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Multi-Zone Energy Performance Assessment of Algerian Social Housing Using a Parametric Approach

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Abstract: In the early stages of building design, decisions are made about the building's form and envelope, but designers rarely base their decisions on sophisticated energy simulations, even though these features are critical to a building's energy performance. This paper employs three methods—empirical, parametric, and uncertainty—to assess the interconnectedness of building form, envelope, orientation, and occupancy regarding thermal comfort and energy consumption for heating and cooling a residential building across three regions: Gdyel (mediterranean climate), Oum El Bouaghi, and Constantine (semi-arid climate). The study variables include indoor air temperature, relative humidity, and energy consumption. The initial findings stem from an experiment conducted in an apartment on the top floor of a building in Gdyel, which allowed us to record the evolution of the variables mentioned throughout the year and validate the parametric results of the multi-zone model created in TRNSYS16 software. This study showed that for the considered climates, a compact form is more suitable; it was found that the top floor with SF = 0.57 needs about 30% to 54% more energy than the inter-floor with SF = 0.21. In addition, the heating and cooling methods and habits adopted by Algerian households are responsible for 18% to 35% on the top floor and the inter-floor, respectively.

Keywords: multi-zone building; shape factor; envelope characteristics; simulation; TRNSYS.16; thermal comfort; heating and cooling; energy consumption; energy-efficient

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1. Introduction

The construction and building industries are critical to addressing the planet's vulnerability and controlling CO_2 emissions. They are the world's most energy-intensive and greenhouse-emitting industries. They will account for 30–40% of total energy usage by 2050 [1]. The European Union wants to see a climate-neutral Europe with no net emissions of green gases, as does Algeria, and like many countries in the world, the energy consumption of the residential sector is constantly increasing, reaching about 42% to 44% of total consumption in 2020 [2,3], 70% of which is for heating and air conditioning [4]. This is why the residential sector must save 30 million TEP (tons of equivalent petroleum) from 2016 to 2030 [5]. The main cause invoked is the failure to take energy saving into account in the design of housing in its various forms due to the imperatives of quantitative objectives to be met and the adoption of unsuitable models.

Like other countries in the world, Algeria is facing numerous challenges: demographic growth, slowing economic growth, and significant environmental pressures. These challenges are exacerbated by climate change, whose harmful impacts are now visible and continuing to grow. In order to address the housing crisis, Algeria has endeavored for several decades to build a large number of housing units that are distributed across several formulas, according to citizens [5] (Table 1).

Table 1. Comparison of housing and population statistics (2008 and 2019).

Category	2008	2019
Housing Stock (units)	6,872,541	9,845,692
Population (ONS)	34,080,030	43,900,000
Urbanization Rate (%)	65.77	70.00
Housing Occupancy Rate	5.1	4.46

Rampant urbanization and the constantly growing demand for new housing led the authorities to prioritize mass production, sacrificing any approach that takes into account the energy economy in this sector. Despite this, since 2015, Algeria has engaged in a strategic energy partnership with the European Union, punctuated by the "TAKA NADIFA" program [6], which aims to support two Algerian government programs: the national renewable energy program and the energy efficiency program. The main measures envisaged concern the thermal insulation of buildings, efficient lighting, and the production of hot water through thermal solar power. Although it is significantly behind some European countries, Algeria has implemented a set of technical regulations for energy efficiency in buildings [6].

Several studies have focused on the energy efficiency of buildings and highlight building characteristics as determining variables of energy consumption, such as the envelope (insulation, inertia), materials, and infiltration, but very few studies have considered building form as a variable to measure [7]. In this context, the building envelope plays an important role in meeting the challenge of energy transition. Indeed, a good design of the envelope effectively contributes to reducing energy consumption, as concluded by several research studies [8,9]. The improvement of energy performance as well as the thermal state of the building depend not only on the satisfaction of the occupants but also on the properties of the envelope (opaque and translucent) as well as the external climatic conditions [10,11]. Caruso states that the shape of the envelope has a significant influence on the energy performance of the building, and the choice of optimal shape depends on the dominant climate [12]. It is defined as the ratio of the total envelope surface area to the habitable volume of a building and depends on the size and morphology of the building [13].

Table 2 shows the passive design studies that dealt with multi-objective optimization in terms of energy, insulation, and glass properties, which are the variables most studied by researchers in optimizing residential models. The window-to-wall ratio (WWR), orientation, infiltration, and shading have been selectively analyzed, taking into account regional climatic conditions [14].

Multiple research projects undertaken in Algeria have specifically examined the energy efficiency of both administrative and residential buildings. The results of this research emphasize the critical significance of taking into consideration the thermal characteristics of the building's outer shell and evaluating the climate conditions [15]. Thermal insulation materials offer a means to enhance the energy efficiency of current buildings, as evidenced by the research conducted by Nait, Sarri, and Rahmani [16–18]. Research conducted by Rais and Badeche [19,20] has shown that the arrangement and positioning of windows play a significant role in improving comfort. Furthermore, it is crucial to consider natural and mechanical ventilation as design solutions to enhance air quality, as highlighted by Rais [19]. In addition, the roof has a significant function in monitoring energy performance, as emphasized by Kadri [21]. Nevertheless, these investigations are limited by the oversimplification of the study model [22], which leads to a lack of attention to the consequences and interchangeability of conditioned and unconditioned environments. Furthermore, it is necessary to handle concerns regarding heating and occupancy modes [18], as well as the inclusion of building infiltration as a constant value without taking into account the climatic environment.

This study seeks to address this gap by investigating the impact of building form, envelope, and occupancy on energy efficiency, with the objective of determining the most effective strategies for thermal renovation and aiding decision-making during the design process. This article primarily aims to verify and assess the effectiveness of the LSP communal housing model, specifically developed for participatory social housing initiatives that receive government backing. The research approach comprises three primary stages. (1) A flat located in the climate of Gdyel was subject to experimental surveillance using in situ measurements of temperature and humidity. (2) Numerical analysis was performed using TRNSYS16 software to simulate building performance in three districts of Algeria: Constantine, Oum El Bouaghi, and Gdyel in Oran. (3) The last stage entails conducting an uncertainty study to verify the accuracy of the model in compliance with the standards outlined in ASHRAE Guideline 14 [23]. The main goal of this study is to gather a complete collection of data that measures the influence of building shape and structure on the amount of energy used for heating and cooling. These factors encompass climate, orientation, wall and window dimensions (both shaded and unshaded), occupancy patterns, nearby conditioned and unconditioned areas, and rates of infiltration.

Table 2. State of the art (1—insulation, 2—property of the glazing, 3—ratio of window/wall (WWR), 4—orientation, 5—airtightness, 6—solar absorption, 7—internal heat gain, 8—form of the building, 9—thermal inertia, 10—thermal regulations).

Studies	**Year**	**Insulation**	**Property Glazing**	**WWR**	**Orientation**	**Airtightness**	**Solar Absorption**	**Internal Heat Gain**	**Form**	**Thermal Inertia**	**Thermal Regulations**
Magnier and Haghighat, Canada, Residential [7]	2010	x	x			x					
Yusuf Yyldyz et al., Turkey, Hot and humid climate [10]	2011	x	x	x	x						
Asadi et al., Portugal, Residential [11]	2012	x	x								
Vasco Granadeiro et al., Lisbon [14]	2013								x		
Rodr′ıguez et al., Spain, Residential [24]	2013		x			x		x			
Huang et al., Taiwan, Residential [13]	2016	x	x	x	x						
La¨etitia Arantes et al., Grenoble (France) [25]	2016								x		
Hamdy et al., Netherlands, Residential [12]	2016	x									
O'Neill and Niu, USA, Residential [26]	2017							x			
Chen and Yang, Hong Kong, Residential [27]	2017		x					x			
Mitja Kosira et al., Central Europe [28]	2018								x		
Harkouss et al., Lebanon, Residential [29]	2018	x	x	x							
Gou et al., China, Residential [30]	2018	x	x	x	x	x	x			x	
Chen and Yang, China, Residential [31]	2018	x	x	x	x	x				x	
Ferrara et al., Italy, Residential [32]	2019	x	x								
Ascione et al., Italy, Residential [33]	2019	x	x				x				
Shadram et al., Subarctic, Residential [34]	2020	x	x								

Table 2. *Cont.*

Studies	**Year**	**Insulation**	**Property Glazing**	**WWR**	**Orientation**	**Airtightness**	**Solar Absorption**	**Internal Heat Gain**	**Form**	**Thermal Inertia**	**Thermal Regulations**
Salata et al., Italy, Residential [35]	2020	x	x				x				
Rosso et al., Italy Residential [36]	2020	x	x				x				
Yujun Jung et al., S. Korea, Residential [22]	2021	x	x	x	x	x	x	x		x	
Michael A, William et al., Egypt [37]	2021	x									
Mehhrdad Rabani et al., Norv'ege [38]	2021	x	x	x							
Nasrollah Nasrollahzadeh [39]	2021	x	x	x							
Ning Li Pekin, China [40]	2022	x				x			x		
Lihua He and Lin Zhang, China [41]	2022	x	x								
Magdi Rashad [42]	2022	x						x			
ALGERIA											
Mohamed Khadraoui et al., Algeria, arid climate [15]	2017	x	x	x							
Nait Nadia et bourbia Fatiha, Algeria, semi-arid climate [16]	2019	x									
Messaouda Rais et al., residential building, Algeria [19]	2020	x	x	x	x						
Mounira Badeche, office building, Algeria [20]	2020		x	x					x		
Marco Morini, Algeria [20]	2021	x							x		x
Abdelkader Sarri, Algeria [17]	2021	x									
Meryem Kadri, Algeria [21]	2021	x					x			x	
Soumia Rahmani, Algeria [18]	2022	x								x	
Present research	2023	x	x		x	x		x	x		x

2. Materials and Methods

The objective of this study is to identify the impact of form and envelope on the energy consumption of a multi-zone residential building in Algeria, considering two scenarios for occupancy and energy demand. In order to achieve this, this study aims to compare the energy performance of each element and identify the element that has the most significant impact on the energy performance of the building in three climatic regions.

A significant number of research studies rely on optimization methods, which are regarded as the most effective design approaches for identifying optimal solutions within a given range of variables and achieving energy efficiency objectives. In general, optimization strategies tend to focus on improving the building envelope [26]. The optimization process becomes more complex in the case of multi-story residential buildings, which is why researchers always opt for simplifying the study model to minimize and reduce simulation time in TRNSYS [22]. Building energy simulation (BES) tools are increasingly used to study the impact of design strategies on building energy consumption, such as TRNSYS, Energy-Plus, EE4, and SIMEB [27].

It is crucial to validate the model to guarantee that the simulation software provides reliable outcomes. This is the rationale behind the concentration of some researchers on the analysis of sources of uncertainty in passive construction strategies, as they have demonstrated their significant influence on results. The majority of analyses focus on uncertainties associated with model simplifications, lacking detailed information on professions, weather data, and economic data [26]. In future studies, the relation between the building envelope and the behavior and personality of occupants should be considered as one of the optimization variables [28].

To achieve this objective, this study was divided into three distinct phases: an empirical study involving on-site measurements in a case study, a parametric approach using simulation in TRNSYS software, and an uncertainty study to validate the model according to ASHRAE Guideline 14 standards. The selected case study, depicted in Figure 1, is a multi-story residential building constructed in 2008 by the Land Agency, conforming to the standards stipulated in the Algerian thermal regulation (DTR). An apartment was leased to facilitate the installation of monitoring and measurement devices. The compact form of the case study was chosen over newer forms of housing in Algeria, such as the AADL (National Housing Improvement and Development Agency).

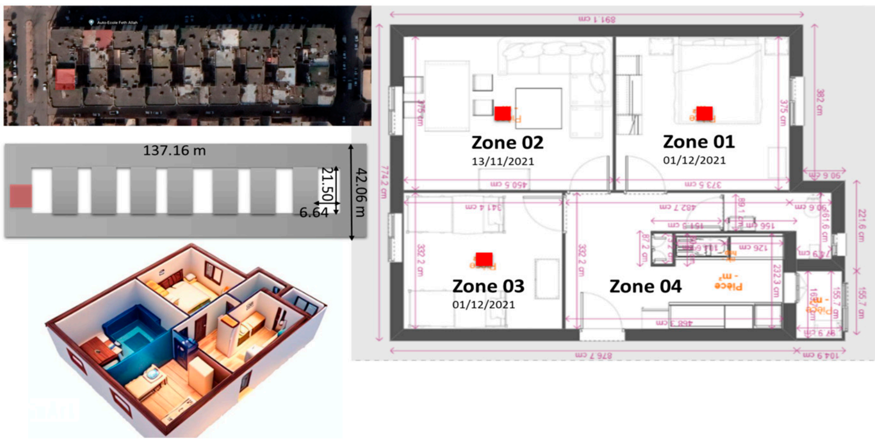


Figure 1. Case study: LSP apartment model. Source: author.

2.1. Description of the Case Study

Located in Gdyel, Oran, the 212-unit LSP residential building has a compact rectangular shape divided by eight interior courtyards with three facades, the two main ones facing southeast and northwest, which include the openings, as shown in Figure 1. The apartment selected for measurement is located on the top floor with a roof terrace and has a surface area of 70 m^2. It is divided into five zones: zone 01 (bedroom 1), zone 02 (living room), zone 03 (bedroom 2), zone 04 (kitchen), and zone 05 (bathroom).

2.1.1. The Shape Factor (SF) (m^2/m^3)

A suitable approach to examining the influence of construction geometry on energy consumption is to use the form factor indicator (SF), which is defined as the ratio of loss surfaces (walls, roofs, etc.) to the volume to be conditioned. This indicator is dependent on the size of the building and its morphology [43]. Each zone is defined by a shape coefficient, summarized in Table 3.

Table 3. Building geometry (shape factor).

	External Faces	Principal Orientation	Second Orientation	Roof	Shape Factor per Zone	Shape Factor per Floor
Top Floor zone 01	3	Northeast	Northwest	+	0.90	0.57
Top Floor zone 02	3	Northeast	Northeast	+	0.85	
Top Floor zone 03	2	Northeast	/	+	0.63	
Top Floor zone 04	2	Northeast	/	+	0.80	

Table 3. *Cont.*

	External Faces	Principal Orientation	Second Orientation	Roof	Shape Factor per Zone	Shape Factor per Floor
Inter-Floor zone 01	2	Northeast	Northeast	/	0.53	0.21
Inter-Floor zone 02	2	Northeast	Northeast	/	0.49	
Inter-Floor zone 03	1	Northeast	/	/	0.26	
Inter-Floor zone 04	1	Northeast	/	/	0.43	

2.1.2. Heat Transfer Coefficient (U) (W/m^2 k)

The subsequent phase of the construction modeling process consists of attributing a suitable structure to each building envelope, considering the heat transfer coefficient (U).

This stage is of significant importance, as it determines the quantity of energy required to regulate the air temperature in each zone of the building to the desired level [42]. A summary of the composition of the envelope and the properties of the materials used is provided in Table 4.

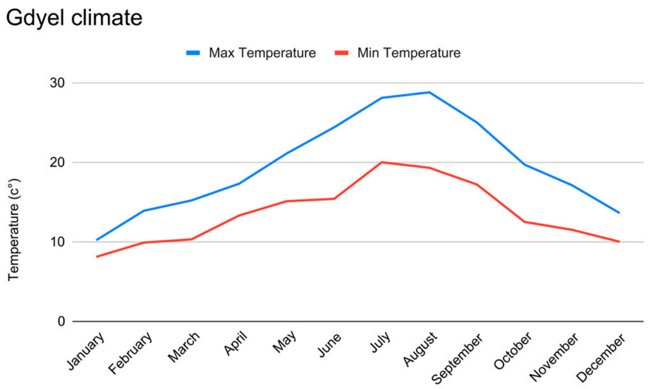
Table 4. Envelope properties.

Envelope	Materials	Thickness (m)	Conductivity (W/m °C)	Conductivity (Kj/h m k)	Capacity (Kj/Kg K)	Density (Kg/m^3)	U (W/m^2 k)
External wall Double hollow brick	cement coating	0.02	1.8	6.48	1	2200	0.555
	hollow brick	0.10	0.5	1.8	0.87	1800	
	Air Blade Coating	0.05	0.047	0.1692	1	1	
	hollow brick	0.15	0.5	1.8	0.87	1800	
	Plaster coating	0.02	0.35	1.26	0.936	960	
Interior Wall	Plaster coating	0.02	0.35	1.26	0.936	960	2.065
	hollow brick	0.10	0.5	1.8	0.87	1800	
	Plaster coating	0.02	0.35	1.26	0.936	960	
Intermediate floor	Plaster coating	0.02	0.35	1.26	0.936	960	2.391
	Concrete	0.20	1.16	4.21	0.1	1372.2	
	Cement coating	0.02	1.3	4.68	1	2200	
	Floor Tile	0.02		3.6	0.94	2000	
Roof	Plaster coating	0.02	0.35	1.26	0.936	960	2.458
	Concrete	0.20	1.16	4.21	0.1	1372.2	
	Waterproof layer	0.01	1.15	4.14	1	1050	
Ground	Floor tile	0.02	1	3.6	0.94	2000	2.771
	Cement coating	0.015	1.3	4.68	1	1900	
	Concrete	0.20	1.16	4.21	0.1	1372.2	

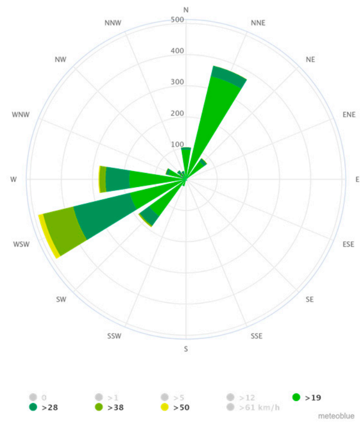
The exterior walls are double walls constructed from hollow bricks with a thickness of 15 cm and 10 cm, respectively. An air cavity of 5 cm separates the two layers. The exterior is covered with a layer of cement plaster, while the interior walls are covered with a layer of plaster on both sides. The roof terrace is constructed from a 20 cm (16 + 4) hollow core slab with a layer of plaster on the inside and a waterproofing layer on the outside. Typical floor slabs are constructed from a 20 cm (16 + 4) hollow core slab with a layer of plaster on the underside and a layer of screed on the top side.

2.1.3. Climate

The city of Gdyel is situated in the northwestern region of Algeria at latitude 35.7822 and longitude −0.423746 (35°46′56″ N, 0°25′25″ W). It experiences a hot Mediterranean climate with a dry summer (Csa), according to the Koppen–Geiger classification. Figure 2a presents the average temperature in the city of Gdyel over the course of a year, which is 19.1 °C, and the average rainfall, which is 347.4 mm. Figure 2b illustrates the typical wind patterns in the area, which are characterized by winds blowing from the west–southwest at speeds exceeding 19 km/h.



(**a**)



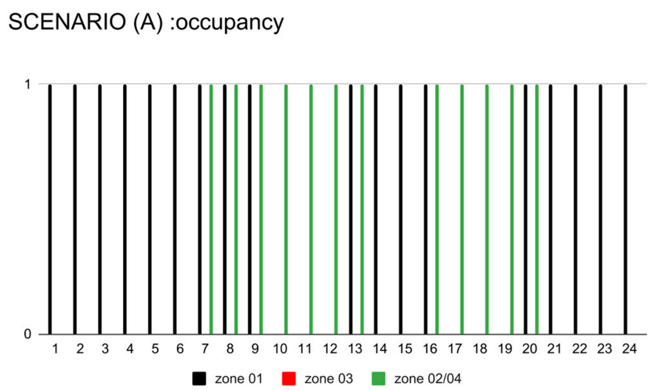
(**b**)

Figure 2. (**a**) Annual temperature of Gdyel, Oran; (**b**) wind speed and direction of Gdyel, Oran.

2.2. Empirical Approach

2.2.1. Measurement Protocol

Geothermal sensors were strategically placed in each zone, with zone 01 facing north-east and zones 02 and 03 facing southwest. To eliminate uncertainty related to occupancy and indoor gains, zone 03 was separated from the other indoor environments of the house. The monitoring period was extended from December to April to cover the entire cold season. The sensors were installed in the center of each zone, at a height of 1.80 m above the floor, and hourly measurements were recorded. The case study was equipped with a split air conditioner unit placed in zone 04 that was used for heating and cooling throughout the apartment. The operating scenario of the air conditioner device and occupancy are described in Figure 3.



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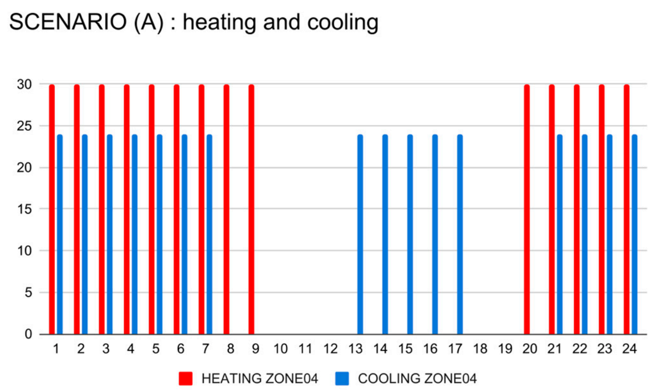


(**b**)

Figure 3. (**a**) Scenario (A) experiment occupancy (source: author). (**b**) Scenario (A) experiment heating and cooling (source: author).

2.2.2. Measuring Instrument

RC-4HA/RC-4HC temperature and humidity data loggers (Figure 4) are mainly used for recording temperature and humidity; they are designed with an optional internal and external temperature sensor, and they are highly sensitive, capable of detecting even slight changes in temperature.

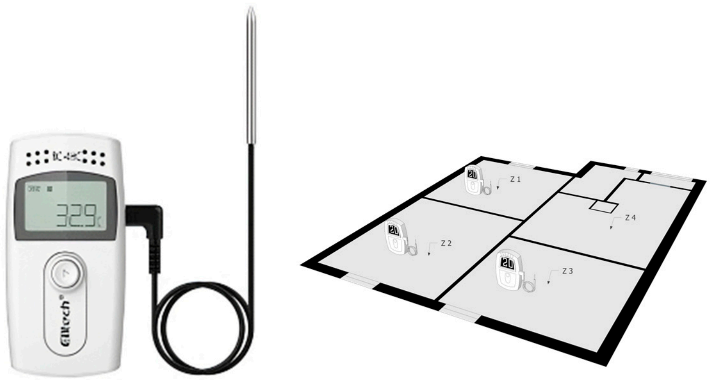


Figure 4. RC-4HA/RC-4HC measurement instruments (source: author).

2.3. Parametric Approach

Although researchers have investigated various aspects of building energy use, including heat loads, ventilation systems, and disease transmission, there has been limited focus on understanding the energy needs for maintaining thermal comfort within the building itself [42]. This study aims to fill this gap by examining the influence of building form, envelope, and occupancy on energy performance, with the goal of identifying optimal solutions for thermal renovation and supporting decision-making in the design phase. To achieve this, this study uses a parametric approach to analyze and evaluate variations in annual energy loads to predict model performance. The simulation concentrates on heating and cooling loads as well as temperature regulation. Although there are several software packages available, we use TRNSYS for its ability to calculate and simulate the behavior of multi-zone buildings and integrated active energy systems.

2.3.1. Simulation Software

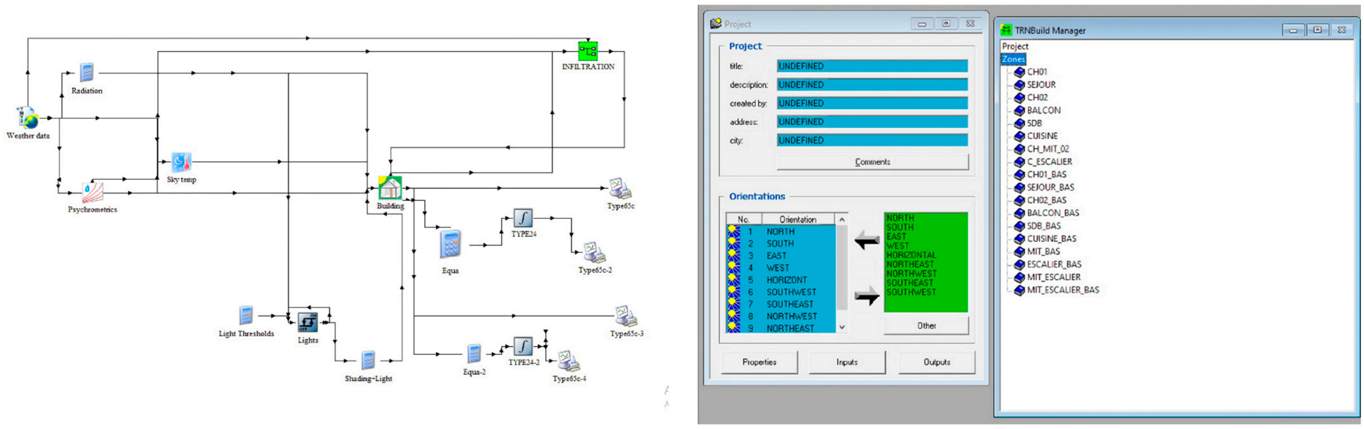
We use TRNSYS to investigate how heat transfers across the structure of a multi-zone model and how these exchanges affect the energy performance of each zone. On an architectural scale, our objective is to analyze the thermal and energy performance of each building area. Several scenarios was created for each zone. These scenarios are validated by comparing the model results to measured data. This approach gives us a detailed and reliable view of the building's energy performance, allowing us to more precisely assess its heating, cooling, and thermal comfort needs in different conditions.

2.3.2. Simulation Conditions

This research project utilized the TRNSYS Simulation Studio, as shown in Figure 5a, which includes a Type 56a building model linked to input variables such as the meteorological file Type TMY2 and new orientations on the radiation matrix, as well as Type 571 for infiltration. To calculate the annual energy loads, the model is also linked to Type 65c for the desired output (results).

- Climate Data: Meteonorm 8.0.3.15910 software was utilized to collect climatic data as input in the Trnsys software for the three regions of interest in this study: Gdyel (Oran) in a Mediterranean climate, Oum El Bouaghi, and Constantine in a semi-arid climate.
- Infiltration: To simulate infiltration as input for Type 56a, Type 571 was employed in the simulation studio. The coefficients (K) for multiple linear regression were defined based on the building's constructive state, with medium K values of K1 (0.10), K2

(0.017), and K3 (0.049) utilized in this study, as shown in Table 5. It is crucial to highlight that the case study building was constructed in 2008.



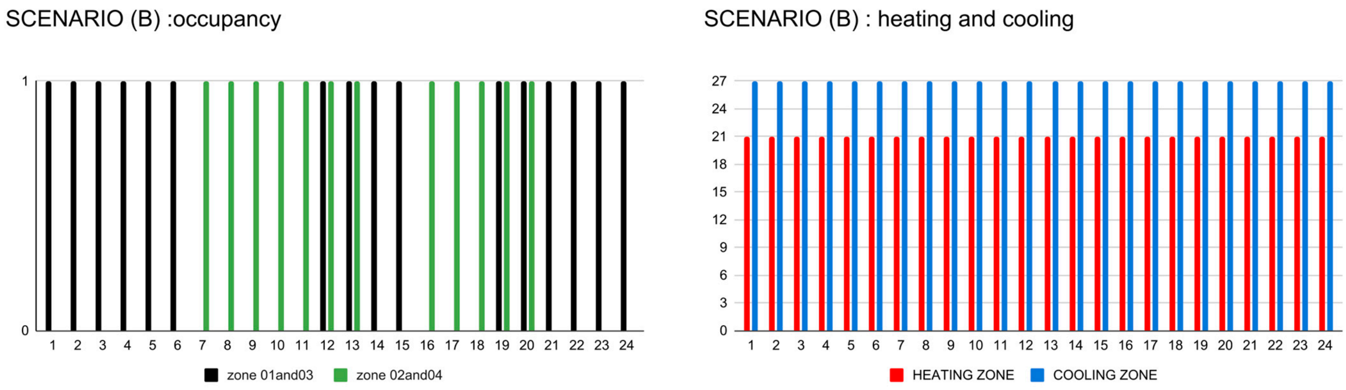
(**a**) (**b**)

Figure 5. (**a**) Modeling of the study project in TRNSYS 16 software (author); (**b**) modeling of the study project in Trnbuild 16 software (author).

Table 5. Coefficients (k) for multiple linear regression; source: mathematical reference TRNSYS documents, "Envelope Property".

Construction	**K1**	**K2**	**K3**	**Description**
Tight	0.10	0.11	0.034	New building where special precautions have been taken to prevent infiltration.
Medium	0.10	0.17	0.049	Building constructed using conventional construction procedures.
Loose	0.10	0.023	0.07	Evidence of poor construction in older buildings where joints have separated.

- Orientation and Windows: New orientations, including southeast, southwest, northeast, and northwest, were generated in TRNSYS to ensure that windows and walls were oriented correctly.
  Modeling in TRNBuild: The resulting multi-zone model in TRNBuild encompasses 18 zones, which detailed the building's geometry and thermal properties for the two upper levels, each containing two apartments and the staircase, which were designed to maintain heat exchange continuity with both external and internal spaces. The material properties are summarized in Table 4.
- Scenarios (occupancy schedule, heating and cooling loads): This study considered two scenarios for occupancy and energy demand for heating and cooling:
  Scenario (A): This is a real-life measurement scenario already defined in the empirical part of this study, as shown in Figure 3. Energy loads were calculated for a temperature demand of 30 °C in winter and 27 °C in summer.
  Scenario (B): This is a standard scenario for the lifestyle of an Algerian family, as shown in Figure 6, in which the demand for heating or cooling depends on the occupancy. The occupancy schedule was planned with a set temperature of 21 °C in winter and 27 °C in summer.
- Gains: Internal gains were taken into account, including the use of computers, artificial lighting, and other heat-generating devices such as ovens in the kitchen (zone 4), summarized in Table 6.



(**a**) (**b**)

Figure 6. (**a**) Scenario (B) standard occupancy (source: author). (**b**) Scenario (B) standard heating and cooling (source: author).

Table 6. Internal gains (source: author).

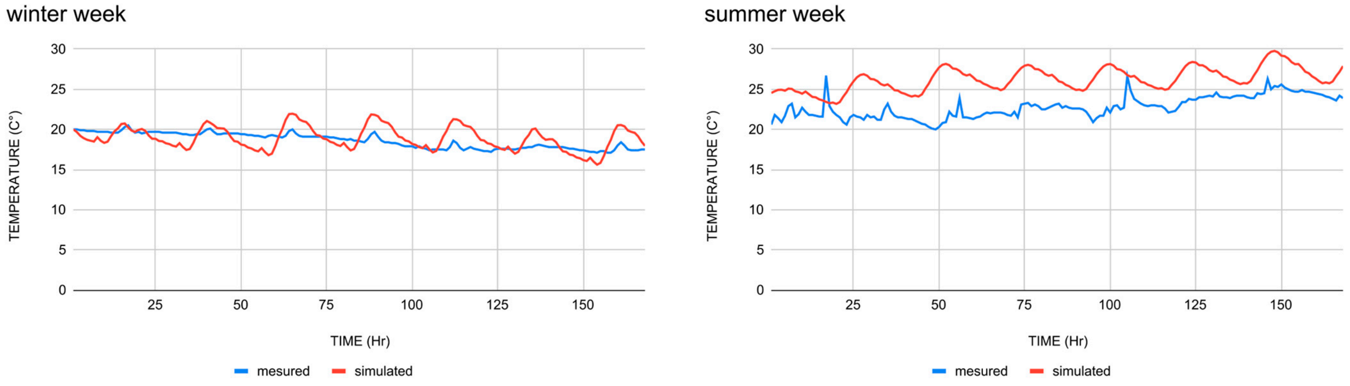
Gain	Persons	Computer	Artificial Lighting	Other Gains
zone 01/02/03 (scenario (B))	iso 7730 [44] Seated, light writing	50 w	19 w/m^2 KVG; direct/40% Leuchstroffrohre	off
Schedule	scheduled occupancy zone 01-02-03	BRIGHT	BRIGHT	off
zone 03 (scenario (A))	off	off	off	off
schedule	off	off	off	off
zone 04	iso 7730 Seated, eating	50 w	19 w/m^2 KVG; direct/40% Leuchstroffrohre	FOUR 120 KJ/
schedule	1	BRIGHT	BRIGHT	scheduled occupancy zone 04

3. Results and Discussion

3.1. Model Validation (Uncertainty Study)

Uncertainty assessment is a critical procedure when using measuring techniques and computations. This involves assessing inaccuracies in model computations and estimating the level of certainty of the actual value. The primary emphasis of validation procedures in Measurement and Verification (M&V) protocols is on quantitative evaluations to determine the degree of correspondence between simulation model outcomes and actual data. Calibration is dependent on two main statistical measures: the coefficient of variation of the root mean square error (CV (RMSE)) and the normalized mean bias error (NMBE). As per the AG14 standards [23], the acceptable criteria for these indices are set at 30% for CV (RMSE) and within ±10% for NMBE, particularly for hourly data.

To confirm the simulation results, the generated values were compared to measured values from the LSP model flat located in an urban site in Gdyel, in the eastern part of Oran, Algeria. This comparison was conducted using three RC-4HA/4HC temperature and humidity recorders. The findings depicted in Figure 7 and Table 7 suggest that the model is well calibrated. Zone 03 has an NMBE of −1.64%, an RMSE of 1.41, and a CV (RMSE) of 7.57%, all of which fall within the tolerance levels indicated by ASHRAE Guideline 14. In addition, the results indicate that the model incorporating internal gains and occupancy in zone 02 is accurately calibrated, with a normalized mean bias error (NMBE) of 3.19%, a root mean square error (RMSE) of 1.93, and a coefficient of variation of RMSE (CV (RMSE)) of 9.73%.



(**a**) (**b**)

Figure 7. (**a**) Model validation (zone 03): winter week (source: author). (**b**) Model validation (zone 03): summer week (source: author).

Table 7. Model validation.

ASHRAE Guidelines 14-2002 [23] Hourly Criteria	Zone 02 with Internal Gains and Occupancy	Zone 03 without Internal Gains and Occupancy
NMBE ± 10% (%)	3.19	−1.64
RMSE	1.93	1.41
CV (RMSE) 30% (%)	9.73	7.57

3.2. Regulatory Assessment (Compliance with DTR C3-4)

Moving from the size of the existing building to the verification of thermal compliance is a methodology to verify the minimum requirements of the thermal regulations of the building. This analysis was carried out in the free application software of the Algerian Thermal Regulation "RETA" developed by CDER (The Renewable Energies Development Center (CDER) is a research center resulting from the restructuring of the High Commissioner for Research, established on 22 March 1988), which is in the form of a graphical interface accessible via the web address http://reta.cder.dz/ (accessed on 26 May 2022). As per the results presented in Table 8, we found that zones 03 and 04 satisfy the minimum obligation target of the thermal regulation; however, in zones 01 and 02, this noncompliance may be due to their envelope properties and orientation.

Table 8. RETA Algerian Thermal Regulation application.

Envelope	D = Σ DT	Σ Dréf	CHECK C-3.2	A = Σ APO + Σ AV	Aréf = ΣAPOréf + ΣAVréf	CHECK C-3.4
ZONE 01	55.02	39.6	1.39 No conformity	542.34	323.14	1.68 No conformity
ZONE 02	45.09	44.57	1.01 Compliant	571.99	420.41	1.36 No conformity
ZONE 03	13.93	25.97	0.54 Compliant	93.8	288.34	0.33 Compliant
ZONE 04	16.08	36.24	0.44 Compliant	92.36	288.29	0.32 Compliant

3.3. Results of the Empirical Part

Measured Results

The results recorded by the hygrothermal sensors are presented in Table 9, which shows that zone 01, facing northeast, had a maximum temperature of 28.7 °C, a minimum temperature of 17.6 °C, an average temperature of 21.8 °C, a maximum relative humidity (RH) of 84.6%, and a minimum RH of 49.5%. Zone 02, facing southwest, recorded a maximum temperature of 27.8 °C and a minimum temperature of 15.6 °C, with an average temperature of 20.2 °C. The maximum RH was 88.6%, the minimum was 46.9%, and the average was 73.3%. However, in zone 03, facing southwest, the maximum temperature recorded was 25.0 °C, the minimum temperature was 16.3 °C, and the average temperature was 19.5 °C. The maximum RH was 78.4%, the minimum was 45.1%, and the average was 66.1%. These results indicate very high humidity levels in this case study, which was visually represented by mold whilst recording measurements.

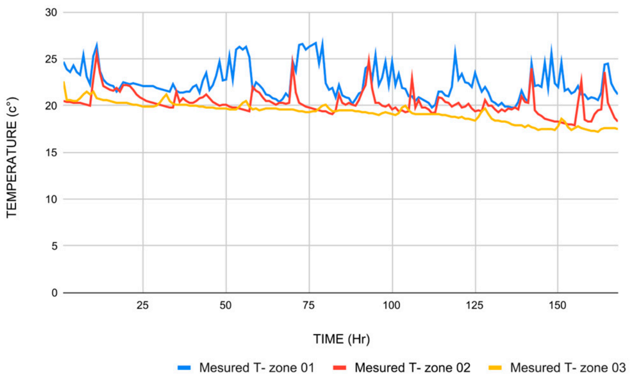
Table 9. Measuring instruments' record.

	Zone 01	**Zone 02**	**Zone 03**		**Zone 01**	**Zone 02**	**Zone 03**
Simulation duration (Hour)	3547	3966	2850		3547	3966	2850
Maximum (Temperature), (°C)	28.7	27.8	25	Maximum (Humidity), (%)	84.6	88.6	78.4
Minimum (Temperature), (°C)	17.6	15.6	16.03	Minimum (Humidity), (%)	49.5	46.9	45.1
Average (Temperature), (°C)	21.8	20.2	19.05	Average (Humidity), (%)	68.9	73.3	66.1

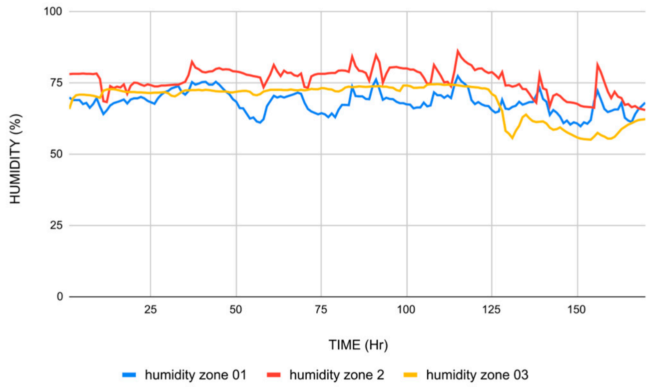
The data collection extended over a period of five months. However, to ensure accurate temperature analysis, we focused on the coldest periods of the year for the two selected climates when presenting the various temperature comparison graphs. In order to ascertain the level of comfort in the different zones, two comparisons were carried out. The first was between zones 01 and 02, which have the same indoor thermal conditions, while the orientations are different (northeast and southwest, respectively). The second comparison was between zones 02 and 03, which have the same orientation and two different thermal conditions. Comparing the temperature curves in Figure 8, it is remarkable that the temperatures in zones 01 and 02 are almost identical. These results revealed that the temperature was influenced by the shape of the building. The northeast facade was protected by the rest of the building unit against the prevailing winds, which created a microclimate in the courtyard. In the second comparison for the same southwest orientation, while zone 03 is isolated from the interior thermal conditions, Figure 8 shows that for a heating demand of 30 °C, there is a 1 °C difference between zones 02 and 03.

According to the two comparisons, for an energy demand of 30 °C for a duration of 15 h out of 24 h over more than 3 months, the average temperature is raised from 0.8 °C to 2.3 °C. The results provide insight into the energy consumption for such a low temperature difference. Beyond just orientation, these findings can be attributed to other factors like the building envelope configuration (infiltration losses) and the building's shape.

During the measurement period, mold was observed in both zones 01 and 03 on the walls facing northeast, northwest, and southwest, concentrated around the thermal bridges such as the windows, the floor/roof corners, and the floor/wall junctions. Through meticulous observation of the conditions inside a given area, we may accurately identify important processes such as thermal stratification and the loss of heat through thermal bridges. This finding underlines the crucial need for outside insulation to preserve an ideal thermal condition.



(**a**)



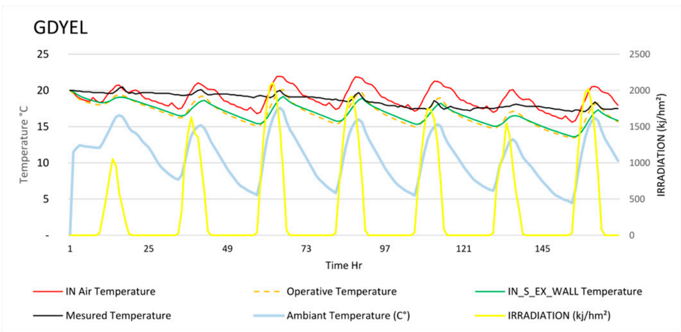
(**b**)

Figure 8. Comparison of the temperature and humidity measurement in the 1st week of January, in the three (03) zones of the LSP Gdyel case study: (**a**) temperature; (**b**) humidity.

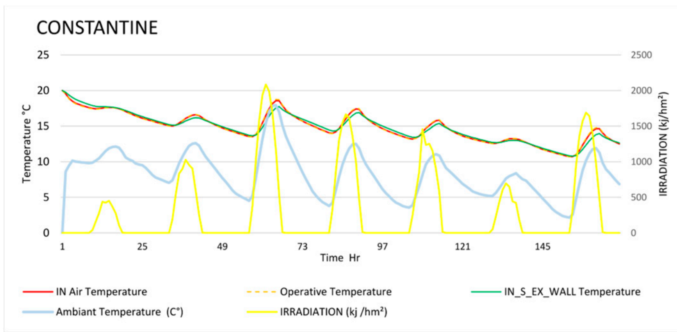
3.4. Results of the Parametric Modeling

3.4.1. Thermal Comfort

To see the envelope's response to external conditions, the results illustrated in Figure 9 show that the indoor temperature in zone 03 varies considerably depending on the external ambient temperature. In the Mediterranean climate of Gdyel, the indoor temperature varied from 14 °C to 20 °C during mid-day; in the semi-arid climate of Constantine, the indoor temperature varied between 11 °C and 18 °C. Since the envelope material contributes significantly to this variation, the building's behavior remains outside the comfort zone when both the heat source and occupancy are deactivated. An indoor temperature that remains below the 21 °C set point during the winter period may give rise to concerns regarding compliance with thermal design standards, such as the Algerian DTR. This suggests that it may be necessary to review the building envelope characteristics, taking into consideration the climate region.



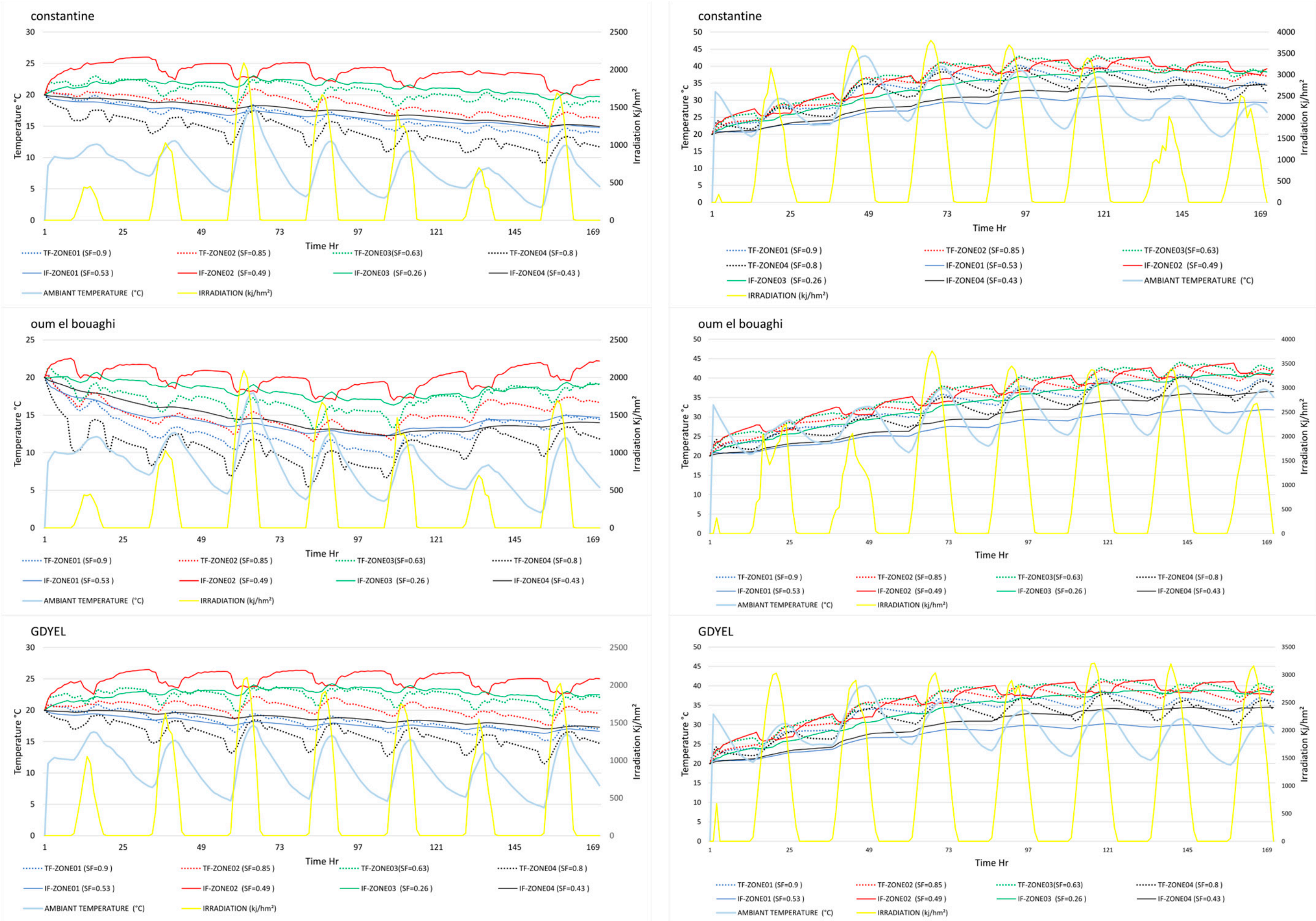
(**a**)



(**b**)

Figure 9. Zone 03 temperature (first week of January); (**a**) Gdyel climate; (**b**) Constantine climate.

In the study model, there are four zones, each with a different shape coefficient. Considering both levels, the top floor and the inter-floor, we have a total of eight zones, each with its own shape coefficient. Comparing these eight forms of zones during winter and summer will allow us to observe temperature variations and understand the impact of shape on indoor comfort level. The results in Figure 10 indicate that in Mediterranean and semi-arid climates, a higher shape coefficient is typically associated with lower temperatures, as corroborated by observations during the winter season. Consequently, areas with higher shape coefficients and north orientation tend to maintain cooler indoor temperatures. The results show that south-facing areas recorded the highest temperatures due to direct sun exposure and heat absorption. On the other hand, areas with lower form coefficients experienced more overheating, which is an important consideration in the design of buildings in such climatic regions. By evaluating how different shape coefficients influence the heat distribution within the building, we gain insights into how variations in building form affect thermal comfort.



(**a**) (**b**)

Figure 10. Simulated temperatures of different zones; external ambient temperature and irradiation in three climatic regions: (**a**) during winter (first week of January); (**b**) during summer (first week of July).

Evaluation of the building form reveals that temperature fluctuations based on heat loss surface area, orientation, and air infiltration caused thermal stratification in zones 1 and 4. The building's behavior in an occupied and heated environment is complex and depends on various variables. The temperature at any given moment is insufficient to assess a building's form and behavior. To obtain a more comprehensive and accurate evaluation, it is necessary to consider the accumulation of energy demand over an extended period.

3.4.2. Energy Consumption

Using the energy consumption rate as an indicator, it becomes possible to assess and conduct a comparison of the different forms of buildings and to demonstrate which offers the best energy efficiency and thermal comfort. Regarding heating, the simulation was conducted for approximately five winter months (from November to March) to evaluate the heating performance of the building in two scenarios, as presented in Figure 11 and Table 10. For the Mediterranean climate in the city of Gdyel, scenario (a) presents a performance of 48.91 kWh/m^2 year on the top floor and 18.25 kWh/m^2 year on the inter-floor, while in the semi-arid climate, the consumption is about 64.35/27.66 kWh/m^2 year in Oum El Bouaghi and 61.75/25.80 kWh/m^2 year in Constantine on the top floor and inter-floor, respectively. As regards scenario (b), the results present 37.30/4.40 kWh/m^2 year in terms of performance on the top floor and inter-floor, respectively, in the climate of Gdyel; however, in the semi-arid climate, the performance is 83, 90/11,14 kWh/m^2 year in Oum Bouaghi and 67.48/13.43 kWh/m^2 year in Constantine on the top floor and inter-floor, respectively. The significance of the results lies in their revelation that the top floor consumed more energy for heating compared to the inter-floor space in both scenarios (a) and (b). A potential factor contributing to this observation could be heat loss through the terrace floor due to its heat transfer coefficient (U = 2.458 W/m^2 k), which facilitates the transfer of heat to the exterior environment. Furthermore, the phenomenon of thermal stratification induced by the heating mode and infiltration could potentially contribute to this variation. However, the exact reasons behind this disparity remain unclear and require further investigation to be fully understood.

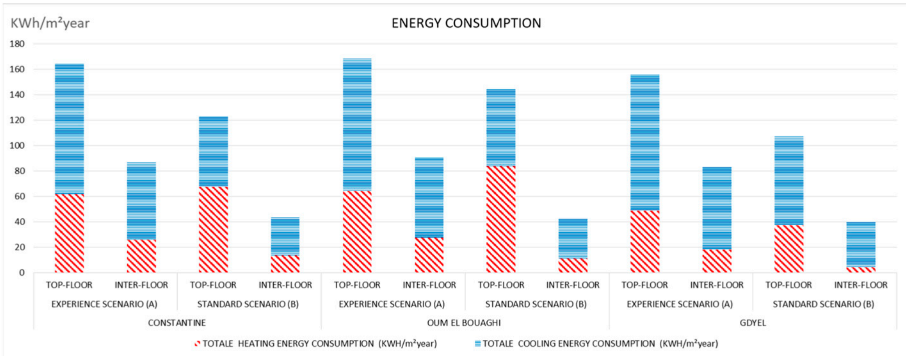


Figure 11. Total energy consumption (kWh/m^2 year).

Table 10. Energy consumption of heating and cooling in the case study.

	Total Heating Energy Consumption (kWh/m^2 Year)				Total Cooling Energy Consumption (kWh/m^2 Year)			
	Experience Scenario (A)		Standard Scenario (B)		Experience Scenario (A)		Standard Scenario (B)	
	Top Floor	Inter-Floor	Top Floor	Inter-Floor	Top Floor	Inter-Floor	Top Floor	Inter-Floor
Constantine	61.75	25.80	67.48	13.43	102.50	61.92	55.62	30.30
Oum El Bouaghi	64.35	27.66	83.90	11.14	104.561	62.92	60.42	31.86
Gdyel	48.91	18.25	37.30	4.40	107.51	64.78	69.98	35.70

The results of the cooling energy consumption obtained from simulation during the summer season cover approximately four months, spanning from June to September, as presented in Table 10 and Figure 11. In scenario (a), the performance in a Mediterranean climate showed energy consumption rates of 107.51 kWh/m^2 year for the top floor and 64.78 kWh/m^2 year for the inter-floor area. In a semi-arid climate, the performance was slightly lower, with energy consumption rates of 104.56 kWh/m^2 year for the top floor and 62.92 kWh/m^2 year for the inter-floor area in Oum El Bouaghi, and 102.50 kWh/m^2 year for the top floor and 61.92 kWh/m^2 year for the inter-floor area in Constantine. In scenario (b), the results indicated improved performance, with energy consumption rates of 69.98 kWh/m^2 year for the top floor and 35.70 for the inter-floor in Gdyel. In the semi-arid climate, the performance was approximately 60.42 kWh/m^2 year for the top floor and 31.86 kWh/m^2 year for the inter-floor area in Oum El Bouaghi, and 55.62 kWh/m^2 year for the top floor and 30.30 kWh/m^2 year for the inter-floor area in Constantine.

It is noteworthy that in all three climatic regions, the energy consumption for cooling is higher on the top floor than on the intermediate floor, in both scenarios. An interesting observation is made when comparing the results for the same floor: the only difference is the type of cooling mode, which adds another interesting element to the analysis. In Figure 11 and Table 10, under scenario (A), cooling energy consumption exceeds heating energy consumption across two floors. In scenario (B), in a semi-arid climate, the top floor shows higher energy consumption for heating, whereas in a Mediterranean climate, it consumes more energy for cooling. Furthermore, the inter-floor area demonstrates higher energy consumption for cooling in both climates.

The analysis of total energy consumption, as detailed in Tables 11 and 12, highlights that the top floor consumes more energy for both heating and cooling compared to the inter-floor across the three climate regions. Notably, the arid climate of Oum El Bouaghi exhibits the highest energy demand, followed by Constantine and then the Mediterranean climate of Gdyel-Oran. Specifically, the top floor, distinguished by a shape coefficient of 0.57, consumes 54.08% more energy in scenario (B) and 30.65% more in scenario (A) than the inter-floor with a shape coefficient of 0.21, as evidenced in Table 11. These results suggest that the top floor, especially in hot regions, may require more energy-efficient design solutions to reduce energy consumption and achieve higher energy performance.

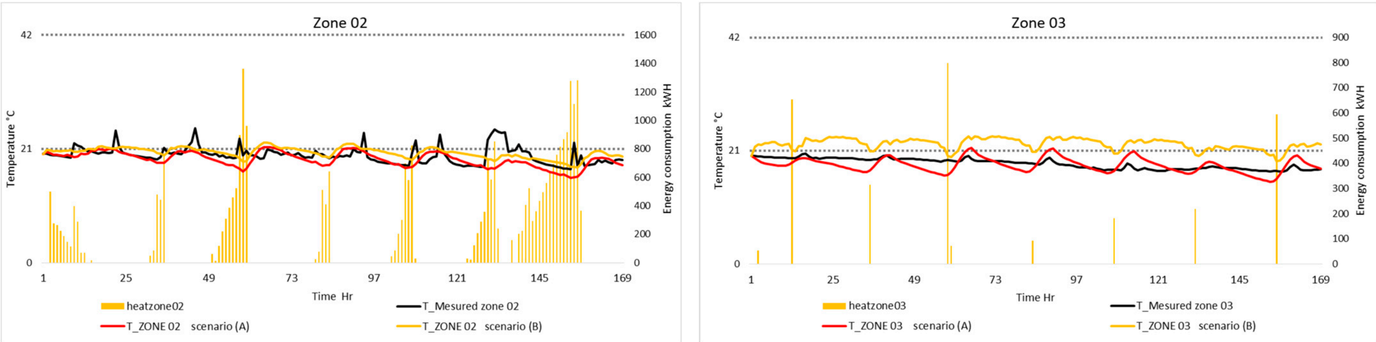
Table 11. Comparison between top floor and inter-floor in terms of total energy consumption (kWh/m^2 year).

	Constantine kWh/m^2 Year		**Oum el Bouaghi kWh/m^2 Year**		**Gdyel kWh/m^2 Year**	
	Top Floor	**Inter-Floor**	**Top Floor**	**Inter-Floor**	**Top Floor**	**Inter-Floor**
scenario (A)	164.259921 65.19% 30.37%	87.7265873 34.81%	168.916667 65.09% 30.18%	90.5900794 34.91%	156.436111 65.32% 30.65%	83.0448413 34.68%
scenario (B)	123.114476 73.78% 47.56%	43.7494484 26.22%	144.325079 77.04% 54.08%	43.0083254 22.96%	107.286754 72.79% 45.58%	40.1095476 27.21%

Table 12. Comparison between scenario (A) and scenario (B) in terms of total energy consumption (kWh/m^2 year).

	Constantine kWh/m^2 Year		**Oum el Bouaghi kWh/m^2 Year**		**Gdyel kWh/m^2 Year**	
	Scenario (A)	**Scenario (B)**	**Scenario (A)**	**Scenario (B)**	**Scenario (A)**	**Scenario (B)**
Top Floor	164.259921 57.16% 14.32%	123.114476 42.84%	168.916667 53.93% 7.85%	144.325079 46.07%	156.436111 59.32% 18.64%	107.286754 40.68%
Inter-Floor	87.7265873 6.72% 33.45%	43.7494484 33.28%	90.5900794 67.81% 35.62%	43.0083254 32.19%	83.0448413 67.43% 34.86%	40.1095476 32.57%

The comparison of the scenarios in Table 12 shows the discrepancy between the actual and required energy consumption of the structure, and it shows how the heating and cooling modes affect the energy consumption. For example, we can see that scenario (A) consumes 18% more energy on the top floor than scenario (B), while scenario (A) consumes about 35.62% more energy in the inter-floors. In conjunction with Figure 12, we compared measured and simulated temperatures (scenario (A), scenario (B)) and energy consumption during scenario (B) in zones 02 and 03. We analyzed the correlation between energy consumption from the simulation and data measured on-site. This thorough comparison would have allowed us to validate the accuracy of the simulation results for energy consumption and assess the building's energy performance, indicating that the actual consumption rate surpasses the results obtained for scenario (B).



(**a**) (**b**)

Figure 12. The correlation between energy consumptions from the simulation and data measured on-site in Gdyel climate: (**a**) zone 02; (**b**) zone 03.

3.4.3. Shape Factor

The energy performance of a building is often analyzed and compared in terms of the form factor, which represents the ratio of the external surface area to volume. Previous studies have shown that a lower form factor and a more compact shape tend to result in better energy performance, as we can see from the earlier findings. This section investigates the impact of the shape factor of each zone on energy demand for heating and cooling in a residential case study located in three Algerian regions, in both the current inter-floor (IF) and top floor (TF), in the same consumption scenario with a fixed window-to-wall ratio (WWR).

A comparison was made of eight zones, each distinguished by a unique form factor, in order to understand their impact on energy demand for heating and cooling, as shown in the results in Figure 13, taking into account the various orientations summarized in Table 13. The simulation results show that heat energy consumption falls linearly as the shape factor decreases, with the exception of zone 4 in both the top floor and inter-floor, where twice as much energy is spent on the top floor compared with zone 01, which has the same orientation, and areas with roughly the same form factor (zones 01 and 02).

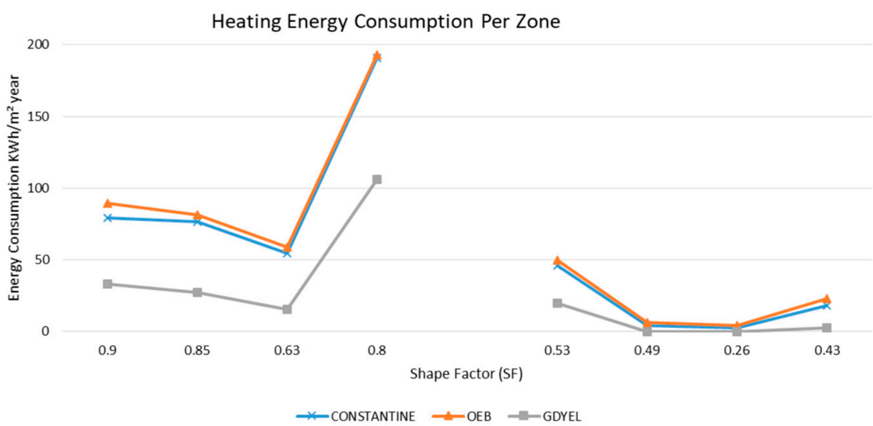


Figure 13. Energy consumption for heating per zone in kWh.

Table 13. Energy consumption for heating and cooling per zone.

Zone	External Faces	Orientation		Roof (m^2)	SF	Heating Energy Consumption (kWh/m^2)			Cooling Energy Consumption (kWh/m^2)		
		Principal (m^2)	Secondary (m^2)			Constantine	OEB	Gdyel	Constantine	OEB	Gdyel
		TF (Top Floor)									
01	3	NE 10.09	NW 10.31	13.76	0.9	79.44	89.21	33.10	65.38	71.40	84.93
02	3	SW 10.09	NW 12.83	16.52	0.85	76.63	81.62	27.40	62.17	67.19	78.76
03	2	SW 9.57	/	13.05	0.63	54.71	59.16	15.56	73.58	78.28	92.21
04	2	NE 4.67	/	15.49	0.80	190.69	193.18	106.19	65.17	72.48	79.14
		IF (Inter-Floor)									
01	2	NE 10.09	NW 10.31	/	0.53	46.05	49.98	19.65	0.78	1.11	0.64
02	2	SW 10.09	NW 12.83	/	0.49	4.20	6.52	0.19	44.40	46.60	52.34
03	1	SW 9.57	/	/	0.26	2.37	4.03	0.04	55.35	56.87	62.36
04	1	NE 4.67	/	/	0.43	18.17	22.91	2.78	55.35	45.61	52.42

When examining cooling energy consumption results, summarized in Figure 14 and Table 13, we found that the influence of the shape factor is not straightforward. We observe that on the top floor, with the same orientation, comparing zone 01 with zone 04 and zone 02 with zone 03, higher shape factors correspond to lower energy consumption. These results suggest that the impact of the form factor on heating energy demand in three climatic regions is influenced by heat transfer through the roof and the proximity to unheated rooms. In the case of cooling, the influence of the form factor is disrupted by orientation. It is also observed that the more compact the form, the more challenging it becomes to dissipate stored heat.

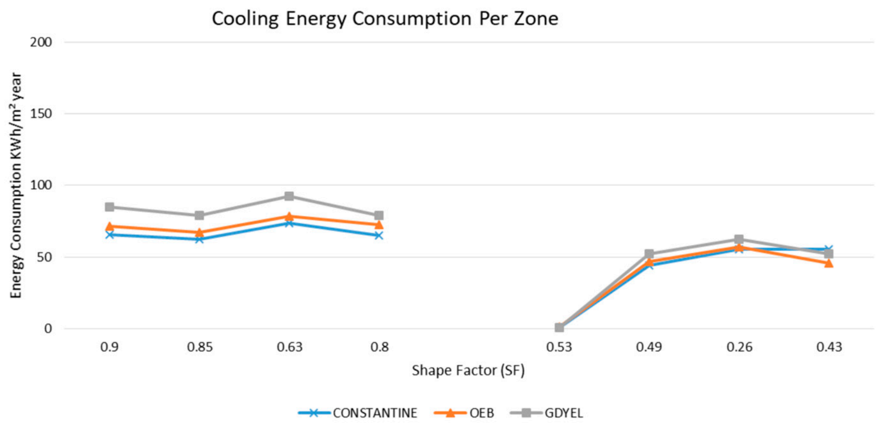


Figure 14. Energy consumption for cooling per zone in kWh.

4. Conclusions

The residential construction sector is the largest consumer of energy in the world, highlighting the crucial importance of evaluating the existing housing stock to integrate energy efficiency into design and decision-making processes.

This study focused on assessing the energy performance of residential buildings in three climatic regions of Algeria, specifically examining the impact of envelope design and shape factor. The research validated a multi-zone study model using TRNSYS software, incorporating empirical field measurements in accordance with ASHRAE guidelines.

The first results of the total energy consumption per floor are consistent with previous research; the results of this study showed that the top floor apartments with SF = 0.57 consumed between 30% and 54% more energy compared to intermediate floors with SF = 0.21. It is also observed that in a semi-arid climate, the top floor has increased energy consumption for heating, while in a Mediterranean climate, it consumes more energy for cooling. Furthermore, in both climatic conditions, the area between the floors consumes more energy for cooling than for heating.

Additionally, our multi-zone model study allowed us to compare energy consumption per zone and identify specific areas that consumed more energy, where the shape factor played a pivotal role in either limiting solar gains or summer overheating. This indicates that a compact form can result in an unexpected increase in energy consumption rather than the expected reduction. It was determined that the heat transfer of the envelope and proximity to unheated zones disrupted the impact of the form factor on energy consumption for heating. The compact form generally has less energy loss through exterior walls. Furthermore, it prevents heat from dissipating quickly, which increases cooling energy consumption. It is recommended that a strategy for roof and north-facing wall insulation be included, as well as a strategy for sealing openings to optimize winter energy efficiency. Protecting south-facing translucent parts to enhance passive design strategies during the summer is also vital.

Studying the behavior of buildings in occupied and heated environments is crucial for comprehending the intricate interactions between the variables involved. These insights can inform the development of more efficacious design and management strategies with the objective of creating comfortable, sustainable, and energy-efficient indoor environments for occupants. This study revealed that the top floor and inter-floor consumed 18% and 35% more energy than necessary, respectively, due to the impact of heating and cooling modes. To address this issue, it is recommended that more efficient systems be implemented.

It is important to acknowledge the limitations of this study. Firstly, there was a lack of resources to provide real-time meteorological data in the studied climatic context. Secondly, there were insufficient means to calculate actual energy consumption. These limitations underscore the need for continued research and innovation in the field of building energy efficiency.

This study's findings have significant implications for the design and decision-making processes related to residential construction. Architects, engineers, and builders can make more informed decisions by understanding how envelope design and shape factor affect energy consumption. Moreover, these findings can also influence the layout of interior spaces within residential housing. For example, knowing which areas of a building consume more energy due to their shape or proximity to unconditioned spaces can guide decisions about the placement of living areas, bedrooms, and utility spaces. Architects and interior designers can use this information to create layouts that balance energy efficiency with functionality and comfort, ultimately enhancing the overall livability of residential spaces.

Future research should consider the environment, allowing for a comparison of the energy efficiency of different forms and envelopes (heat transfer coefficient) used in Algerian housing. The construction industry can play a crucial role in mitigating the effects of climate change by prioritizing energy-efficient building design, thereby reducing greenhouse gas emissions.

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Abbreviations

TEP	Tonnes of equivalent petroleum.
LSP	Participatory social housing.
DTR	Algerian thermal regulatory document.
AADL	National Housing Improvement and Development Agency.
SF	Shape factor (m^2/m^3).
SFZ	Shape factor per zone (m^2/m^3).
U	Heat transfer coefficient (W/m^2 k).
K	Coefficients for multiple linear regression infiltration.
NMBE	Mean bias error.
RMSE	Root mean square error.
CV(RMSE)	Coefficient of variation of the root mean square error.
Ex	Exterior.
IN	Interior.
IN-S-EX-WA	Interior surface temperature of the external wall.
TF	Top floor.
IF	Inter-floor.
T	Temperature (°C).
S (A)	Scenario (A) (experience scenario).
S (B)	Scenario (B) (standard scenario).
WWR	Window-to-Wall ratio
OEB	Oum El Bouaghi

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