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Development of Spatial Distribution Maps for Energy Demand and Thermal Comfort Estimation in Algeria

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Abstract: Climatic spatial maps are essential for understanding the thermal conditions of cities and estimate their cooling and heating energy needs. Climate maps allow building designers and city planners to get adequately informed without accessing, analyzing or interpreting dense textual information. In this study, a representative residential benchmark model was simulated in seventy-four cities of Algeria. The simulation results were interpolated using geographic information systems to generate six high-resolution maps that spatially estimate and visualize the discomfort hours and cooling/heating energy needs. The unique methodology relies on a reliable weather dataset (2004–2018) and combines the power of building performance simulation and geographic information systems. The results of these analyses provide easy to understand and web-based atlas that can be used to explore regional and local climate and quantify the discomfort hours, the heating/cooling energy needs and energy use intensity. The spatial maps are not a static product, but rather data-rich content, which can be expanded to include the most important cities of Algeria. The capabilities of the tool allow architects and urban planners to understand the climate better and propose practical design guidance.

Keywords: climatic zoning; geographic information system; building performance simulation; discomfort hours; residential building

1. Introduction

Climatic zoning and climatic spatial maps are indispensable for sustainable city planning and design. They can help identify climate patterns, climatic classifications, thermal comfort boundaries and climatic threshold temperatures for cooling and heating degree day [1–4]. In the last forty years, climactic zoning became essential in building energy efficiency programs [5]. Historically, climatic zoning and climatic analysis were used in the field of urban planning and building design by simply analyzing weather and climatic data in association with bioclimatic charts and spatial maps [6,7]. The work of several early researchers, in the built environment domain, aimed to visualize climatic data worldwide using simple statistical methods [8–12]. Consequently, more than 80 study in 60 countries in the world are investigated the climatic classification and zoning for bioclimatic and energy efficient buildings design.

The classical research methodology used in climatic zoning studies is based on processing weather and climate variables to visualize and compare data in relation to specific thermal comfort thresholds. Clustering methods or other statistical analysis techniques are used to support the identification of climatic zones and suggesting passive urban and building design recommendations to achieve maximum thermal comfort [11–13]. The quantification and classification of climate are based on large data sets of measured data without the use of building simulation tools and supporting thermal regulations and design guides with statistics-based design guidance.

1.1. State of the Art of Climatic Zoning

In the recent ten years, researchers profited from the advancement in the building performance simulation (BPS) and the geographic information systems (GIS) domains to make climatic zoning research more accurate. The progress of computational programs allowed researchers to define new climatic zoning analysis and maps incorporating typical reference buildings resulting in refined climatic maps and zoning classification. This includes the works of Attia et al. [1] and Praene et al. [14] in Madagascar, Verichev et al. [15] in Chile, Groppi et al. [16] and Moghadam et al. [17] in Italy, Borah et al. [18] and Singh et al. [19] in India, Roshan et al. [7] in Iran, Pajek et al. [20] in Slovenia, Walsh et al. [21] in Nicaragua and Pajek et al. [22] in Europe. Thus, the proliferation of climatic analysis based on GIS and/or BPS techniques reflects a structural tendency. There is an imminent transition in the scientific community where GIS and BPS techniques are combined to become fundamental methods for future climatic analyses [5].

The relation between climatic zoning and sustainable city design is significant and is translated into planning tools and maps among several countries. In some states, typical values of weather data for city planning and building energy load calculations are established for each climatic zone. In contrast, the energy use intensity should respect specific limit for each zone [19]. In other countries, there are particular performance targets for each climatic zone [23]. The importance of climatic zoning is high in countries with a weak regulation landscape and energy efficiency implementation infrastructure. In most of the cases, there is no information available on the relationship between zoning and urban design guidelines or building energy performance [5].

1.2. Studies on Climatic Zoning in Algeria

Like many other countries, Algeria is looking forward to updating its existing climatic zoning maps and revises its energy efficiency programs for cities. Algeria is increasingly urbanized, and its future will be shaped in dense energy-dependent cities. Already, some existing studies investigated the climatic zoning in Algeria, including the work of CNERIB [24,25], Mesri et al. [26], Ghedamsi et al. [27], Beck et al. [28] and Mokhtara et al. [29]. However, none of those studies combined the weather data analysis with GIS and BPS, as shown in Table 1. Nothing found in literature on climatic zoning in Algeria is up-to-date except in the light of GIS, BPS and this current work.

Therefore, our study aims to develop new spatial distribution maps for energy demand and thermal comfort estimation in Algeria. This work combines the powers of BPS and GIS tools with a recent weather files dataset and analyses the climate of Algeria, taking into account the impact of typical and representative housing archetype. Based on a current dataset (2003–2017) of seventy-four weather stations and a calibrated residential benchmark model, the study presents new zoning maps based on the thermal energy demand and indoor-discomfort hours of the current social residential building archetype in Algerian territory.

The results provide a higher resolution climatic classification of the Algeria with nine climate zones. Each climate zone is associated with quantified calculation of the discomfort hours and cooling and heating energy needs. The study findings are useful for architects, building engineers, city planners and decision-makers in a critical moment, where the Algerian government is looking forward to revising the existing Algerian code. There is a need for climatic spatial maps of cities that embed careful analysis, acceptable forecasting and planning abilities [1]. This study brings researchers one-step closer to realize a new and more accurate climatic zoning to help navigate the sizeable Algerian terrain of climate uncertainty across a landscape of potential. Climate maps allow building designers and city planners to get adequately informed without accessing, analyzing or interpreting dense textual information [29,30]. The outcomes are essential to facilitate the management of energy efficiency and building design across Algerian cities. They can help to minimize the uncertainty in the estimation of discomfort hours and energy demand in residential buildings. Moreover, an extensive weather dataset (2003–2017) is used, which is not common to see a work dealing with climatic zoning and comfort optimization [23,31–33]. This study contributes to research efforts that analyses and visualize climatic data for sustainable city development [5,21].

Table 1. Comparative analysis of Algeria's climate classifications found in the literature.

	Köppen [28]	**CNERIB [24,25]**	**Mesri et al. [26]**	**Ghedamsi et al. [27]**
No. of zones	5 climate zones	6 climate zones	3 climate zones	7 climate zones
Classification parameters	- Vegetation - Air temperature - Rainfall	- Daily mean outdoor air temperature	- Sunshine duration - Temperature - Water vapor pressure - Evaporation - Relative humidity - Rainfall	Daily mean outdoor air temperature
No. of Weather stations	Several stations worldwide	31 stations	52 stations	48 stations
Classification Approach	Cluster analysis	Heating and cooling degree-days	Clustering method	Heating and cooling degree-days

2. Characterization of the Algerian Housing Sector

The building sector in Algeria is the largest consumer of fossil energy, consuming 46% of the total national energy bill, out of which residential buildings consume the most significant part of 37% (Appendix A). The breakdown of energy use by sector is shown in Figure 1a. As shown in Figure 1b, the energy use of the residential sector increased considerably in the last ten years (2009–2018) from around 9000 KTep to more than 17,700 KTep (Appendix A). The main reason associated with this increase in energy demand is the substantial increase in population and housing units [34].

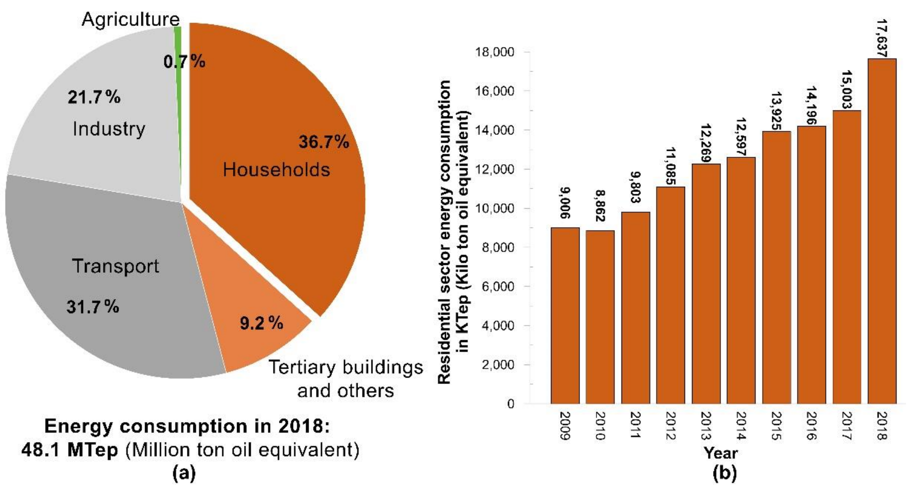

Figure 1. Energy use in Algeria. (**a**) Breakdown of energy use by sector; (**b**) evolution of energy use of the residential sector between 2009 and 2018 (Appendix A)

In the last decade, the Algerian authorities built more than three million dwellings. For example, between 1999 and 2018, more than 3.6 million dwellings were built (Appendix B). The residential building sector in Algeria is generally composed of two main typologies: (i) multifamily apartment buildings, which represent 51% of the residential sector and (ii) single-family houses, which represent 49% of the residential sector. The latter is divided into rural housing and self-constructed housing (see Figure 2a) (Appendix B).

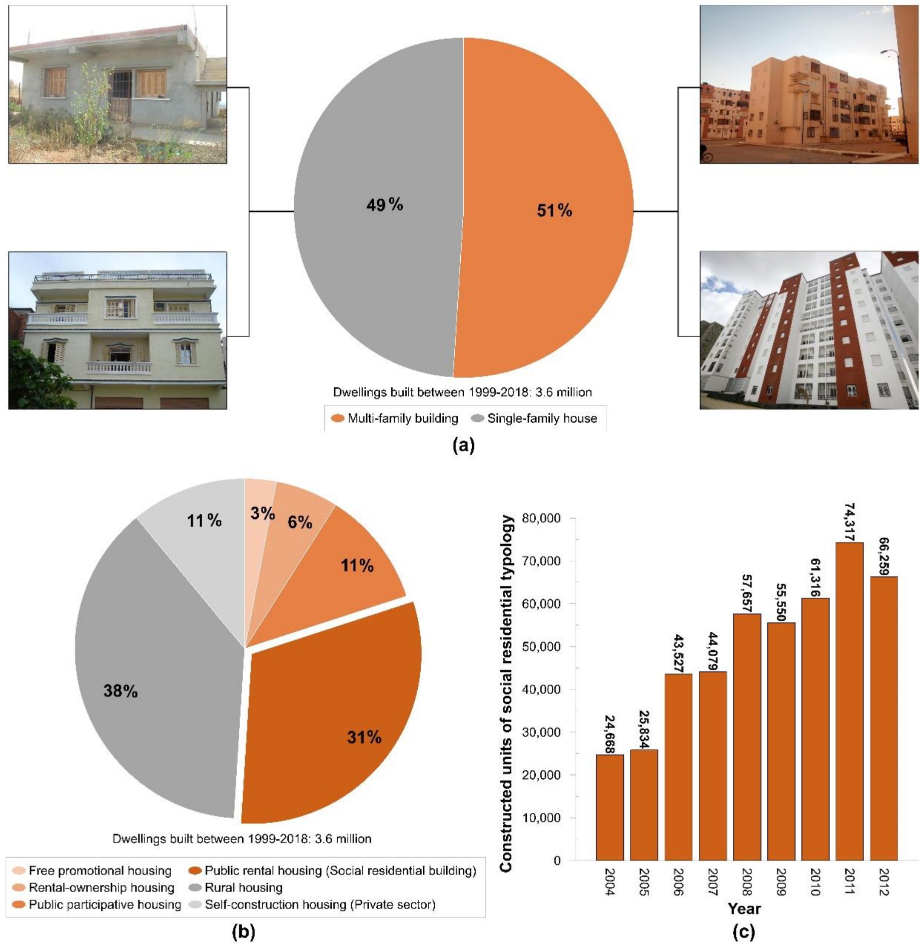

Figure 2. Characterization of residential housing typologies in Algeria. (**a**) Dwellings archetypes; (**b**) dwellings contract types; (**c**) evolution of social housing units (Appendix B).

There are several categories of the multifamily apartment building archetype depending on the contract type that reflects the residents' income (Public rental housing, participatory public housing, rental–ownership housing and free promotional housing) (see Figure 2b). The social residential buildings category (Public rental housing) represents the central part (31%) in the multifamily building's archetype. This category is intended for the low-income population in Algeria (Appendix B). The percentage of residential housing typologies by contract type is shown in Figure 1b. The dwellings of the social housing building category have been increased every year, as shown in Figure 2c, which presents the evolution of constructed social residential units. The Algerian Ministry of housing, urbanism and the city launched a program of 800 thousand dwellings between 2009–2014 and 800 thousand dwellings between 2015 and 2019 (Appendix B).

Therefore, we aimed at selecting the most common housing archetype in Algeria to estimate the energy demand and thermal comfort and create new spatial distribution maps. By including the building characteristics in our climatic analysis, we claim to present accurate climate analysis and inform better designers about the climate influence on the most commonly constructed residential housing archetype in the country. The following section explored further in detail the research methodology, assumptions and boundary conditions.

3. Methodology

The research methodology resulted in a calculation and visualization approach for thermal energy demand and indoor-discomfort hours of multifamily social residential buildings in Algeria. The used calculation method is based on a dynamic building performance simulation approach applied to the calibrated model of multifamily social residential buildings. Figure 3 presents the detailed conceptual framework of the study describing the steps of the research methodology. The research methodology of this study is divided into four significant steps. Each step is described in detail in the following sections.

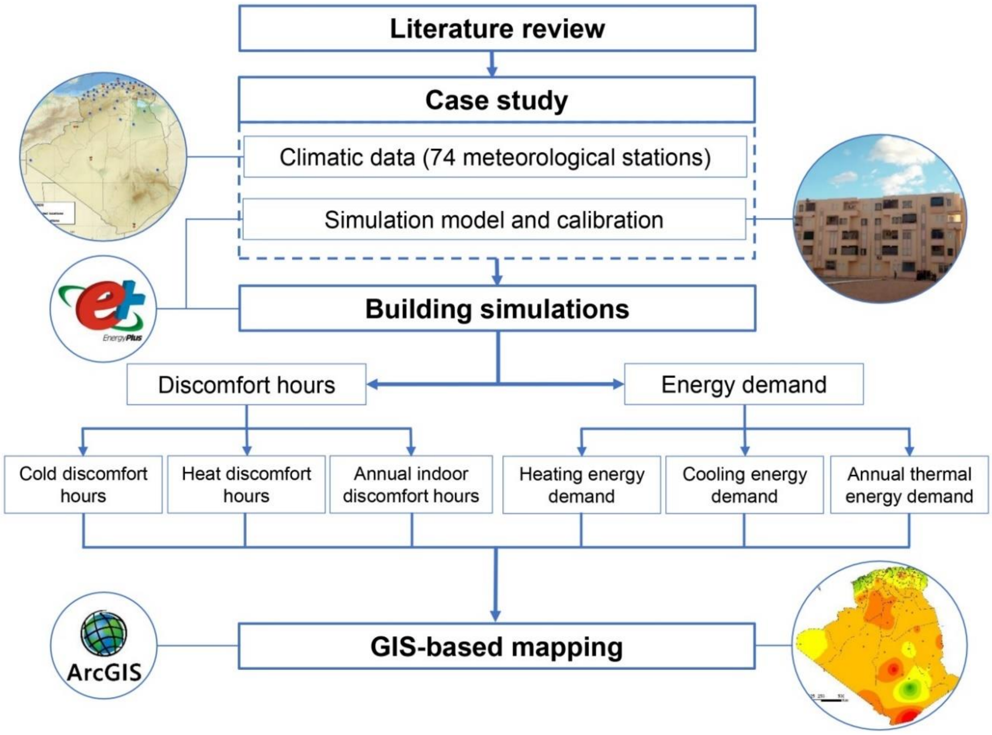

Figure 3. Study conceptual framework.

3.1. *Climate Data and Reference Model Creation*

The second step of the methodology was to select a representative dwelling archetype. This step involved a simple characterization of the Algerian housing sector, identification and acquisition of available weather stations and weather files, monitoring of a representative dwelling, and finally, the creation of a virtual and calibrated building performance simulation model.

3.1.1. Characterization of the Housing Sector

The Algerian Census Database of the residential sector was analyzed between 1999 and 2018, to understand the relationship between the energy use of the building sector and the residential building stock in Algeria. In addition, the national energy use data of the residential building sector, between 2009 and 2018, were collected. The data on the energy use of each building archetype was found websites of the Algerian Ministry of Energy web site [34], the Ministry of Housing [35] and the National Office of Statistics [36]. The data were analyzed, organized and visualized to represent the energy use in Algeria by sector and the evolution of energy use of the residential sector. The compiled data can be found in Appendices A and B

3.1.2. Climatic Data

The different climatic zones described by the Algerian Thermal Regulation (DTR C3-2) indicate six distinct climatic zones [24,25]. Zone (A): in the North of Algeria, including the coastal zone;

Zone (B): in the South of the zone (A), including the plain behind the seashore; Zone (C): in the South of the zone (B), including the highlands; Zone (D): in the South of Algeria, including the desert; and the climate zones (B′) and (D′), representing subzones within the central zones (B) and (D), respectively. However, this classification is outdated because it relies on old weather datasets (1960–1990) and is too generic, with only six climate zones for a country of 2.382 million km^2. Therefore, this study opted for a higher resolution classification resulting in seventy-four selected locations within the forty-eight Algerian provinces (see Figure 4).

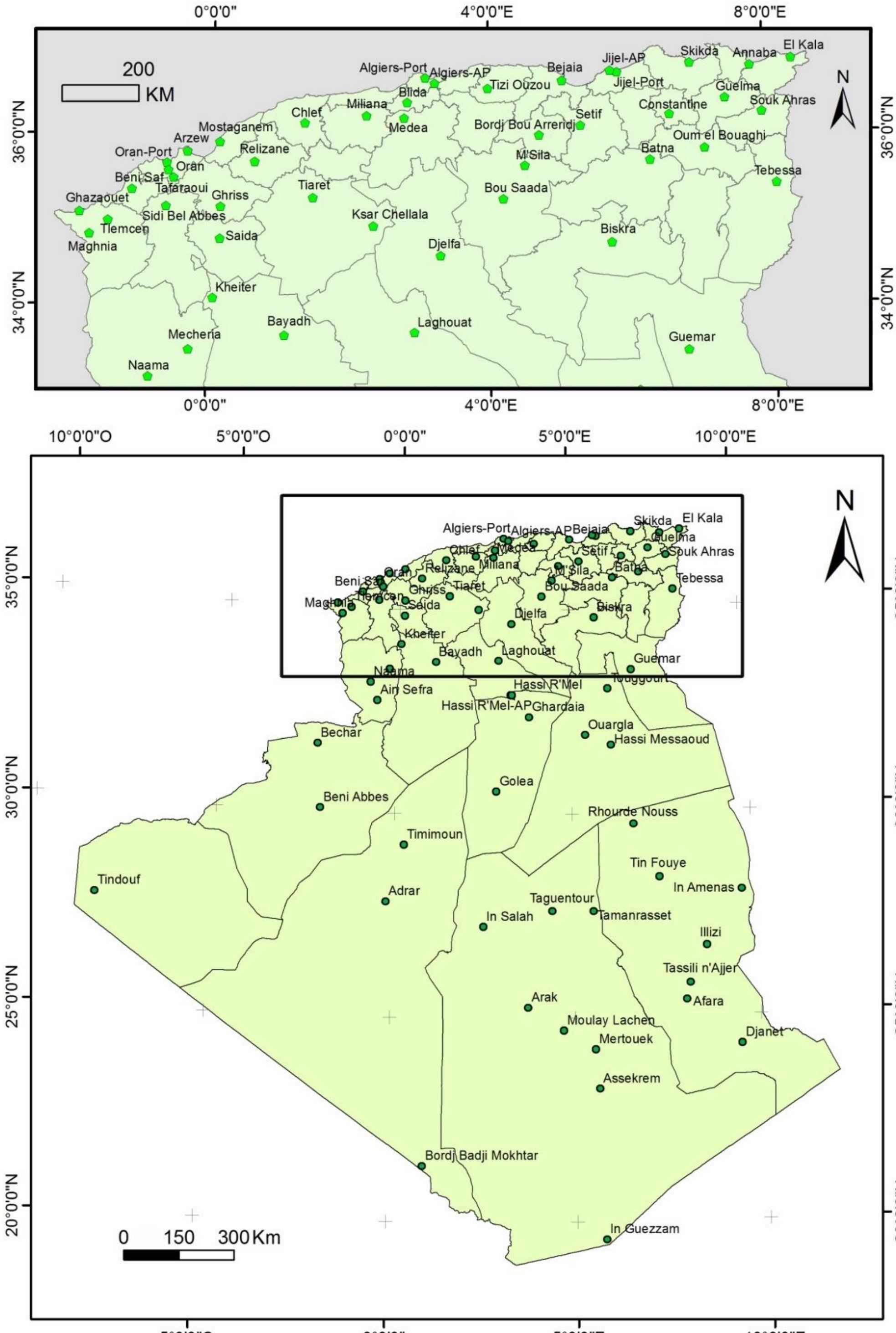

Figure 4. Distribution of the 74 studied locations across Algerian territory.

The weather data used in this study are the averages of fifteen years (2004–2018), which represents the recent weather datasets for the seventy-four selected locations. The chosen locations represent new meteorological stations in Algeria with an extensive territorial coverage. This choice was confirmed by the lack of availability of TMY3 (1991–2005) for the seventy-four selected locations. Each weather file consists of hourly records of dry-bulb temperature, dew point temperature, pressure and total horizontal solar radiation. The weather data were made available by the United States Department of Energy [37].

3.1.3. Reference Model Creation and Calibration

Based on the characterization of the Algerian housing stock, the selected building model for this study represents a typical multifamily social residential building (see Figure 5). The number of floors of this archetype is ranging between two and six stories. Each level is subdivided into two flats. The floor height is 2.8 m, and the floor area of each household is approximately 70 m^2. The building geometry (see Figure 6) of the real building components was used as the simulation model input.

Figure 5. Multifamily social residential building archetype in Algeria.

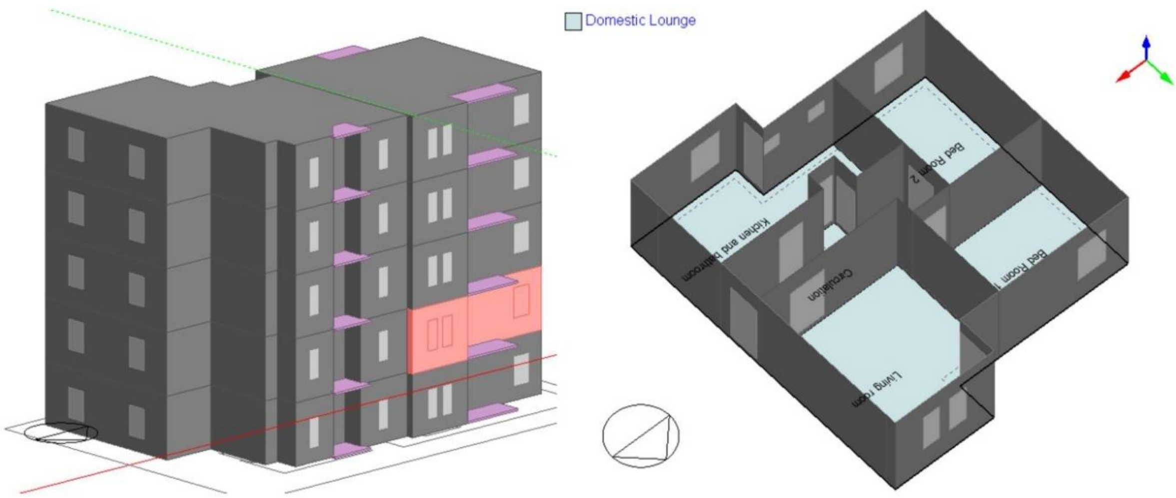

Figure 6. Simulated building model developed using DesignBuilder and EnergyPlus.

A walkthrough visit was performed to identify appliances, and questions were asked to create occupancy profiles and occupancy schedules. The indoor air temperatures and humidity were continuously recorded from January 2016 to July 2016. The Testo-480 measurement kit was used to create the monitoring datasets. The measurement range was −20 °C to +70 °C at an accuracy of ±0.5 °C. The instrument was installed in the living room. The measurements taken in the main living space of the apartment are considered representative, like the work of Colton et al. [38], Giancola et al. [39] and Lai et al. [40]. The instrument was placed in the center of the space at a height of 1.4 m, which is the medium clear height of the living room. The monthly electric and gas uses (kWh) were registered during 2016; the data were collected from electricity and gas meters. The building model is calibrated under hourly and monthly data through winter and summer indoor temperature and electricity and gas use. The calibration and validation process of model accuracy is described in detail in a previous study by the authors [4]. The thermophysical properties of the building elements, according to the Algerian Thermal Regulation of Residential Buildings [24].

3.2. Calibration Method

The calibration focused on how closely the simulated results match the monitored data. The calibration was an essential step to allow the creation of a reliable simulation model. The simulation model was calibrated using the present building physics conditions and patterns of energy use. To calibrate the building simulation model, ASHRAE Guideline 14, was followed. Three indices of the ASHRAE Guideline 14 were used for our manual calibration: (1) mean bias error (MBE), (2) coefficient of variation or root-mean-square error [CV (RMSE)] and (3) the coefficient of determination R2. The MBE is a nondimensional measure of the overall bias error between the measured and simulated data with a known time resolution. The CV (RMSE) indicates how well the simulation model describes the variability in the measured data. The coefficient of determination, denoted R2 is the proportion of the variance in the dependent variable that is predictable from the independent variable(s). The MBE, CV (RMSE) and R2 values were calculated using the following equations:

$$MBE = \frac{\sum_{i=1}^{Np}(Mi - Si)}{\sum_{i=1}^{Np} Mi}\ (\%) \tag{1}$$

$$CV\ (RMSE) = \frac{1}{M}\sqrt{\frac{\sum_{i=1}^{Np}(Mi - Si)^2}{Np}}\ (\%), \tag{2}$$

$$R2 = \frac{\mathrm{SSres}}{SStot} \tag{3}$$

where Mi and Si are the measured and simulated data at a time interval, I and Np is the total number of data values used for the calculation.

According to ASHRAE Guideline 14 [41], the simulation model is considered calibrated if:

hourly MBE values are within ±10% and hourly CV (RMSE) values are below 30%
monthly MBE values are within ±5% and monthly CV (RMSE) values are below 15%

The simulation was calibrated using two data categories: (1) hourly indoor temperature and (2) monthly energy use. Each data category has two subcategories: winter and summer indoor temperature and electricity and gas use. A manual calibration was used, and the initial model (reference case) went through several trial-and-error modifications. The airtightness values, schedules (occupancy, lighting, heating, cooling and DHW), and setpoint temperature values were modified during the calibration. The MBE and CV (RMSE) values were calculated after each simulation run and compared with the accuracy thresholds of ASHRAE Guideline 14. We calculated R2 for hourly indoor temperature (during summer and winter time) and monthly energy use (gas and electricity use). R2 values, the correlation between the monitored and simulated data are strong for monthly electricity and gas use, while there is a mean correlation for summer and winter indoor air temperature. Table 2 shows the results of the calibration indices. The results of the validation of the simulation model calibration are described in Section 4.2.

Table 2. Calibration results of the building simulation model.

Validation Criteria	Winter Indoor Air Temp.	Summer Indoor Air Temp.	Monthly Electricity Use	Monthly Gas Use
MBE (%)	−2	−1.52	−0.68	0.4
CV-RMSE (%)	5.12	4.97	7.83	6.67
R2	0.75	0.63	0.92	0.98

MBE: mean bias error, CV (RMSE) root-mean-square error and R2 the coefficient of determination.

3.3. Building Performance Simulation

In this study, EnergyPlus V8.9.0 software was used. EnergyPlus is developed by the US Department of Energy (DOE) and is one of the most widely used detailed and dynamic energy simulation programs [42]. The annual indoor-discomfort hours and the annual energy demand were simulated in the seventy-four selected locations (meteorological stations).

3.3.1. Discomfort Hours

The number of indoor-discomfort hours was calculated based on the adaptive comfort model ASHRAE 55-2017 [43]. The selection of the ASHRAE 55-2017 adaptive comfort model was based on the recommendations of Attia et al. [1,44] who consider it as the best available socioeconomic model that sets no humidity limit, which is essential in the coastal cities of Algeria [45]. Three categories of discomfort hours were calculated:

The cold-discomfort hours. They represent the number of hours, which the operative temperature is lower than the temperature of the comfort range (see Figure 7).

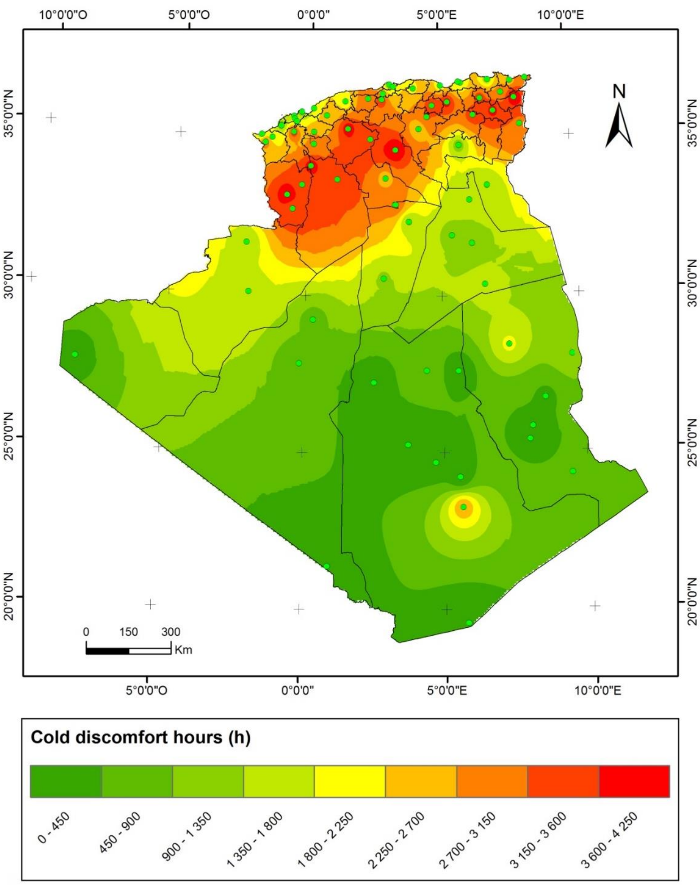

Figure 7. Cold-discomfort hours map.

The heat-discomfort hours. They represent the number of hours in which the operative temperature is upper than the temperature of the comfort range (see Figure 8).

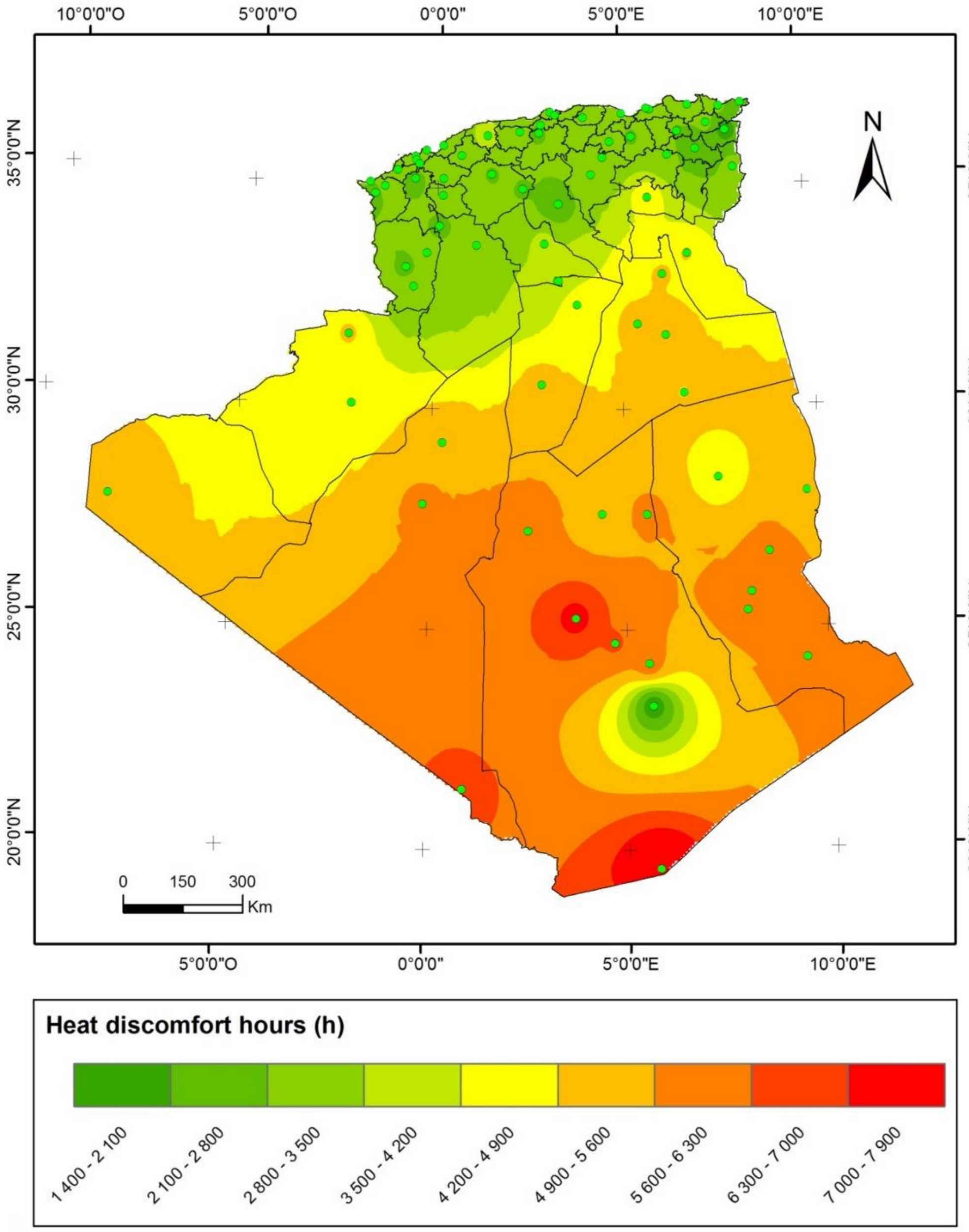

Figure 8. Heat-discomfort hours map.

The annual indoor-discomfort hours. They represent the addition of the cold-discomfort hours and the heat-discomfort hours (see Figure 9).

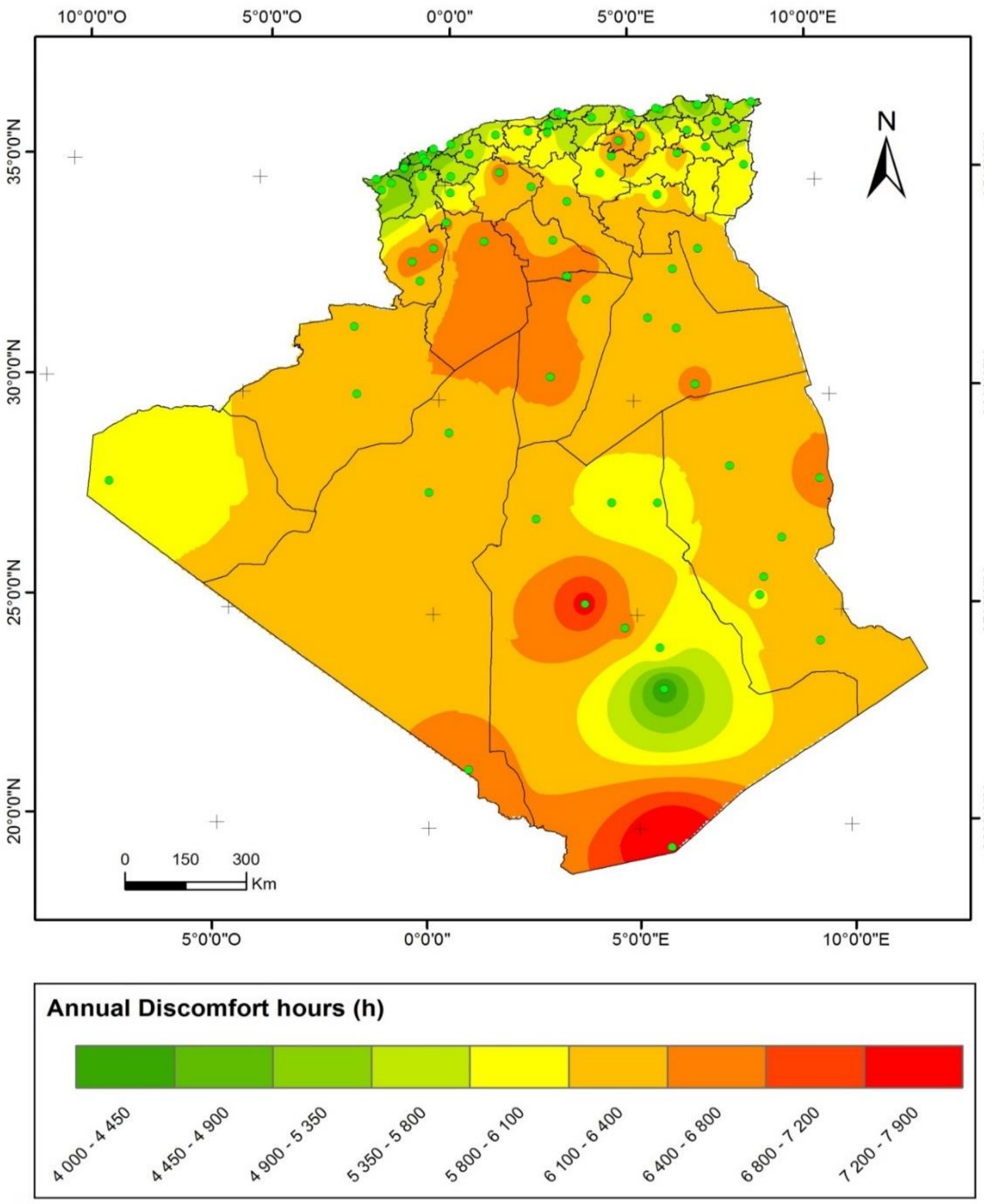

Figure 9. Annual indoor-discomfort hours map.

Equations (4) and (5) provide the basis of the discomfort-hours calculation:

Optimal comfort temperature (°C) [46]:

$$T_c = 0.31 f(T_{out}) + 17.8 \quad 10\ ^\circ\mathrm{C} \le f(T_{out}) \le 33.5\ ^\circ\mathrm{C} \tag{4}$$

Upper 80% acceptability limit (°C):

$$T_c = 0.31 f(T_{out}) + 20.3 \quad 10\ ^\circ\mathrm{C} \le f(T_{out}) \le 33.5\ ^\circ\mathrm{C}$$

Lower 80% acceptability limit (°C):

$$T_c = 0.31 f(T_{out}) + 15.3 \quad 10\ ^\circ\mathrm{C} \le f(T_{out}) \le 33.5\ ^\circ\mathrm{C},$$

where $f(T_{out})$ is the prevailing mean outdoor air temperature ($t_{pma(out)}$) in ASHRAE 55 for 2013 and 2017 and the mean monthly outdoor air temperature in ANSI/ASHRAE 55 for 2004 and 2010.

Prevailing mean outdoor air temperature (°C) [43]:

$$\bar{t}_{pma(out)} = (1-\alpha)\,[t_{e\,(d-1)} + \alpha \cdot t_{e\,(d-2)} + \alpha^2 \cdot t_{e\,(d-3)} + \alpha^4 \cdot t_{e\,(d-4)} + \ldots\,], \tag{5}$$

where α is a constant ranging between 0 and 1 and $t_{e\ (d-1)}$ is the daily mean external air temperature at time d of a series of equal intervals (day).

In the last two versions, ANSI/ASHRAE 55 suggests an α value of 0.9 for climates in which the day-to-day temperature variation is relatively minor, such as the humid tropics and a lower α value of 0.6 for mid-latitude climates in which the day-to-day temperature variation is more pronounced.

3.3.2. Energy Demand

The energy demand of the residential building model was simulated in seventy-four selected locations. The heating and cooling system activation is based on the setpoints of heating and cooling temperatures. Three categories of energy demand was calculated: (1) heating energy demand, (2) cooling energy demand and (3) annual thermal energy demand, which represents the addition of heating energy demand and the cooling energy demand.

3.4. Plotting on GIS-Based Maps

The visualization of the discomfort hours and energy demand results used a geographic information system (GIS) techniques. Geographic information systems (GIS) are commonly used to represent spatial data and visualization issues associated with multiscale geographic data. An essential feature of a GIS is the ability to generate new information by integrating the existing diverse datasets sharing a compatible spatial referencing system. GIS methods allow direct viewing of the spatial difference and a direct comparison of values associated with the region use pattern on the map. To present the spatial distribution of residential building energy demand and indoor-discomfort hours in Algeria, we adopted the following steps:

The first step is the creation of an administrative map of the study area, extracted from the Weather Algeria website [47]. Then, critical thematic layers were identified for curing out the target application after the normative calibration of the under-studied map. The climate data were rastered and georeferenced to allow conducting a more detailed spatial analysis of the features of thematic layers. We have identified first, three layers, (1) the provinces layer, (2) the Mediterranean Sea layer and (3) the neighboring countries layer. The geographic coordinate system projection facilitated the creation of layers and the shapefiles characterizing the study areas. The findings are presented by areal entities in polygons formats representing the major Algerian provinces (or Willayat).

The second step consists of integrating an Excel table with the GIS software ArcGIS. ArcGIS software version 10.0, developed by the Environmental Systems Research Institute, was used (ESRI 2019). The objective of this step is to make it possible to read the digital data of used meteorological stations, which were generally characterized by their geographic coordinate system projection and their climatic parameters. The seventy-four stations were identified in ArcGIS as 74 seventy-four (see Figure 4). The meteorological station's layer has been added for the sake of beginning the deterministic spatial method explained in the follow step.

The third step involved data treatment using the inverse distance weighted (IDW) interpolation method. The (IDW) method is used to interpolate spatial data, which is based on a concept of distance weighting [48]. The IDW method involves the process of assigning values to unknown points by using values from a scattered set of known points [48]. Hence, the main objective of this technique is to provide (interpolate) new data in locations where there were no meteorological stations. The simulation results of the building performance simulation were georeferenced (74 locations) to produce residential building performance maps. The final step was the visualization of annual spatial distribution maps for residential building energy demand and indoor-discomfort hours for Algeria and assigning a legend.

4. Results

The resulting estimates of the indoor-discomfort hours and building energy demand in the seventy-four selected locations were visualized in ArcGIS to show the distribution of annual spatial distribution in Algeria [45]. This section covers two categories of the calculation results. (1) The first category is the number of indoor-discomfort hours, including the cold-discomfort hours, hot-discomfort hours and annual-discomfort hours; (2) The second category is the thermal energy demand, including the heating energy demand, cooling energy demand and annual energy demand.

4.1. Indoor-Discomfort Hours

4.1.1. Cold-Discomfort Hours

Figure 7 shows the spatial distribution of annual cold-discomfort hours in all regions of Algeria. Based on the cold-discomfort hours map, Algeria can be grouped into three main zones and nine subzones. The first zone represents the northern coastal zone. The second one includes the subcostal zone and highlands zone, which is situated between the coastal zone and the desert zone. The third zone covers the South of Algeria (desert).

Based on our simulation, we found that the maximum number of cold-discomfort hours is registered in Souk Ahras on the Northeast of Algeria, with 4213 h of cold discomfort, which represents 48% of hours in the year. Djelfa follows with 4190 in the Center of Algeria and Naama with 3988 h in the West of Algeria (see Figure 7). On the opposite, In Guezam (Tamanrasset) and Bordj Badji Mokhtar (Adrar) in the extreme South of Algeria, both have the minimum number of cold-discomfort hours with 0 and 16 h, respectively (see Figure 7). Assekrem, in the extreme South of Algeria, has a high number of cold-discomfort hours around 2657 h due to its high altitude of 2726 m above sea level.

Results indicate a significant difference between the maximum and minimum the number of cold-discomfort hours in Algeria, which exceeds 4200 h. Table 3 shows the percentage of the Algerian territory occupied by each range of the cold-discomfort hours. The cold-discomfort hours, in 77.2% of Algerian territory, is ranging between 0 and 1800 h. It represents around 20% of the total hours of the year. The cold-discomfort hours in 17.6% of Algerian territory is ranging between 2250 and 4250 h, which represents, respectively 25.5% and 48.5% of the total hours of the year. The cold-discomfort hours in the rest of Algeria, (around 5.2% of Algerian territory) is ranging between 1800 and 2250 h, which represents, respectively 20.5% and 25.5% of the total hours of the year.

Table 3. Territory surfaces in percentage of cold-discomfort hours zones.

Cold-discomfort hours range (hours)	0–450	450–900	900–1350	1350–1800	1800–2250	2250–2700	2700–3150	3150–3600	3600–4250
Territory surface in percentage (%)	18.3	25.8	16.9	16.2	5.2	4.7	6.5	5.6	0.7

4.1.2. Heat-Discomfort Hours

Figure 8 shows the spatial distribution of annual heat-discomfort hours in all regions of Algeria. Based on the heat-discomfort hours, Algeria can be grouped into three main zones, which are divided into nine (09) subzones. The first zone in the North of Algeria is situated between the Mediterranean Sea and the Southern Highlands zone. The second zone covers the North of the desert zone. The third zone represents the South of the desert zone.

Based on building performance simulation results, the maximum number of heat-discomfort hours is registered in In Guezam (Tamanrasset) on the extreme South of Algeria with 7879 h, which represents 90% of hours in the year. It is followed by Arak (Tamnrasset) with 7294 and Bordj Badji Mokhtar (Adrar) with 6475 h (see Figure 8). On the opposite, Assekrem (Tamanrasset) in the extreme South of Algeria has the minimum number of heat-discomfort hours with 1489 h. Assekrem (Tamanrasset) is followed by Sidi Bel Abbes in the West of Algeria with 1983 and Djelfa in the center of Algeria with 2048 h.

Results indicate a significant difference between the maximum and minimum number of cold-discomfort hours in Algeria, which is around 6400 h. Table 4 shows the percentage of the Algerian territory occupied by each range of the heat-discomfort hours. The heat-discomfort hours in 61.5% of Algerian territory is ranging between 4900 and 7900 h, which represents 56% and 90% of the total hours of the year, respectively. The heat-discomfort hours in 23.3% of Algerian territory is ranging between 3500 and 4900 h, which represents 39.9% and 55.9% of the total hours of the year, respectively. The cold-discomfort hours in the rest of Algeria (15.2% of Algerian territory) are ranging between 1400 and 3500 h, which represents 15.9% and 55.9% of the total hours of the year, respectively (see Table 4).

Table 4. Territory surfaces in percentage of heat-discomfort hour zones.

Heat-discomfort hours range (hours)	1400–2100	2100–2800	2800–3500	3500–4200	4200–4900	4900–5600	5600–6300	6300–7000	7000–7900
Territory surface in percentage (%)	0.2	2.3	12.7	5.3	18	31.8	25.8	3	0.8

4.1.3. Annual-Discomfort Hours

Figure 9 shows the spatial distribution of yearly-discomfort hours in all regions of Algeria. Based on the yearly-discomfort hours, Algeria is divided into three major zones, which are divided into nine subzones (see Figure 9). The first zone occupies the coastal zone on the North except Tipaza and the South of Chlef. It holds the subcostal in the east and west. This zone includes Assekrem (Tamanrasset) in the extreme South of Algeria.

The second zone is bordered by the coastal zone and the desert zone in the east and the South of the highlands in the west of Algeria (except Bordj Bou Arreridj and the southeast of Setif). This zone includes some locations in the desert zone in the South of Algeria like Tendouf and Taguentour, Aguemar and Mertouek in Tamanrasset. The third zone occupies the desert zone and the south part of the highlands in the west of Algeria like Tiatret and Naama. This zone includes two subzones that have several annual-discomfort hours higher than the central zone. The first subzone includes Al-bayadh, the South of Laghouat, the west of Ghardaïa and Bordj Badji Mokhtar (Adrar). The next subzone includes In Guezam and Arak in Tamanrasset.

Based on simulation results, the maximum number of annual-discomfort hours is registered in In Guezam and Arak. Both locations are in Tamanrasset with 7879 and 7344 h, respectively. On the opposite, the minimum number of annual-discomfort hours is registered in Oran with 3895 h, followed by Beni Saf (Ain Temouchent) on the west of Algeria with 4107 h and Assekrem (Tamanrasset) with 4146 h. Table 5 shows the percentage of the Algerian territory occupied by each range of the annual-discomfort hours.

Table 5. Territory surfaces in percentage of annual indoor-discomfort hours zones.

Annual indoor-discomfort hours range (hours)	4000–4450	4450–4900	4900–5350	5350–5800	5800–6100	6100–6400	6400–6800	6800–7200	7200–7900
Territory surface in percentage (%)	0.2	0.5	1.5	4.3	16.5	62	12.9	1.2	0.8

In addition, results indicate the annual-discomfort hours in 77% of Algerian territory is ranging between 6100 and 7900 h, which represents 70% and 90%, respectively, of the total number of hours of the year. In 16.5% of Algerian territory, the number of annual-discomfort hours is ranging between 5800 and 6100 h, which represents 66% and 70%, respectively, of the total number of hours of the year (see Table 5). Only in 6.5% of Algeria territory, the number of annual-discomfort hours is ranging between 4000 and 5800 h, which represents about 45% and 66%, respectively, of the total number of hours in the year.

4.2. Thermal Energy Demand

Following the indoor-discomfort hours of the social residential building archetype, the thermal energy demand of this archetype, was analyzed across all the Algerian territory. This section illustrates the spatial maps for the heating and cooling demand and annual energy demand.

4.2.1. Heating Energy Demand

Figure 10 shows the spatial distribution of annual heating energy demand in all regions of Algeria. Based on the heating energy demand, Algeria is divided into three main zones, which can be divided into nine subzones. The first zone represents the coastal zone, the subcostal zone and the North of the desert. The second one includes the highlands, situated between the subcostal zone and the North of the desert zone. The third zone covers the South of Algeria (desert).

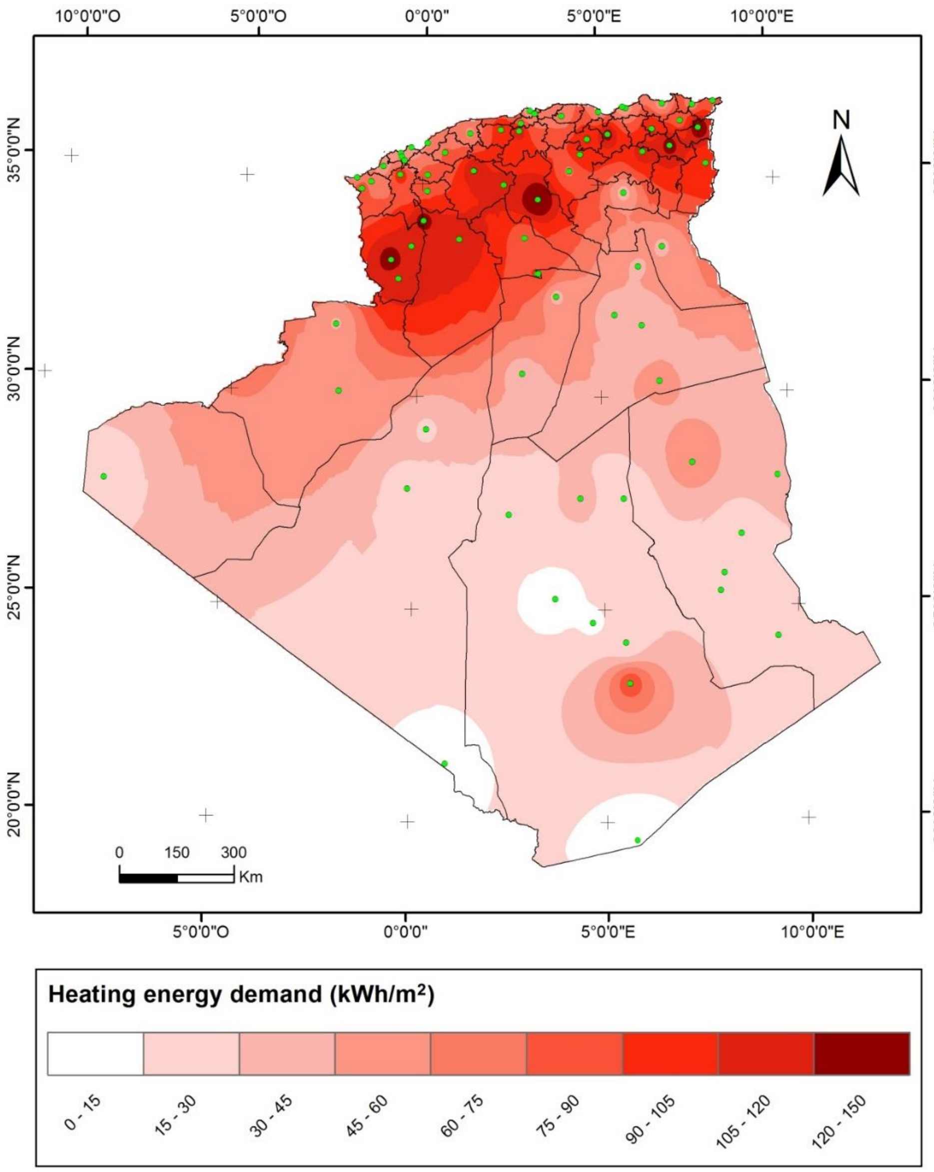

Figure 10. Heating energy demand map.

Based on simulation results the maximum heating energy demand is registered in Djelfa in the Center of Algeria with 150.5 kWh/m^2 followed by Souk Ahras on the Northeast of Algeria with 143.4 kWh/m^2 and Naama with 132.7 kWh/m^2 in the West of Algeria (see Figure 10). On the opposite, In Guezam, Arak (Tamanrasset) and Bordj Badji Mokhtar (Adrar) in the extreme South of Algeria have the minimum of heating energy demand with 2, 5.6 and 8.9 kWh/m^2, respectively (see Figure 10). Assekrem (Tamanrasset) in the extreme South has a high heating energy demand of around 84.2 kWh/m^2.

In addition, results indicate a significant difference between the maximum and minimum of heating energy demand in Algeria, which is about 148 kWh/m^2. Table 6 shows the percentage of the Algerian territory occupied by each range of the heating energy demand. The heating energy demand in 78.3% of Algerian territory is ranging between 0 and 60 kWh/m^2. The heating energy demand in 16.4% of Algerian territory is fluctuating between 75 and 150 kWh/m^2. The heating energy demand in the rest of Algeria (around 5.3% of Algerian territory) is ranging between 60 and 75 kWh/m^2 (see Table 6).

Table 6. Territory surfaces in percentage of heating energy demand zones.

Heating energy demand range (kWh/m^2)	0–15	15–30	30–45	45–60	60–75	75–90	90–105	105–120	120–150
Territory surface in percentage (%)	3.8	33.8	24.2	16.4	5.3	6	5.6	4.2	0.5

4.2.2. Cooling Energy Demand

Figure 11 shows the spatial distribution of annual cooling energy demand in all regions of Algeria. Based on the cooling energy demand, Algeria is divided into three main zones with nine subzones. The first zone includes the North of Algeria, which is situated between the Mediterranean Sea and the North of the desert zone. The second zone represents the extreme South and the southwest of Algeria (Adrar and the west of Tamanrasset). Moreover, the third zone is situated between the previous two zones. Based on our simulation we found that the maximum cooling energy demand is registered in In Guezam (Tamanrasset) on the extreme South of Algeria with 140.9 kWh/m^2 followed by Arak (Tamnrasset) with 131.1 kWh/m^2 and Bordj Badji Mokhtar (Adrar) with 113.3 kWh/m^2 (see Figure 11). On the opposite, Assekrem (Tamanrasset) in the extreme South of Algeria has the minimum cooling energy demand with 0 kWh/m^2 due to its high altitude. Souk Ahras follow it on the east of Algeria with 1.3 kWh/m^2 and Djelfa in the center of Algeria with 2.8 kWh/m^2 and Sidi Bel Abbes on the west of Algeria with 3.6 kWh/m^2.

Results indicate a significant difference between the maximum and minimum of cooling energy demand in Algeria, which is more than140 kWh/m^2. Table 7 shows the percentage of the Algerian territory occupied by each range of the cooling energy demand. The cooling energy demand in 57.7% of Algerian territory is ranging between 45 and 90 kWh/m^2. The cooling energy demand in 21.9% of Algerian territory is fluctuating between 90 and 140 kWh/m^2. The cooling energy demand in the rest of Algeria (around 20.4% of Algerian territory) is ranging between 0 and 45 kWh/m^2 (See Table 7).

Table 7. Territory surfaces in percentage of cooling energy demand zones.

Cooling energy demand range (kWh/m^2)	0–15	15–30	30–45	45–60	60–75	75–90	90–105	105–120	120–141
Territory surface in percentage (%)	9.3	6.9	4.2	12.7	30.8	14.2	16.8	3.6	1.5

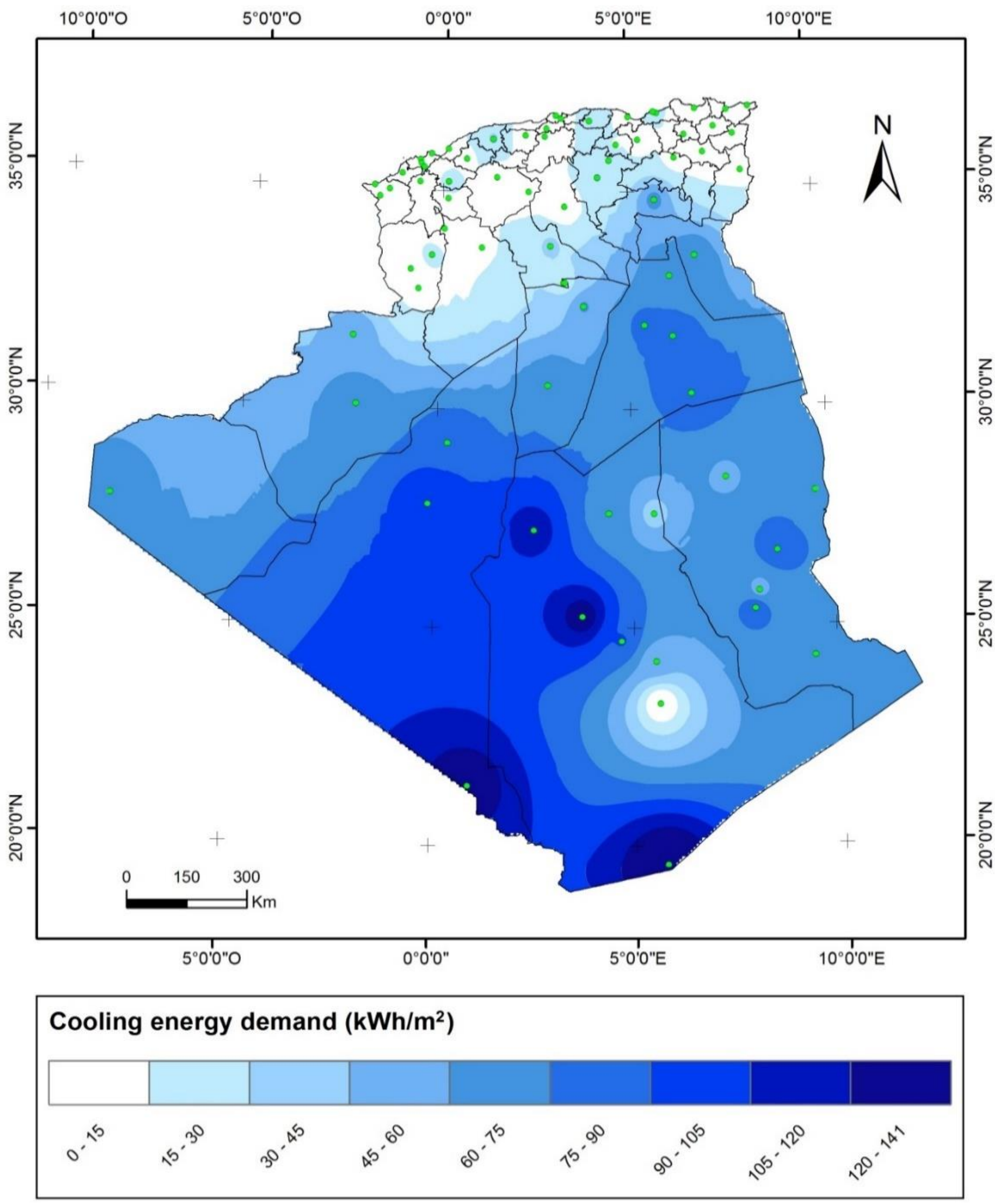

Figure 11. Cooling energy demand map.

4.2.3. Annual Energy Demand

Figure 12 shows the spatial distribution of annual thermal energy demand in all regions of Algeria. Based on the yearly thermal energy demand, Algeria is divided into three major zones, which are divided into eight subzones (see Figure 12).

The first zone occupied the coastal zone on the North except Tipaza and Chlef. This zone includes some locations in the desert zone in the South of Algeria like Aguemar, Mertouek, Assekrem in Tamanrasset and Tindouf. The second zone consists of the subcostal zone and the North of the highlands zone in the west of Algeria. This zone also comprises M'Sila, the North of Biskra and the southeast region of Algeria like Illizi and the east of Tamanrasset. The third zone occupies the desert zone, the highlands in the east and the south part of the highlands in the west of Algeria like Tiaret and Naama. This zone includes two subzones that have an annual energy demand higher than the central zone. The first subzone includes Djelfa, Naama, Rhourde-Nouss (Ouargla), Bordj Badji Mokhtar (Adrar) and In Guezam and Arak in Tamanrasset. The next subzone includes Tiaret, Al-Bayadh, Mecheria and Ain Sefra in Naama, Beni Abbes (Bechar), Belkebir (Adrar) and In Salah (Tamanrasset).

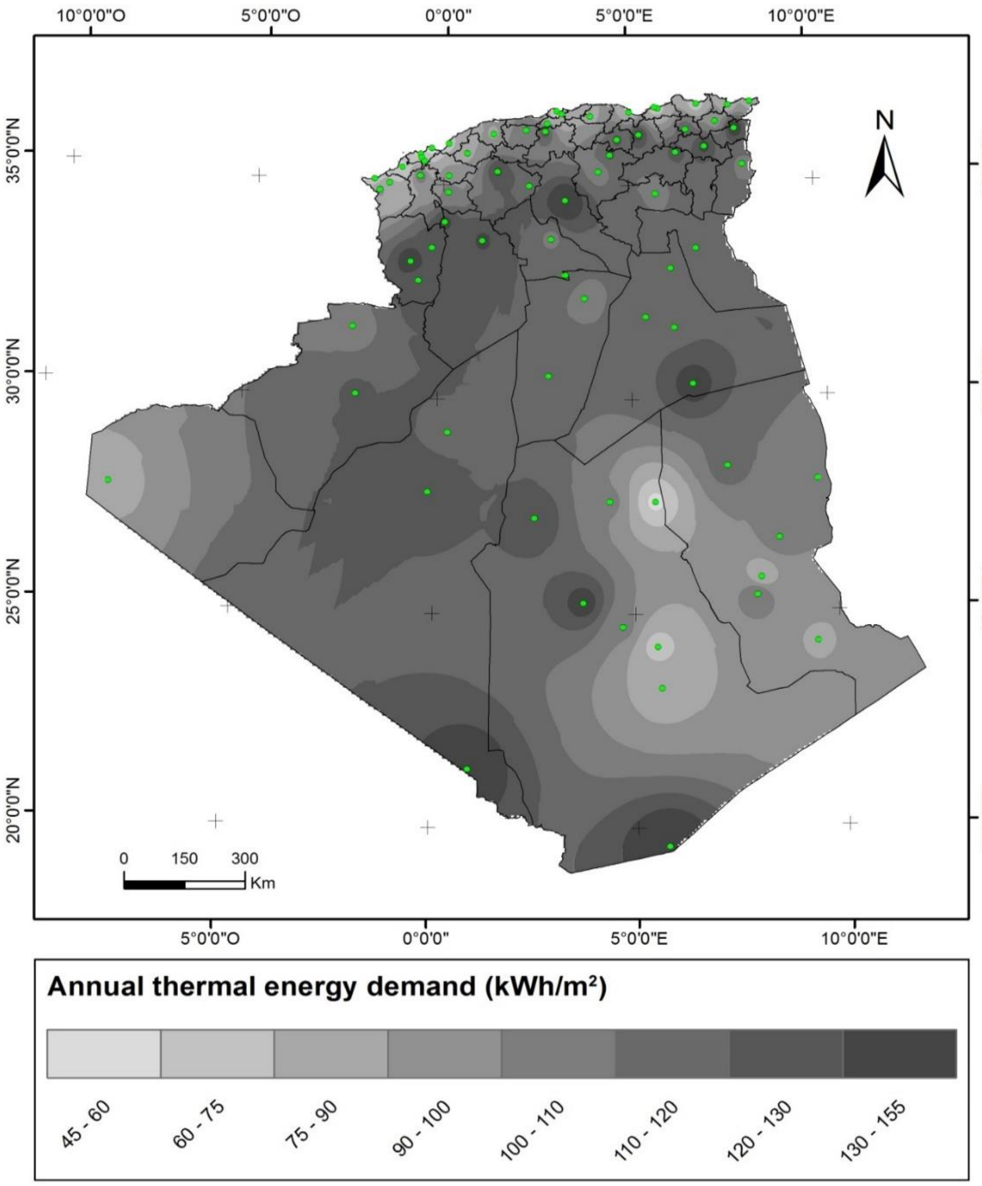

Figure 12. Annual thermal energy demand map.

Based on simulation results, the maximum annual thermal energy demand is registered in Djelfa with 153.3 kWh/m^2, followed by Souk Ahras with 144.7 kWh/m^2 and In Guezam with 142.9 kWh/m^2. On the opposite, the minimum annual thermal energy demand is found in Oran with 44.2 kWh/m^2, followed by Algiers with 45.8 kWh/m^2 and Beni Saf (Ain Temouchent) on the west of Algeria with 55 kWh/m^2. Table 8 shows the percentage of the Algerian territory occupied by each range of the annual energy demand.

Results indicate the yearly energy demand in 64.7% of Algerian territory; the annual energy demand is ranging between 110 and 155 kWh/m^2. In 28.6% of Algerian territory, the yearly energy demand is fluctuating between 90 and 110 kWh/m^2. In 6.7% of Algeria territory is ranging between 45 and 90 kWh/m^2 (see Table 8).

Furthermore, Figure 13 illustrates the climatic map of Algeria, including the average annual temperature distribution. Mean annual temperatures range from 16 °C in the North to 24 °C in the South of Algeria. In Algeria, generally, there are relatively large variations between summer and winter temperatures. Although Figure 13 represents the climate variations similar to Figure 12, it is difficult to estimate the energy demand and comfort conditions. Figures 10–12 remain more informative regarding the energy needs and cooling and heating loads estimation for the seventy-four investigated city.

Table 8. Territory surfaces in percentage of annual thermal energy demand zones.

Annual thermal energy demand range (kWh/m^2)	45–60	60–75	75–90	90–100	100–110	110–120	120–130	130–155
Territory surface in percentage (%)	0.1	0.9	5.6	13.7	14.9	42.8	19.2	2.7

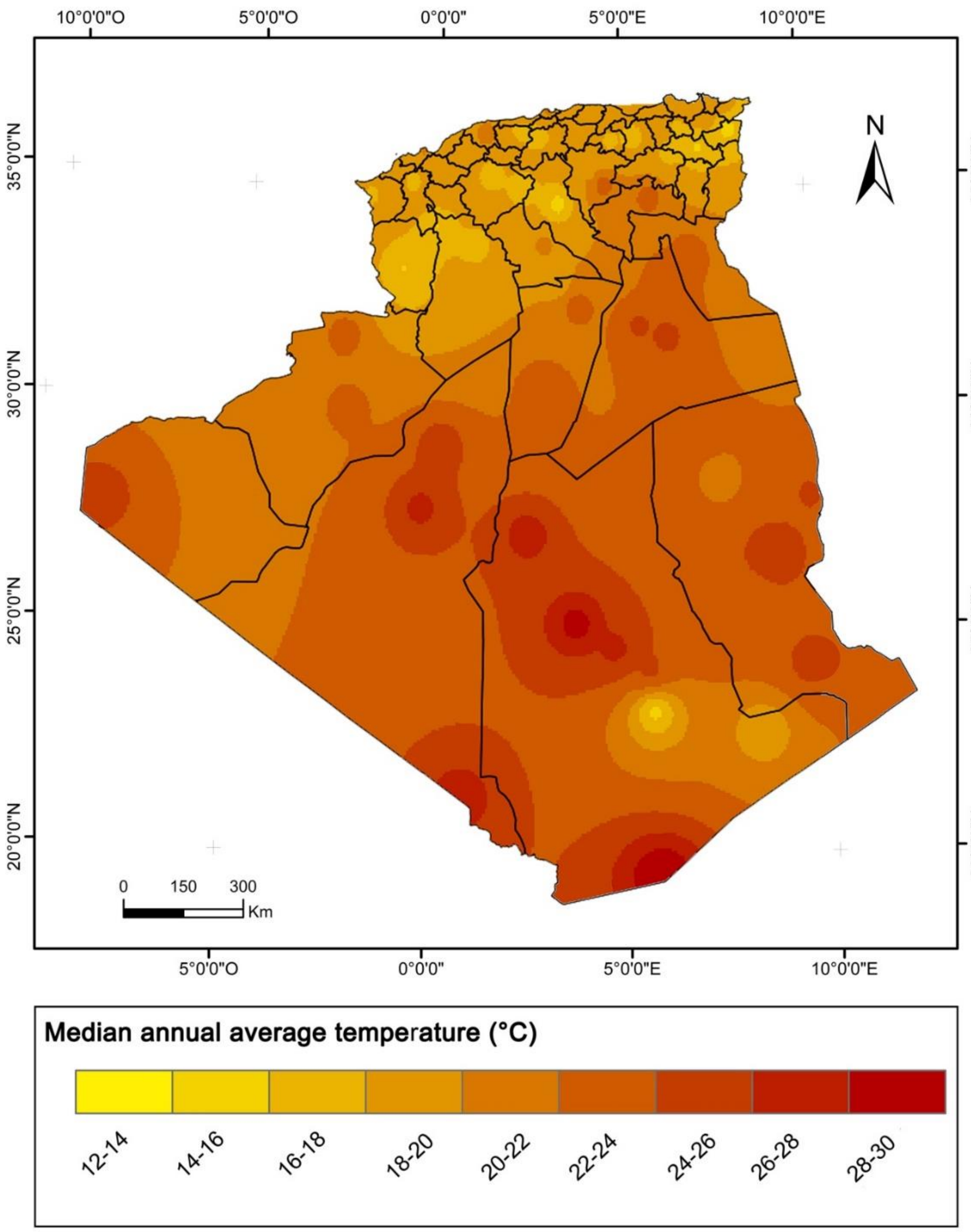

Figure 13. Median annual average temperature distribution across Algeria.

5. Discussion

In this study, thermal energy demand and the indoor-discomfort hours of a social residential building archetype was investigated in seventy-four locations across to the 48 provinces of Algeria. With the support of a Geographic Information Systems (GIS) tool, new zoning maps of the spatial distribution of thermal energy demand and indoor-discomfort hours for a social residential building archetype across Algerian territory were created. The following discussion highlights the main study findings and elaborates on the study strength and limitations, explains the implications for the practice and proposes future research.

5.1. Summary of the Main Findings

The study findings indicate that the thermal and energetic behavior of the current social residential building archetype is different in each location across the Algerian territory. The disparity between the maximum and minimum the number of annual-discomfort hours in Algeria is significant and reaches 3900 h. The discrepancy between the maximum and minimum of cold-discomfort hours is 4200 h; however, it is 6400 h for heat discomfort. Regarding the thermal energy demand, our results indicate a significant difference between the maximum and the minimum, which is around 109 kWh/m^2.

The difference between the maximum and the minimum of cooling energy demand is 141 kWh/m^2. However, it is 148 kWh/m^2 for heating energy demand. This difference is due to the contrast between the conditions of climates zones. For example, the highlands zone has a continental climate with hot, dry summers and freezing dry winters. Nevertheless, the desert zone has an arid climate with dry, very hot summers and cold winters and sunny weather almost year-round [4].

Concerning the primary outcomes of the spatial distribution of the-discomfort hours and thermal energy demand, we obtained three major climatic zones with nine subzones for five selected indicators: annual indoor-discomfort hours, cold-discomfort hours, heat-discomfort hours, heating energy demand and cooling energy demand. There are similarities between the zoning of cold-discomfort hours and heating energy demand. Moreover, the heat-discomfort hours zoning is so like the cooling energy demand zoning. From 56% until 90% of the year (between 4900 and 7900 h), the current social residential building archetype across more than 61.5% of Algerian territory has a heat-discomfort state. This zone covers the desert zone, which has a hot and dry climate. The cooling energy demand required in this zone is ranging between 60 and 141 kWh/m2. For this zone, passive cooling strategies must be given more importance by the architect. Only in 17.7% of Algeria territory, the current social residential building archetype has a cold discomfort from 25.5% to 48.5% of the total hours of the year (between 2250 and 4250 h). This zone covers the subcostal zone and highlands zone, which has a very cold climate in winter. The heating energy demand required in this zone is ranging between 90 and 150 kWh/m^2. For this zone, passive heating strategies must be given more importance by architects.

5.2. Strength and Limitations of the Study

This study presents six new maps that show the spatial distribution of thermal comfort and energy use demand in Algeria. The maps are in high-resolution and consistent based on recent weather data sets, representing seventy-four meteorological stations. This study provides a more substantial spatial coverage for the Algerian territory involving data compared to previous studies that used data from forty-eight locations [27] and forty locations [29], respectively. The study presents nine sub-zones instead of only the three or only seven zones obtained by the previous studies. This new classification is more accurate and informative than the current official Algerian climatic zoning, which has only six climatic zones [24]. In addition, the used interpolation method to generate the spatial maps is a suitable way to determine mapping zones in areas without available data across Algerian territory [49]. Therefore, our maps will be more accurate (high resolution) than previous research. Thus, the results are reliable and provide an opportunity for future designers to estimate the thermal and energetic performance expected in social residential housing, for all locations of Algeria.

Regarding the methodology, none of the previous studies, found in literature, calculated the energy demand and the indoor-discomfort hours based on a calibrated reference building that complies with the Algerian construction standards and passive design principles and best practices [4]. Worldwide, few studies combine GIS and BPS techniques with recent weather data set to generate up-to-date climatic zoning maps [5]. Our methodology is based on building performance simulation that requires hourly data of multiple variables for the 8760 hours of the year. Building performance simulation provides more accurate results compared to the degree-days method [27], cluster analysis, Givoni's bioclimatic chart and Mahoney tables [5,21,49]. Therefore, the methodology can be transferred to any other climatic regions in the Global South. The methodology provides a data-driven approach based on GIS and BPS techniques to generate high-resolution maps that can help designers to find patterns or identify climates that difficult to grasp from weather files. We strongly believe that our methodology is valid and straightforward to apply in countries that are in an early stage of implementing energy efficiency measures for their building sector. This includes countries in Africa and, more specifically, the Middle East and North Africa (MENA) region. After the oil crisis in the 1970s, climate zone maps were used as an instrument in Northern Countries to inform designers. Today, many countries in the Global South, are obliged to deliver energy efficiency targets. Those countries do not have up-to-date climatic characterization maps that are building-related. Therefore, the importance of climatic zoning is high in countries with a weak energy policy landscape. Therefore, this methodology can be transferred to fill in this gap.

On the other hand, this study has some limitations. The most important limitation is the use of only one housing archetype. Even though the used multifamily residential archetype represents the dominant household typologies of Algeria, single-family households represent a large part of the residential building stock. The selected housing archetype design does not embed many climate-responsive features. However, we need to remind the reader that it is the first study to present spatial maps based on an original monitored building in Algeria. The selected archetype is used in an identical way throughout all the 74 study locations in 48 provinces, which makes it strongly representative. Therefore, it is recommended to explore other building typologies (offices, schools, hospitals, etc.) and climate-responsive archetypes, in the future. Moreover, the proposed thermal comfort is mainly based on the adaptive model of ASHRAE [43]. The results would have been influences if we chose another thermal comfort model [44]. The same applies to the choice of EnergyPlus for building performance simulation. The result would have been influenced if another tool such as TRNSYS, Modelica, etc. was used. Therefore, designers should rely on the relative comparisons between the different cities based on the particular and limited reference conditions of this study.

5.3. Implications for the Practice and Future Research

Algeria has a very large surface area around 2.4 million km^2 and a disparity of topographic variations, which leads to various climatic zones across its territory. We can find littorals zones (Mediterranean Sea), plains zones, highlands zones, mountain zones, desert zones. The Algerian territory knows many levels of altitude, which is ranging between −40 m to 2900 m. Algeria has a various geographic distribution of annual global solar irradiation, which is ranging between 4500 Wh/m^2 to more than 7000 Wh/m^2 from the North to the South (M.R. Yaiche et al. 2014). These causes can explain the difference in thermal comfort and energy demand across the Algerian territory.

The new spatial maps allow building designers and decision-makers to make quick and easy assessments of the thermal energy demand and indoor-discomfort hours in each location in Algeria. The maps quantify the expected performance results with high precision to inform professionals, including architects and building engineers and policymakers.

More important, the study proves that the current residential building archetype of social housing is not adapted to the climatic conditions and disparity between many locations of Algeria. Despite falling in North Africa and having most of its cities between the latitude from 23° to 37° (North), Algeria has a significant topographic variation (highest point: 2900 m and lowest point: −40) consisting of massive areas extensively dissected into mountains and oasis. Reflecting on the study findings, the importance of developing more climate-responsive buildings that correspond to the nine different climatic zones of Algeria emerges as an essential recommendation.

Therefore, the spatial maps allow future designers to better react to the climate disparity of Algerian cities and think about the best fit for climate bioclimatic principles, strategies and solutions to design and implement comfortable and efficient residential buildings. The maps can provide quantifiable guidance regarding the heat and cold indoor-discomfort hours and the expected heating and cooling energy use. We hope that our study findings can form the basis for a new climatic zoning map or tool for Algeria and get integrated into the future development of the Algerian building thermal standard.

Future work will focus on identifying optimal solutions related to building design for each zone in Algeria. These solutions include building orientation, opaque building envelope, transparent building envelope, shadings and the control of mechanical systems. In addition, the influence of climate change can be modeled by using future climates to create long-term predictions and develop future sensitive spatial distribution maps.

6. Conclusions

The estimation of thermal comfort and energy demand for newly built construction is fundamental. Therefore, designing buildings and estimating their energy needs for heating and cooling a major concern correctly. This study created six novel and accurate spatial maps with the help of geographic information systems, building performance simulation and a rich dataset of weather data. The research methodology combined the results of running simulations of a multifamily residential benchmark model in seventy-four cities of Algeria with their geographic locations. The research methodology reflects a novel approach to the development of climatic analysis based on GIS and/or BPS techniques. The spatial maps were used to estimate future energy needs for cooling and heating as Algerian cities and regions continue to grow and target their thermal comfort expectations. Conventional climatic zoning and spatial mapping studies are based on only weather data regardless of the influence of the building physical properties. Therefore, the methodology can be used in other climatic regions worldwide. However, we know from building performance simulation that the thermal comfort and energy needs of buildings vary widely based on location. Finally, this study offers data-rich maps that are visual and can help designers to find patterns or identify climates that difficult to grasp from weather files.

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Appendix A Energy Use in Algeria

https://www.dropbox.com/sh/82ldz0l5lni05me/AAD5NyIUjJjAOZ4-8a9huHqba?dl=0

Appendix B Residential Housing Typologies in Algeria

https://www.dropbox.com/sh/z6r2nhi32sbbcg9/AADDrrb0ZKo2p8oa24CrTZTVa?dl=0

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