are numerous, analogies of birds to be applied to aviation and planes, and eye structure in birds used to develop zoom lenses just to mention. Relationships among animal mass, volume, surface area, and energy consumption have been studied to understand such relationships and their probable applications; in a study of 126 species of pollinating insects from 4 orders, water loss was measured at very dry conditions by investigating the surface to volume ratio of those insects, small insects with larger surface area had the highest water loss. The surface-to-volume ratio provided a promising method to predict physiological responses, improving the potential of body mass isometry alone that assume geometric similarity [3]. Surface-volume relationships are of widespread functional significance in biological systems which shape the surface-volume relationships, a study depicted a mathematical relationship between the surface area and the volume of 29 species of birds' eggs [4]. Buildings, as they are considered a subsystem in the overall ecologic system, consume energy and emit pollution, as the building is basically for human occupancy it consumes energy either for cooling or for heating, thus the volume of the indoors is strongly related to the filtering system which is the external surface area, on the one hand; on the other hand, on the urban level, the issue of energy consumption is of great importance, and the concept of surface area and volume applies, but in some different way; a concept called urban compactness. Many studies have been conducted on the urban level in different regions of the world. Salvati et al. [5] explored the double effect of urban compactness on building energy performance in a Mediterranean climate, the increase of urban heat islands and the intensity of solar radiation availability on buildings' facades, results showed that compact urban textures are more energy efficient than less dense urban patterns; Sun et al. [6] reviewed indexes for urban compactness like Spatial Autocorrelation, Nearest Neighbour Distance, Shape indexes, and Gravitation indexes. A considerable number of works have been implemented regarding the compactness of buildings and its effects on energy consumption. Mokrzeka [7] investigated the impact of preliminary design decisions such as building shape and orientation on heating demand, a squared-shaped building has been studied and analyzed in terms of functional layout and shape; similar studies are found in references [8-10]. For a complete list of literature refer to Table 1.

**Table 1.** Previous studies explored and studied the concept of the compactness factor of buildings and its effects on energy consumption and thermal performance

| Authors and Research Location | Research Method and Tools | Results and Conclusions |
|---|---|---|
| D'Amico and Pomponi [11] | Numerical Analysis with case studies from different countries. Google Earth assisted. | Quantified how much a building form deviates from optimality and identifying the domain of alternative geometries. Results are purely theoretical. |
| Koźniewski et al. [12] | Numerical analysis, comparative analysis with a sphere case base compared with cuboid geometric shapes. | A set of proposed indicators that allow for a description of the compactness of the building model applied to two groups: standing buildings and projects still on table. |
| Pessenlehner and Mahdavi [13] | Extensive parametric thermal simulations. Examining the reliability of simple compactness indicators for energy-related evaluative assessments. | An initial proposal for energy and thermal performance codes on a base of numerous building simulations in which a compactness factor is included. |
| Steadman et al. [14] | Using LIDAR remote sensing technologies to survey 3.2 million blocks in London to explore Bon's relationship between wall area and volume scaled as W- $V^{0.77}$, and Steadman similar relationship. | Results found that allometric coefficients converge to values of around 0.77, confirming the magnitude of Bon's relationship, proving that this relationship could be generalized to the very largest urban scale. |
| Almumar [15] | A new understanding for building compactness, an investigation of the variation effect of the thermal envelop area on the indoor environment efficiency as a function of surface-to-volume ratio. The method is purely numerical. | A contribution of architectural design process to ensure efficient indoor environment and energy saving. |

## 3. MATERIALS AND METHODS

Analyzing nature as a source to innovate new approaches and strategies to improve energy efficiency in buildings is found in the literature.

Architecture is intended to serve human beings in all of their lives, this is supposed to be in complete harmony with the surrounding environment, yet, an ideal architecture fits completely with the needs of human beings, and at the same time in full harmony with its environment.

To solve this problem, researchers attempted many approaches; such as organic architecture, climate-responsive architecture, and recently sustainable and green architecture. Still, such approaches need to be refined and only provide short-term solutions.

This article investigates this issue, including adapting to climate change to allow continual growth and human development.

The main method depends mainly upon the analytical approach as a first phase. Then, a descriptive approach attempts to categorize strategies and techniques explored in nature that produce creatures in complete harmony with nature and the environment according to minimum energy requirements. The final phase tries to develop a system inspired by natural design procedures to be involved in architecture as a preliminary target, energy efficiency issues will be investigated, but this will be determined definitely after completing phase one and phase two, in this stage, software packages and numerical approaches might be used, but not limited to them. A research methodology is carried out to accomplish research objectives; an analytical study for cases from nature is presented and analyzed into three levels: form, process, and ecosystem. This multi-level approach is most effective for achieving solutions that inspire sustainable performance, then analyzing analogies from nature; a comparison between two or more living organisms, typically based on their structure, and for explanation and clarification. Finally, a set of principles is generated mostly to lead to system development. Figure 1 shows a comprehensive procedure to develop guidelines for buildings obtained from the analysis of living organisms' relationships among organism volume, surface area, and energy consumption with their relationship with the surrounding environment.

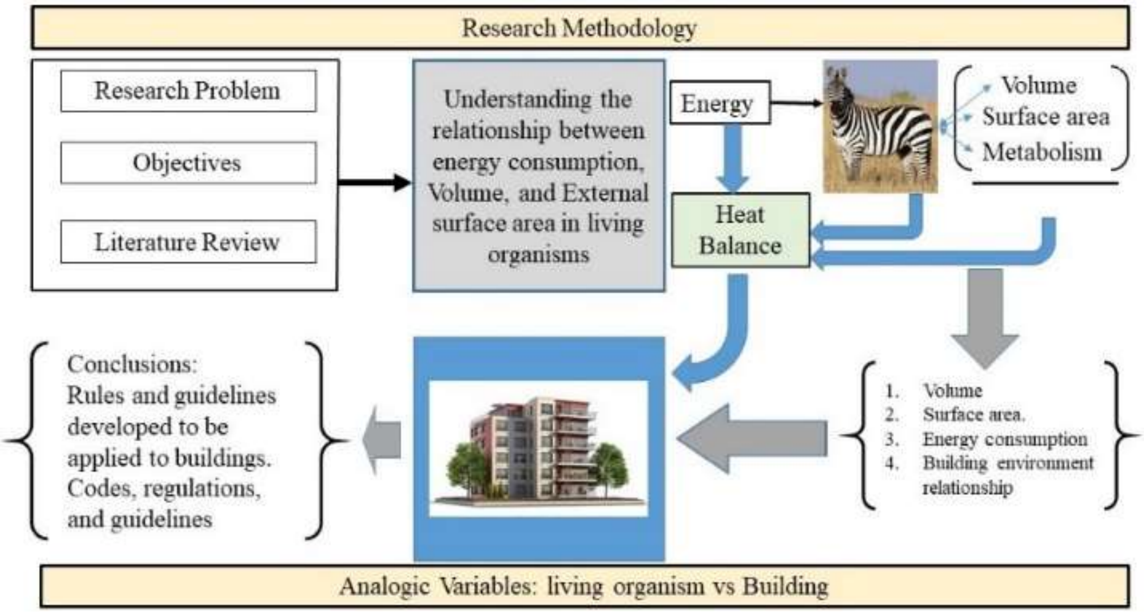



**Figure 1.** Summary of the research methodology adopted in this article

The transformation of procedures accessible in nature into specialized solutions to improve energy efficiency in buildings is a complex multidisciplinary process. It turns out to be much more complex and frequently conflicts arise when incorporating various methodologies from various organisms to accomplish improved solutions. Therefore, an extended methodology aimed at the preliminary design stage. This stage involves managing the investigation process and organisms' examination and ends up leading the architect to a design concept.

According to Gruber's [16] book, the classification of biophysical data tends to be difficult because it relies on functional aspects to build a proper analogy. Additionally, various elements are assigned to each other according to their affiliation, which was also confirmed by Steadman [17].

## 4. THERMAL BEHAVIOR OF BUILDINGS

Efficient use of energy and sustainability have become crucial issues for almost all energy policies. Energy efficiency and sustainability specifications emerged in the building construction industry too since buildings consume the most significant amount of energy.

The thermal behavior of buildings is one of the most important criteria of effective building design, giving the most comfortable environment for occupants and in this manner limits the energy demand for cooling and heating purposes. Its significance is related to the energy crisis, environmental pollution, and climate change, which was brought about by the inordinate utilization of energy in buildings. It manages the heat flow among buildings and outdoor environments, expressed as heat gain and loss. Building parts, for example, walls, windows, and roofs, and their materials influence these mechanisms. Additionally, it will clarify the methods of heat transfer among the building and its surroundings, which comprise conduction, convection, and radiation. It will outline the factors that affect thermal performance: design variables, material data, building usage data, and weather data. handling sources of heat gain and heat loss. Finally, examining building operations and occupancy.

## 5. MORPHOLOGICAL CONFIGURATIONS INSPIRED BY NATURE

### 5.1 The relation of the parts to the whole in the organism

Critics and philosophers of ancient Greece regarded natural organisms as an ideal model of harmonious balance and proportions between pieces of design that are in line with classical beauty ideals. The quality of wholeness, integrity, and structural unity is central to Aristotle`s aesthetics and natural history, as all parts are involved in the effect or intent of the whole and cannot be eliminated without compromising the whole. Concept, Aristotle's view of the characteristics of both creatures and the best work of art. Moreover, Aristotle's natural history is not limited to the fact that each member or structure serves a particular purpose or function. However, each of these features of the part serves and contributes to the overall purpose of the whole [18].

There are two interpretations of the analogy, one related to visual appearance or composition and the other related to function. Although both are related.

One of the basic geometrical properties of buildings studied in the past on a low scale and on small samples is the surface-to-volume ratio or volume to external wall area, without considering roofs, the pioneer of studying this concept was Ranko Bon who was a member of the Philomorphs in the 1960s who extended the biological concept to social systems, cities, and buildings [19]. The description of the ways in which organisms change shape as they increase in size during development in order to preserve certain geometrical properties for physiological function is called "Allometry", which was first coined by Huxley and Teissier in 1936 [20]. The surface-to-volume ratio is one of these properties, this characteristic affects heat loss or gain through the skin, thus establishing a strong relationship between the animal's mass, volume, and external skin surface area. Criticism has been made against drawing analogies between animal physiology and the functioning of buildings [17]. Buildings do not grow rather they are extended, while the form of animals is more flexible than buildings; despite this, there can be allometric relationships between the volumes and external surface areas of a building.

### 5.2 Form and the concept of compactness

Mechanical, environmental, and processes dictate organisms' form corresponding to some physics laws. for example, the weight of a blue whale could be 10 million times more than the weight of a mouse, on the other hand, the surface area larger only 10 thousand times [21].

Scientists have studied the issue of body size and function for at least three centuries. Inquiries stemmed both from theoretical hypotheses concerning the similarity of structure and function in animals and from practical deliberation. For example, how to quantitatively figure out food amounts for humans and animals, considering contrasts in size [22], as for the relationship between organisms' mass. The energy required for movement and survival is dictated by the experimental rule called the "quarter power" relationship suggested by Kleiber: energy (metabolic rate) = $\sqrt[3]{(organism\ mass)^4}$ ; the observation that for most animals, metabolic rate scales to the 0.75 power of the animals mass [23-25].

Natural organisms demonstrate consistent relationships between body volume, body mass, and external surface area with metabolism measured in watts/m$^2$, an example of this is the metabolism of the human body, Du Bois (1916), Wang's geometric model, and Lee JY (2008), developed experimental equations to quantify these variables, the Du Bois equation reads:

$$\text{External surface body area (m}^2\text{)} = (0.202) \times (\text{body mass (kg)})^{0.425} \times (\text{body height (m)})^{0.725}$$

This is related to the heat produced by the human body due to different human activities [26].

### 5.3 Analysis of Bergman's rule

As indicated by Bergmann's rule; surface to volume ratio is a critical factor for animals occupying cold environments to keep internal heat level over the encompassing heat, where bigger creatures have to produce less heat relatively than smaller animals [27]. As shown in Figure 2, below basal metabolic rate (BMR) correlated to size exponentially and that applied to nearly all animals [28]. Besides, the inclination to have bigger protruding parts, such as ears, limbs, and tails; in individual organisms of the same species inhabiting cold and warm climates, is higher in warm conditions than in cool ones according to Allen [29]. Body size, sex, and age influence the relationship between size and metabolic rate [30], which could be a base for an analogy between living organisms and building thermal performance.

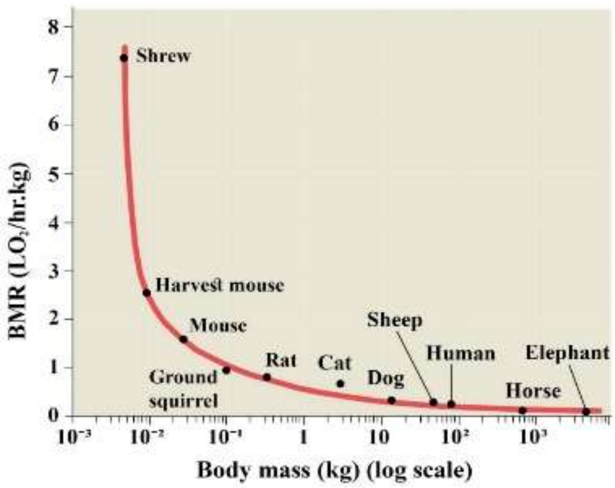



**Figure 2.** Relationship between body mass (x-axis) and basal metabolic rate also known as 'resting energy demand' (y-axis) [31]
(http://katclassics.files.wordpress/2015/06/metabolic-rate.jpg, retrieved July 2023)

As illustrated in Bergmann's and Allen's principles, in most cases, a significant relation between the size, growth, and shape of an animal and the temperature of the surroundings. The surface area to volume ratio plays a major role in dissipating or retaining heat. The increase in size correlated with heat conservation and, the decrease in size correlated with heat dissipation, where an optimal surface area to volume is applied. Analogic to living organisms in nature as subsystems in nature, buildings represent a subsystem in within the surrounding environment; therefore, minimizing the envelop surface area for a certain enclosed volume is a clear objective to maximize the energy efficiency of buildings in a certain climatic region; which in turn, help lower embodied energy and environmental impacts [11, 32, 33].

### 5.4 Impact of building form on energy performance

Shape plays an important role in the environmental and energy performance of buildings [34]. Since the early 1960s, some principles for optimizing building form have been established, based on the assessment of the climatic characteristics of the site. More recently, various authors developed varied studies focused on establishing the correlation between the energy efficiency of buildings and design Analysis from parametric simulations forms the basis of the majority of these works. Nevertheless, there is a lack of comparative analysis of the influence of building form under very different climatic conditions. In parallel, few studies attempt to simultaneously examine the impact of building shape on the three main energy loads: heating, cooling and lighting [35, 36]. As for the compactness of single buildings affects energy efficiency; it is worth mentioning the compactness on the urban level, Salvati et al. [37] found that compact urban textures are more energy efficient than less dense patterns in a Mediterranean climate.

Hajtmanek et al. [38] used and analyzed Robinson and Stone's cumulative Sky algorithm and Kittler and Mikler's model as tools to analyze the surface-to-volume ratio for facades, aiming to maximize solar facade exposure. They quantified energy generation based on the concept of surface-to-volume ratio.

A considerable amount of energy for cooling and heating is used in our buildings. Buildings account for over 40% of the worldwide energy consumption while heating and cooling account for 50-70% of the total energy consumed in buildings. The thermal performance of buildings is impacted by the physical properties of materials applied in construction, where conductivity, emissivity, and absorptance play major roles. Significant energy savings could be accomplished in buildings if materials are adequately designed, selected, and applied [39]. This issue can be explored by analyzing the relationship between organism volume, external surface area, and compactness factor, as shown in Figure 3.

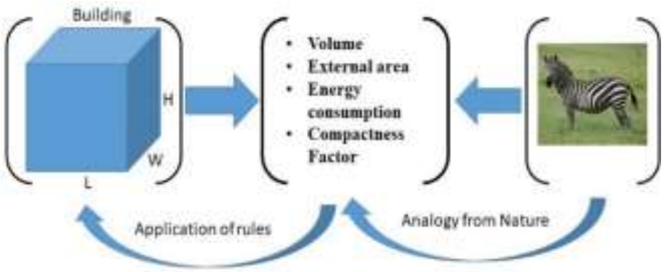



**Figure 3.** Inspiration from nature as a source to develop the thermal performance of buildings
Source: Authors, 2023.

Most organisms use morphological characteristics to supplement physiological and behavioral thermoregulatory strategies [40].

### 5.5 Parametric research

This study is based on results of parametric research conducted using Design Builder/Energy Plus building energy simulation programs. The key energy loads, heating, cooling, and lighting, were calculated for eight different scenarios, considering the climate of the Al Mafraq region, to determine each building form's overall heat balance. To evaluate the performance of energy efficiency measures in the model house, the parameters of the dwelling that affect energy consumption will be defined and the most important modeling criteria are explained in the following sections. The parameters are:

- Weather data.
- House characteristics.
- Building envelope.
- Cooling and heating systems.
- Lighting.

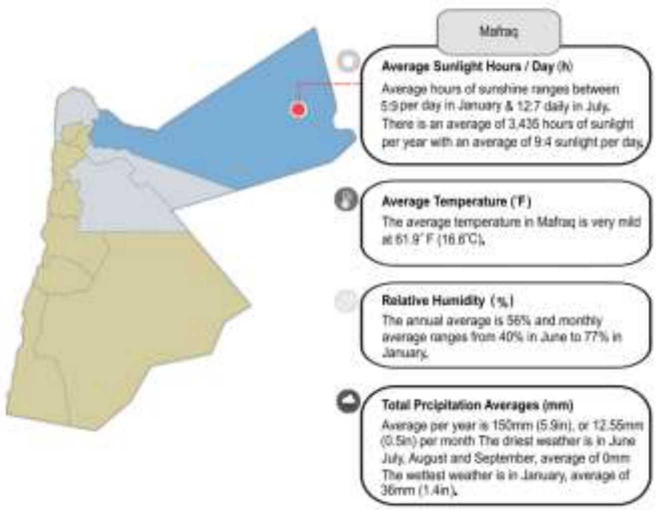
## 6. DESIGN BUILDER SOFTWARE

Design Builder is a user-friendly modeling environment where you can work (and play) with virtual building models. It provides various environmental performance data such as annual energy consumption, maximum summertime temperatures, and HVAC component sizes. Some typical uses are: Calculating building energy consumption and evaluating façade options for overheating and visual appearance. Thermal simulation of naturally ventilated buildings. Daylighting-models lighting control systems and calculates savings in electric lighting. Visualization of site layouts and solar shading. Calculating heating and cooling equipment sizes. Communication aid at design meetings. An educational tool. A comprehensive range of simulation data can be shown in annual, monthly, daily, hourly, or sub-hourly intervals: Energy consumption broken down by fuel and end-use. Internal temperatures, weather data Heat transmission through building fabric including walls, roofs, infiltration, and ventilation. Heating and cooling loads. $CO_2$ generation, heating and cooling plant sizes can be calculated using design weather data. Parametric analysis screens allow you to investigate the effect of variations in design parameters on a range of performance criteria. Generate Energy Plus IDF files and work with these outside Design Builder to access Energy Plus system functionality not provided by Design Builder [41].

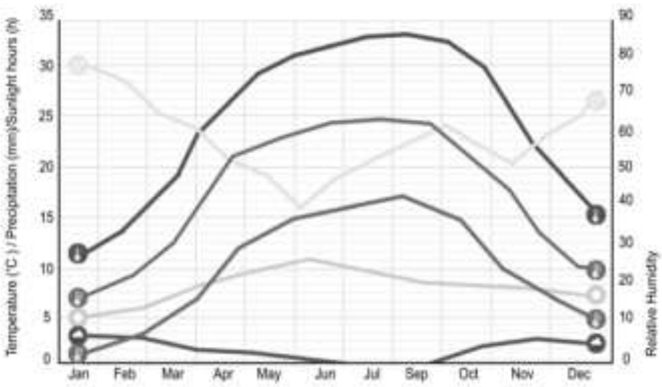
## 7. STUDY AREA: CLIMATE AND ENVIRONMENT

Mafraq is located in the west of Mafraq Governorate. At the intersection of longitude 36.1 degrees east and latitude 32.2 degrees north. It is far from Amman around 65 kilometers. Its location borders three Arab countries: Syria to the north, Iraq to the east, and Saudi Arabia to the south. The city is directly linked with the governorates of Irbid, Jerash, and Zarqa by main roads.

The climate in Mafraq is semi-desert, as depicted in Figure 4, and distinguished by hot, dry weather in summer and cold weather in winter. Two main seasons are dominant: summer, which begins in mid-May and ends in September, and winter, which begins in November and ends by the end of April. Spring does not extend beyond April and May, while autumn is limited to September and October. The highest monthly average temperature is in August and reaches 32.6°C; the lowest monthly average temperature is 2°C in January, with an annual average temperature of 16.6°C according to the Department of Meteorology in Jordan. In addition, the city has an average relative humidity of 36%. The city has the lowest annual rainfall average in the country, which does not exceed 150 millimetres a year (Figure 4).




(A)



(B)

**Figure 4.** (A) Mafraq Governorate, Hashemite Kingdom of Jordan (32.2°N 36.1°E, 705m), (B) Climate Summary illustrates the typical weather data in Mafraq, based on a statistical analysis of historical hourly weather reports from January 1, 1980, to December 31, 2016 [42]
Source: Authors, 2023.

## 8. THE CASE STUDY: DEVELOPING BUILDING CUBOID SCENARIOS

Eight scenarios of building forms are proposed according to a modular scheme. All building shapes consist of a certain number of square modules: 20 modules; 12m by side as shown in Figure 5. In addition, all building shapes have a room height of 3m and an internal volume of 3840m³ (Table 2). The compactness factor is measured using the formula: Compactness factor=external surface area of the building / total confined volume by the external envelop; abbreviated as follows:

$$CF = S / V \quad (1)$$

where,

CF: Compactness Factor, $m^{-1}$.

S: external surface area of the building, $m^2$.

V: Building volume confined by the external envelop $m^3$.

For a parallelogram geometric-shaped building, the external surface area is calculated as follows:

$$S= [[\sum_{i=1}^{n}(length \times height) \times (number\ of\ walls)] + [\sum_{i=1}^{n}(width \times height) \times (number\ of\ walls)] + \sum_{i=1}^{n} roof\ area] \quad (2)$$

Different building design scenarios emphasizing the concept of keeping the same confined air volume while varying different external envelop area are developed; which implies different ratios of compactness, this is to study and investigate the influence of the relationship between the building volume and the corresponding external surface area, on the thermal performance and consequently on the annual heating and cooling loads. The main idea was to create different building block configurations representing complete and functional design blocks, with fixed indoor air volume and varying external surface area. This was resulted in eight different basic geometric functional building shapes; they are shown in Table 2 for scenarios from 1 through 8, and they are numbered in the table from scenario one to scenario 8. The proposed scenarios are just to cover the varying range of probable design alternatives but not restricted to them; a further study might explore a wider range of geometric shapes and typologies. The different scenarios shown below are restricted to cuboid building geometry, while other possibilities might be obtained such as octagonal, circular, and cuboid spread-out shapes.

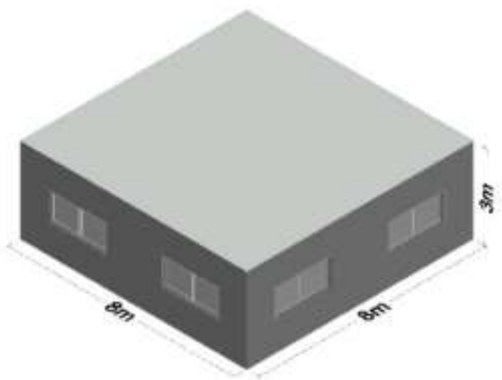
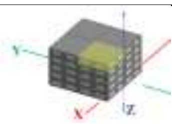



**Figure 5.** An example of basic module in all building scenarios (Variables are width, length and height)
Source: Authors, 2023.

**Table 2.** Modular definition of building form scenarios, cuboid category

| **Building Geometric Variations to Confine the Same Indoor Volume While Obtaining Different External Envelop Surface Area and Different Compactness Factor** | | | | |
|---|---|---|---|---|
| Scenario Number | Scenario Category | Number of Modules (x, y, z) (meter) |  Modular Definition of 7 Building Forms | External Surface Area (S) Total Confined Volume (V) F: (S, V) |
| 1 | Scenario A F (1,4,5) Total volume (8640) $m^3$ | Building dimensions Width=8 Length=32 Height=15 |  | S=1200+256=1456$m^2$ V=3840$m^3$ S/V=0.37$m^{-1}$ |
| 2 | Scenario B F (1,5,4) | Building dimensions Width=8 Length=40 Height=12 |  | S=1152+320=1472$m^2$ V=3840$m^3$ S/V=0.38$m^{-1}$ |
| 3 | Scenario C F (1, 1, 20) Total volume (8640 $m^3$) | Building dimensions Width=8 Length=8 Height=60 |  | S=2880+64=2944$m^2$ V=3840$m^3$ S/V=0.76$m^{-1}$ |

| | | | | |
|---|---|---|---|---|
| 4 | Scenario D F (1, 2, 10)<br>Total volume<br>($8640m^3$) | Building dimensions<br>Width=8<br>Length=16<br>Height=30 |  | $S=1440+128=1568m^2$<br>$V=3840m^3$<br>$S/V= 0.4m^{-1}$ |
| 5 | Scenario E F (2, 5, 2)<br>Total volume<br>($8640m^3$) | Building dimensions<br>Width=16<br>Length=40<br>Height=6 |  | $S=672+640=1352m^2$<br>$V=3840m^3$<br>$S/V=0.35m^{-1}$ |
| 6 | Scenario F F (2, 2, 5)<br>Total volume<br>($8640m^3$) | Building dimensions<br>Width=16<br>Length=16<br>Height=15 |  | $S=960+256=1116m^2$<br>$V=3840m^3$<br>$S/V=0.25m^{-1}$ |
| 7 | Scenario F separated F (2, 2,5)*4<br>Total volume<br>($8640\ m^3$) | Building dimensions<br>Width=16<br>Length=16<br>Height=15 |  | $S=1920+64=1984m^2$<br>$V=3840m^3$<br>$S/V=0.5m^{-1}$ |
| 8 | Scenario G F (4, 5, 1)<br>Total volume<br>($8640m^3$) | Building dimensions<br>Width=32<br>Length=40<br>Height=3 |  | $S=432+1280=1712m^2$<br>$V=3840m^3$<br>$S/V=0.44m^{-1}$ |

Source: Authors, 2023.

**Table 3.** General dimensions and parameters of the building scenarios

| Scenarios (Row × Modules × Story No.) | General Dimensions and External Surface Areas | | | | | | | | | Shape Parameters | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | H(m) | L(m) | W(m) | No. of Levels | Walls ($m^2$) | Floor ($m^2$) | Ext. Surf. ($m^2$) | Glazing ($m^2$) | Vol./Ext. Surf | Ext. Surf./Vol. | Wall/Ext. Surf. | Wall/Vol. |
| Scenario A 1×5×4 | 15 | 48 | 12 | 5 | 1800 | 576 | 2376 | 506.22 | 3.63636 | 0.28 | 0.76 | 0.21 |
| Scenario B 1×4 ×5 | 12 | 60 | 12 | 4 | 1728 | 720 | 2448 | 283 | 3.5 | 0.28 | 0.70 | 0.2 |
| Scenario C 1×20 | 60 | 12 | 12 | 20 | 2880 | 144 | 3024 | 793.44 | 2.857143 | 0.35 | 0.95 | 0.33 |
| Scenario D 2×10 | 30 | 24 | 12 | 10 | 2160 | 288 | 2448 | 606.84 | 3.529412 | 0.28 | 0.88 | 0.25 |
| Scenario E 2×5×2 | 6 | 60 | 24 | 2 | 1008 | 1440 | 2448 | 369.76 | 3.529412 | 0.28 | 0.41 | 0.12 |
| Scenario F 4×5 | 15 | 24 | 24 | 5 | 1440 | 576 | 2016 | 406.4 | 4.285714 | 0.23 | 0.71 | 0.17 |
| Scenario F 4×5 -modules separated | 15 | 29 | 29 | 5 | 2880 | 576 | 3456 | 797.28 | 3.650174 | 0.27 | 0.83 | 0.23 |
| Scenario G | 3 | 60 | 48 | 1 | 648 | 2880 | 3528 | 190.28 | 2.44898 | 0.41 | 0.18 | 0.08 |

External walls area refers to the net area including the glazing area.
Source: Authors, 2023.

**Table 4.** Physical properties of each material for internal walls

| Material | Thickness (mm) | K (W/m.k) | R ($m^2$.K/W) |
|---|---|---|---|
| R. | | | 0.040 |
| plaster | 25 | 0.72 | 0.034 |
| Hollow block | 100 | 0.74 | 0.135 |
| plaster | 25 | 0.7250 | 0.034 |
| $R_{\circ}$ | | | 0.13 |
| **U Value (W/$m^2$-K)** | | | 2.152 |

Source: Authors, 2023.

The following describes the different building scenarios developed for this study:

*Scenario A*

Scenario A building type, which consists of four columns and five rows of modules (each resembles a 144 square meter apartment). Columns 1 and 4 have the largest areas of exterior walls and windows which means higher exposure and contact with the exterior environment and weather conditions, whereas columns 2 and 3 have fewer external surfaces thus less energy losses to the exterior environment and more gains from attached modules.

*Scenario B*

Scenario B resembles a building that consists of five vertical columns and four vertical rows, using 20 modules with 12×12m dimensions for each module. Each exterior wall is glazed by 30 percent low-E glass windows.

*Scenario C*

Scenario C consists of 1 column and 20 rows consisting of 20 identical 12×12m modules with a 30% glazed area on each façade. Which is the most commonly used form in residential buildings in Jordan.

*Scenario D*

Scenario D consists of 2 columns and 10 rows. Each row consists of two 12×12m modules. Each one of the exterior walls has 30 percent glass in its total area.

*Scenario E*

Scenario E, consists of the same modules in previous scenarios, yet in this scenario, an arrangement of horizontal plane modules, which means larger ground areas are required for this arrangement, described as 10 columns, each 5 are attached to the others around a long axis, each has two rows (ground and first floor only).

*Scenario F*

Scenario F consists of 20 identical modules, arranged in 4 attached columns; each has 5 rows which resembles 5 stories building with a 576 square meter floor area, with 30% glazed area of total exterior wall area, columns are attached with interior wall with layers shown in Tables 3 and 4, it's not insulated which allows energy transfer between all these modules.

*Scenario F with spacing*

Scenario F with spacing is almost the same as the previous scenario, yet all four columns are separated with 5 meters spacing, so each module has four exterior walls, and the surrounding buildings shading will affect it. Each column resembles a separate five-story building. This option provides more daylight and natural ventilation for each module when compared to the previous one.

*Scenario G*

Scenario G consists of a single level of 20 modules, arranged in rectangular 48×60m. All modules are attached with no spacing. In addition, all modules are attached to the ground from the ground floor slab and exposed to the external environment from the roof side.

The basic concept of this methodology is to generate a wide range of building shapes while standardizing their geometric properties. Building shapes with one or more floors are displayed in an improved manner, including only the upper, lower and one of the mezzanine floors.

The total glazing area varies depending on the building shape, as shown in Table 2. Additionally, these parameters are listed for the seven scenarios along with their general dimensions. It is important to note that the entire exterior surface includes walls, roof and exterior floor.

It was observed that the largest façade of each building shape was modeled facing south. Given that the primary goal of this research is to determine how form affects a building's energy performance, shape-defining parameters are especially important. Based on an initial examination, the subsequent parameters appear to have a higher potential for identifying the connection between form and energy efficiency:

Vol. / Ext. Surf. - Total internal volume divided by Total external surface area (Compactness).

• Ext. Surf. / Vol. - Total external surface area divided by Total internal volume (Form factor).

• Wall / Ext. Surf. - Total wall surface area divided by Total external surface area.

• Wall / Vol. - Total wall surface area divided by Total internal volume.

## 8.1 Internal gains

Internal gains, which in this context are strongly related to the use of buildings, were grouped into three general categories: occupancy, amenities and artificial lighting. To simplify the analysis, one type of module was adopted; each module resembles a 122-square-meter residential apartment unit for four people, which includes a typical kitchen, living room, two bedrooms, and a toilet. The modules are identical in all scenarios, but differ in their arrangement. Maximum win rates are taken into account for occupancy, amenities and lighting.

## 8.2 Building envelop

Regarding the buildings' thermal performance, the same set of constructions utilized in all the simulation models has a largely neutral effect. The basic measure that indicates the thermal performance of all building boundaries, which separate the indoor from the outdoor, is the overall transmittance value (U-value). To calculate the U-value, the Thermal resistance of each material is defined as follows:

$$R = d / k \tag{3}$$

where,

R: Thermal Resistance (m². K/W).

d: Material Thickness (m).

k: Thermal Conductivity for each material (W/m. K) and thermal resistance for multilayer of composite wall construction is:

$$R_{total} = \sum\left[R_{I+}R_1 + R_2 \ldots\right] + R_{\circ} \tag{4}$$

where,

$R_{total}$: Total Thermal resistance (m². K/W).

$R_i$: Internal surface thermal resistance (m². K/W).

$R_{\circ}$: Outer surface thermal resistance (m². K/W).

$R_1$, $R_2$...$R_i$: Composite material thermal resistances (m². K/W).

In addition, the thermal transmittance (U-Value) for composite wall construction will be as follows:

$$U = 1 / R_{total} \tag{5}$$

where,

U= Overall Thermal transmittance (W/m². K).

External envelopes interact with the outdoor thermal condition dynamic continuously; therefore, not only is the interaction through the external building surface restricted to conduction, but also by radiation and convection, more information is found in study [18].

## 8.3 Cooling and heating systems

The main settings of the cooling and heating system are the following:

- The heating system runs with a set point temperature of 21℃ during occupied times and 12℃ during unoccupied times.
- The cooling system, which has a set point temperature of 25℃, only runs when people are present. The primary set points fall within Standard EN 15251:2007's recommended ranges.
- Both set points are based on operating temperatures, meaning that heating and cooling systems must account for both convective and radiative components of the global thermal balance. This approach provides greater sensitivity for comparing the performance of different building forms.
- The set point relative humidity for dehumidification is ninety percent, and for humidification it is ten percent. It indicates that during occupied periods, the relative humidity of the interior air was maintained between 10% and 90%.
- A fresh air rate of 10 l/s-person is taken into consideration when using mechanical ventilation.

## 8.4 Lighting

As for artificial lighting, its control in the peripheral zones (not in the central ones) is modeled based on daylight availability. Besides, we used LED lighting with normalized power density (W/m$^2$-100 lux); and luminaire light to maintain the required level of illuminance during occupied periods. These modelling criteria intend to evaluate how building shape determines the potential performance of indoor daylight factors.

### 8.5 The impact of shape and form

Using parametric simulations, energy loads were determined for each of the seven climate scenarios in Al Mafraq. These loads included lighting energy consumption as well as loads related to HVAC systems (heating and cooling). In this investigation, the energy load - which includes lighting, heating, and cooling-is proposed as a comprehensive way to measure, compare, and forecast the energy performance of the various building forms.

Figure 6 shows an ascending ranking of building shapes according to their level of compactness, the different configurations concentrate on the effect of the relationship between the external surface area and the confined air volume of the building, as the external surface area is the variable which controls and filters the thermal exchange between the outdoor climatic variables and the indoor of the building. According to the heat transfer conduction formula:

$$Q(\text{Watts}) = \text{Area} \times \text{overall thermal transmittance value} \times (|T_{outdoor} - T_{indoor}|)$$

Which implies that the larger the area, the greater the heat transfer between indoor and outdoor areas, considering the physical properties of the external walls as shown in Table 5.

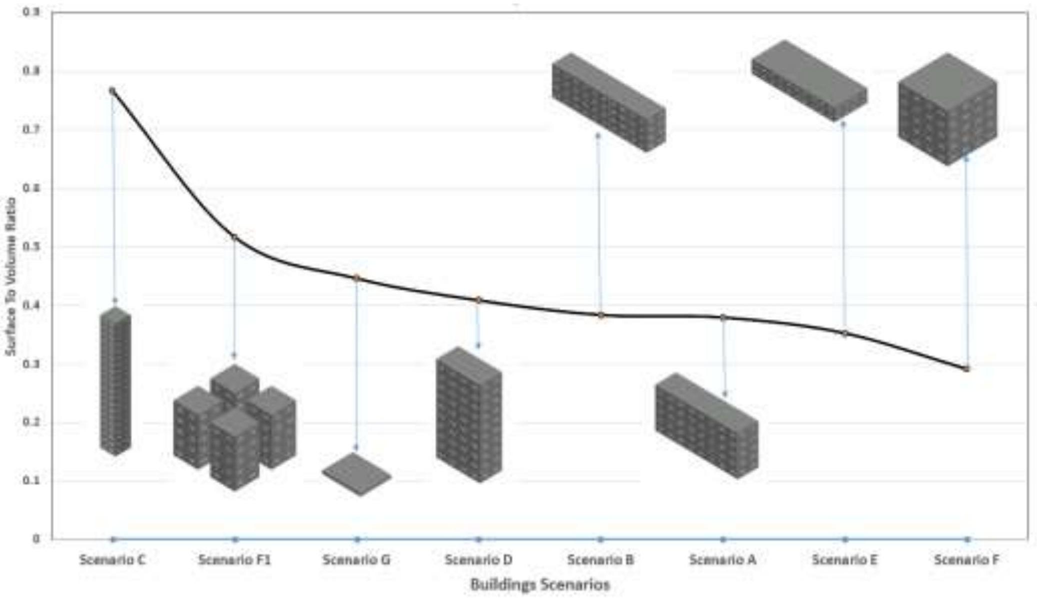



**Figure 6.** Descending the ranking of surface-to-volume ratio as a function of building dimensions and geometry for the developed scenarios

The most compact form is scenario F, and the least compact form is scenario C.

**Table 5.** Physical properties of each material for external walls

| Material | Thickness (mm) | K (W/m.K) | R (m².K/W) |
|---|---|---|---|
| R. | | | 0.04 |
| dimensioned stone | 30 | 2.27 | 0.013 |
| Aerated Concrete | 100 | .16 | 0.625 |
| Insulation: Expanded Polystyrene (EPS) | 50 | .046 | 1.08 |
| Hollow concrete block | 100 | 0.74 | 0.135 |
| Plaster | 20 | 0.72 | .028 |
| R$_\circ$ | | | .13 |
| U value (W/m².K) | | | 0.49 |

Source: Authors, 2023.

## 9. RESULTS AND DISCUSSION

Since the main goal was to connect variations in energy loads with parameter values, an analysis of correlations between form parameters and energy loads was attempted. To ascertain parameters pertaining to energy loads, the outputs underwent analysis.

High coefficients of determination for the Wall/Volume parameter were found for lighting loads in almost all scenarios. There is a comparison between cooling loads and the Wall/External surface parameter and between heating loads and the External surface/Volume parameter. Put differently, lighting, heating, and cooling loads are correlated with Wall/Volume, External surface/Volume, and Wall/External surface parameters, respectively.

A more thorough analysis of thermal performance provides very interesting information. The energy consumption values are displayed in the ensuing graphs, Figures 7 and 8, as the difference between the minimum and maximum values for the various scenarios. These ranges might convey the degree to which form has an impact in this particular climate type.

As shown in Figure 9, scenarios 1, 2, 4, 5, and 6, are the most compact geometric forms among the total scenarios group, but the corresponding annual energy consumption for heating and cooling loads do not tell a clear correlation between the (s/v) variable as a compactness measure and the corresponding annual energy consumption; this is because the total energy consumption includes lighting which it seems of no relation with the compactness factor. Heating and cooling loads may correlate with the compactness factor, but this might hide some uncontrolled variables such as openings sizes and varying thermal transmittance, which might affect the influence of compactness on thermal performance. However, it is strongly recommended to explore a new method to establish a correlation between compactness factor and annual energy consumption.

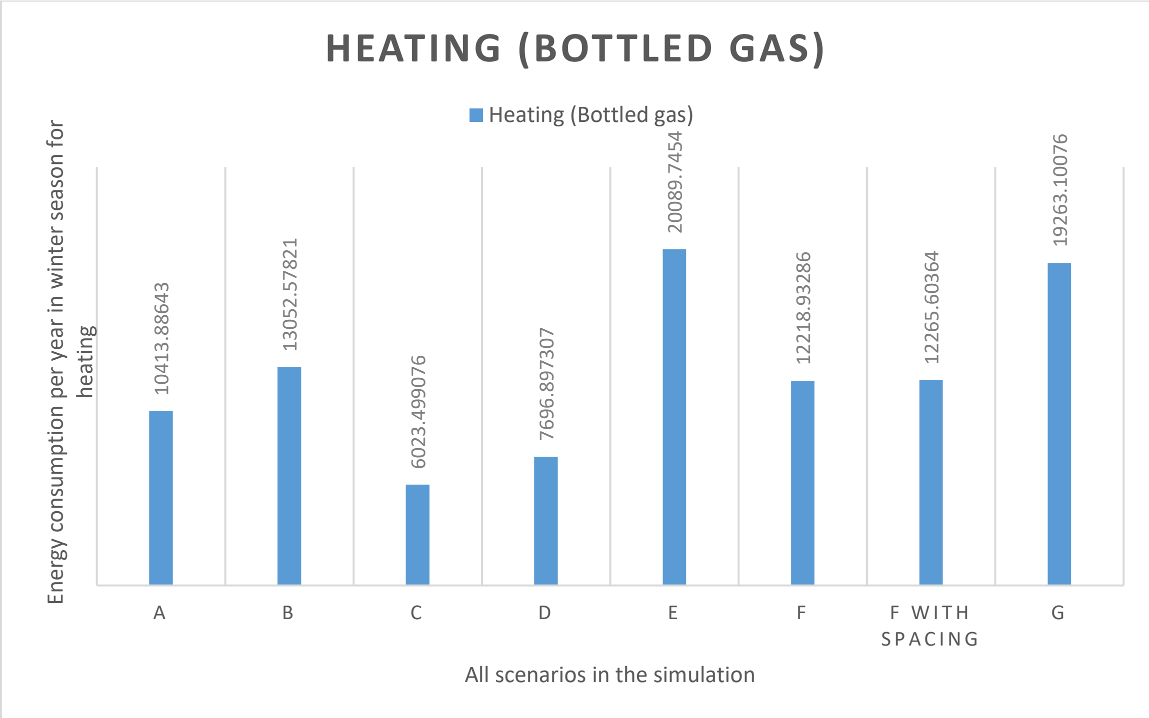



**Figure 7.** Total energy consumption per year for heating (kWh)
Source: Authors, 2023.

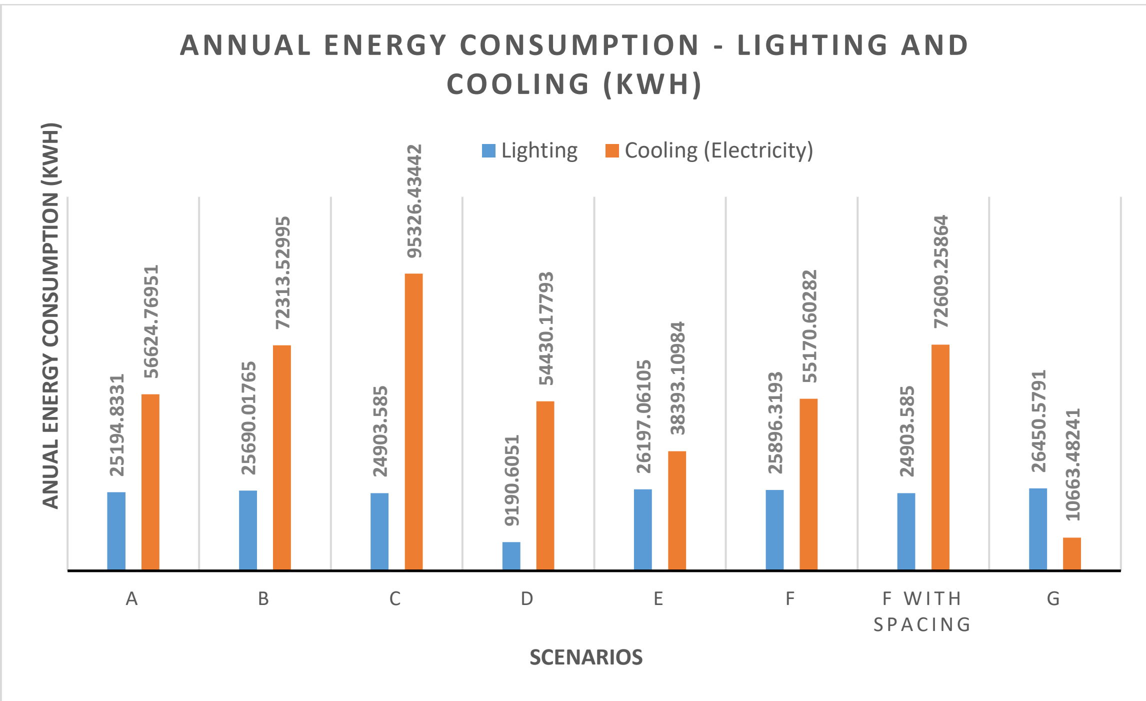



**Figure 8.** Total energy consumption per year on cooling and lighting (kWh)
Source: Authors, 2023.

At this point, and on the light of the obtained results, the relationship between the surface area and the volume of scenarios 1, 2, 4, 5, and 6 are strong candidates to be developed as a base to consider as a base for building design intended for better thermal performance.

In order to develop a police decision making strategy, which might be embodied in a code for practice for thermal performance building design, this work might be a promising starting point.

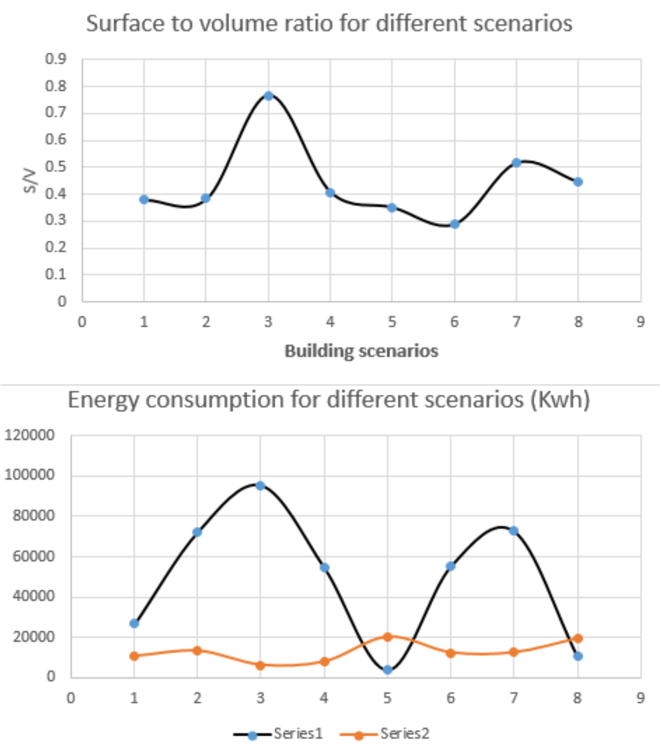



**Figure 9.** Correspondence surface-to-volume ratio with annual heating and cooling energy consumption for different building scenarios

The results obtained from the adopted method and procedure are possibly compared with other studies. The works of Danielski et al. [43], Geletka and Sedláková [44], Lylykangas [45], Chabanov [46], Danielski [47] show extensive previous studies explored this issue, this work might fit well with the results obtained from previous studies.

Danielski et al. [43] established a relationship between the shape factor of buildings in general and heat losses in cold climates, five existing buildings were studied to depict the final energy demand related to shape factor using simulation of twelve different scenarios in four climatic zones; in warmer climates a reduction in shape factor was so efficient. Geletka and Sedláková [44] studied the connection between whole building energy demand including building orientation of buildings and glazing-to-wall ratio; Geletka and Sedláková concluded that the effect of building shape on total building energy use depends primarily window to wall ratio; in addition, relative compactness of buildings can be a proper indicator to assess the impact of shape on the energy efficiency of a building.

This current article established a relationship between the shape factor with climate and used simulation tools to simulate the final energy demand. The study found that even if there is an effect of the external surface area of the building related to its volume on the final energy demand, but still this factor is still affected by other variables such as the outdoor climate, function, window glazing, and the thermal design of the building envelop. This issue requires more investigation, as the results of the current investigation is not far away from other studies conducted in different locations.

As a starting point, it is recommended to compare each geometric shape of any building with a base case curve or the benchmark curve of a sphere as it is considered the most compact shape in geometric volumes. This approach will establish a clear relationship of the relative compactness with the benchmark curve as shown in Figure 10. Then the relative compactness would be:

Relative compactness of a given Cuboid $\chi=[(s/v)_{\text{Cuboid}(\chi)}/(s/v)_{\text{Sphere – case base}}]$.

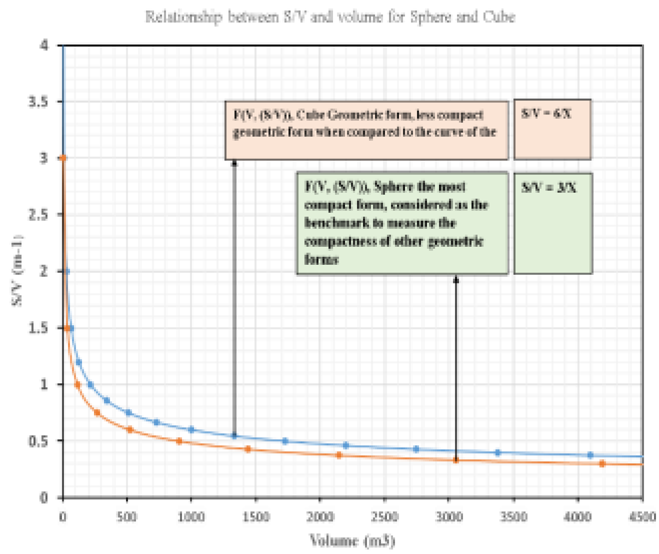



**Figure 10.** The curve F (V, (s/v)) for the Sphere with (s/v=3/x): Benchmark for measuring relative compactness of various geometric shapes

In this case, the relative compactness will allow to search for different approaches to compensate for the difference between compactness factors; for example, using the equation of heat transfer, Q=Area*U-value*(ΔT), where Q is heat transfer rate (watt/m$^2$), U-value is the overall thermal transmittance (watt/m$^2$.K), and T the temperature difference between indoor and outdoor. The possibility of modifying the U-value to compensate for the difference between the compactness of any cuboid shape and the sphere base case is one of the proposed methods that needs further exploration; this is open for future research works.

## 10. CONCLUSIONS AND RECOMMENDATIONS

### 10.1 Conclusions

Organisms managed to keep up a satisfactory heat balance. Different strategies found in nature for heat gain, retention, and dissipation are refined by physiological, behavioural, and morphological methods.

The parametric simulation concluded as follows:

- Based on climatic conditions, distinct patterns of association between the building form and its energy performance were found.
- The surface area to volume ratio (shape factor) is an important variable responsible for the thermal performance in a residential building, influenced by different geometric forms.
- Knowing the surface area-to-volume ratio for the form can help predict the increase in energy consumption rates between forms with the same volume.
- The last floor has the maximum total rates in heating and cooling loads.
- In residential buildings with more than three levels, all levels except the last level have approximate heating and cooling rate values.

- There is a direct correlation between form patterns and energy loads in every scenario. For example, forms with separated modules tend to increase the heating and cooling loads regardless of the composite of envelope constructions.

Similarly, forms with larger modules typically have lower heating and cooling loads.

- Depending on the climate, form has a different impact on a building's energy performance in both absolute and relative terms.
- This study attempted to draw the conclusion that each component of energy loads has a strong correlation with one of the form parameters examined, even though it has not been possible to pinpoint a parameter that can explain the energy loads in a particular climate. If expanded, this data might be useful in enhancing prediction models.
- In Jordan, where there is no widely used method for calculating the surface area to volume ratio, there is a lack of interest in determining form parameters during the design process. This issue is open for future studies, open problems related to this issue still need more exploration, the climate zones in Jordan ranges from cold climates to hot dry climates; furthermore, climate zones are distinct in their characteristics, and this requires research design to characterize the shape factor relationship with different climatic zones in Jordan; and they should be included in the thermal design codes of practice in Jordan, a topic that should be deeply investigated.

### 10.2 Recommendations

Research in the field of adaptation and regulation strategies found in nature in terms of heat gave knowledge into some dominating factors and processes for adaptation. It provided the beginning of a database, given these factors and strategies. Following the same rules of classification and categorization is possible, and create an expandable database, for the convenience of generating design concepts.

- Generating design prototypes is significant for the realization of emerging innovative ideas, as materials and production methods may differ from the standard. A multidisciplinary platform for biomimetic innovation in engineering, where researchers and industry collaborate, is essential for design concept validation, as the arising technical solutions may open new visions for the future of building design.
- Multi-functionality is one of the prevailing perspectives in natural systems. A specific particular may perform heat regulation and simultaneously control humidity changes and heat transfer. Further elaboration is needed with accentuation on improving the classification of processes and factors, which permits a likely integration of numerous angles in one design concept. Accordingly, the arising multi-functional systems will adjust to environmental changes and create a new level of sustainable building design.

This kind of research requires an intensive examination of interdisciplinary fields and state-of-the-art knowledge.

- Building form is one of the most important factors considered in design and planning codes, apart from building energy regulations.
- This parametric simulation is a component of a larger study that will include more intricate forms and a range of building sizes. Furthermore, the influence of additional design elements was taken into account, including the window-wall ratio, various insulation levels, and thermal mass.

## ACKNOWLEDGMENT

We would like to express our gratitude to The University of Jordan for their support in providing the facilities and services necessary to complete this research. This research received no funding from any external sources.

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