Exploring the distribution of energy consumption in a northeast Chinese city based on local climate zone scheme: Shenyang city as a case study

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Abstract
The local climate zone (LCZ) scheme is now used to investigate urban heat islands, which provides additional reference for energy consumption simulation. Based on the LCZ scheme, a LCZ mapping of Shenyang, a city in northeast China, was first constructed using the World Urban Database and Access Portal Tools (WUDAPT) Level 0 method. Subsequently, DeST-h was considered to simulate the energy consumption of urban buildings with concentration areas. The results show that with Shenyang being a severely cold area, the annual energy consumption of heating is approximately twice that of refrigeration for an individual building. The total energy consumption of open-distributed single buildings is higher than that of compact-distributed single buildings. Consequently, the unit cumulative energy consumption in compact-distributed buildings is higher than that in openly distributed building areas. The compact high-rise buildings (LCZ 1) have the highest energy consumption, with a unit annual energy consumption of 123,771.150 MW·h, which is equivalent to 41,257 tons of standard coal combustion power generation. Considering the energy consumption of residential buildings, the central high-rise buildings group and the compact centralized middle-rise buildings in the downtown area are high energy consumption areas. For future urban planning, design strategies such as energy-saving transformation and energy planning should be considered. The research results can provide a scientific basis and theoretical support for reducing building energy consumption, alleviating the urban heat island effect, and the development of modern urban planning.
Keywords
Local climate zones, building energy consumption, simulation research, urban planning, urban heat island, WUDAPT

Introduction
With the emergence of multidisciplinary approaches involving meteorology, urban and rural planning, geographic sciences, etc., the use of technology around data information, algorithmic methods, and professional tools has increased. Multiple studies on urban climatology have been conducted globally (Bechtel et al., 2016; Houet and Pigeon, 2011; Lelovics et al., 2014; Mills, 2008). However, the extraction and application of urban climate information in urban planning and development is limited. Urban climatology has been experiencing slow growth owing to the neglect of the relationship between urban planning and the corresponding urban climate impact. Oke (2006) stated that urban climatologists, urban planners, and urban landscape designers lack communication between existing urban climate information and related fields. Stewart and Oke (2012) proposed a local climate zone (LCZ) scheme that standardized the description of the urban heat island effect, realized the visualization of city-scale energy consumption simulation, and promoted the research of urban energy planning (Deng et al., 2019; Jiang, 2005).

Owing to rapid urbanization in China, many natural areas have been covered by impermeable ground. Therefore, the urban heat island effect has intensified, and the urban climate and environment have continued to deteriorate. To comprehensively improve the ability of cities in adapting to climate change, China’s National Development and Reform Commission and the Ministry of Housing, Urban-Rural and Rural Development have jointly formulated the “City Adaptation Action Plan” with relevant departments. The objective is to promote the construction of urban ecological civilization, actively focus on the development of strategies to alleviate the urban heat island effect, and reduce building energy consumption (Giorgio et al., 2014; Pan et al., 2008).

As the political, economic, and cultural center of Northeast China, Shenyang is located in the center of the Northeast Asian Economic Circle and the Bohai Rim Economic Circle. In the recent research, most scholars have applied the LCZ scheme to the study of urban heat island intensity and urban development planning, and few have combined the LCZ scheme with the energy consumption of urban areas. In this study, we combine the LCZ scheme with the energy consumption of urban areas and construct the urban heat island intensity distribution map. Subsequently, we construct the urban residential area civil building energy distribution map, which is a preliminary research and analysis.

This study has the following procedure:

1. The WUDAPT Level 0 method was used to construct a LCZ mapping of Shenyang based on the LCZ scheme, and identify the urban heat island intensity distribution and potential trend of spreading of the heat island effect.
2. Based on the constructed LCZ mapping of Shenyang, DeST-h was used to simulate the energy consumption of civil buildings (LCZ1-LCZ6) in concentrated residential areas.
3. Based on the LCZ scheme of Shenyang, the energy consumption of various buildings was classified, and the energy consumption distribution map of civil buildings (LCZ1-LCZ6)
in the concentrated residential area was constructed to provide guidance for city planning and energy planning in Shenyang.

Research methods and energy consumption simulation

Research area

Shenyang is located in the central region of Liaoning Province, China. It is connected to the Liaodong Peninsula in the south and located at 123°25′31.18″ E and 41°48′11.75″ N (Figure 1) in the middle of the Liaohe Plain. In 2018, the urban area was 3495 Km². The permanent population, urban population, and urbanization rate are 8.316 million, 6.736 million, and 81%, respectively. According to the classification based on China’s “Code for Thermal Design of Civil Buildings” (GB50176 - 2016), Shenyang belongs to severely cold areas I and D. In Shenyang, the annual average temperature is 6.2 – 9.7°C, the extreme maximum temperature is 38.4°C (August 2, 2018), and the extreme minimum temperature in the central city is −32.9°C (January 15, 2001).

Construction of local climate zone mapping

Stewart and Oke (2012) found that urban heat islands have a significant impact on the thermal environment and energy consumption of buildings. The traditional simple “urban” and “rural” temperature difference models ($\Delta T_{U-R}$) that use fixed locations to measure temperature to compare heat island effects have limitations. To supplement the
shortcomings of the urban-rural division, the diversity and operability of urban climate zoning should be further increased. Furthermore, Stewart and Oke established a standard and universal “Local Climate Zone” (LCZ) scheme. It was established to analyze the relationship between the surface types of different cities and the corresponding urban heat island intensity, and also to redefine the current urban heat island using standard unified description methods. Stewart and Oke (2012) divided the basic types of LCZ into 17 regional types, including 10 built types (LCZ 1—10) and 7 land cover types (LCZ A—G).

Following the proposal of the LCZ scheme, climate scholars globally have conducted numerous scientific studies. There are three main classification methods globally for LCZ: manual sampling classification methods (Liu et al., 2017; Song et al., 2015); classification methods based on Geographic Information Systems (GIS) (Geletić and Lehnert, 2016; Perera and Emmanuel, 2018; Zhang et al., 2016; Zheng et al., 2014); and classification methods based on remote sensing satellite images (Cai et al., 2018; Gamba et al., 2012; Nassar et al., 2016; Zhou et al., 2020).

The classification method based on remote sensing satellite images automatically divides the remote sensing image into different types of LCZ through spectrum and spatial information (Brousse et al., 2016). Bechtel et al. (2015) and other scholars from Germany, Austria, Canada, the United States, and other countries with meteorological, geographic, and environmental backgrounds jointly developed the WUDAPT program. WUDAPT is an international community-generated urban canopy information and modeling infrastructure that facilitates urban-focused climate, weather, air quality, and energy-use modeling application studies (Bechtel et al., 2018; Ching et al., 2018, 2019). In summary, the WUDAPT classification method based on remote sensing images has a higher practical and research value, especially for areas with insufficient urban data (Chen and Tang, 2017; Geletić et al., 2019; Hammerberg et al., 2018). Huang et al. (2018) conducted the construction of LCZ mapping with the aim of understanding the local climate zoning framework level.

This study uses the WUDAPT Level 0 method to divide the LCZ classification using open data and open source software, which involves three main steps: (1) Obtain the Landsat satellite image containing the selected area from the USGS Earth Resource Manager, (2) Create 10 to 20 samples of various training LCZ with an area of not less than 1 Km² on Google Earth, and (3) Use the random forest algorithm (ViGra) of supervised classification in SAGAGIS to classify the study area by LCZ. Steps (2) and (3) are iterative verification processes until the recognition rate meets the specified requirements, and the final LCZ mapping construction is completed (Verdonck et al., 2017). Bechtel et al. (2015) showed the specific construction workflow of LCZ mapping. The LCZ mapping of Shenyang was constructed with reference to the LCZ workflow established by Bechtel et al. (2015) (Figure 2).

Reference samples with 9965 pixels were selected on Google Earth for comparison. Since the land cover type is easy to recognize, the type of LCZ sample was selected based on the land use planning map of downtown Shenyang (Urban Development Bureau of Shenyang, 2017; Figure 3). The number of reference pixels for each LCZ type is indicated in the sum column of the confusion matrix (Table 1). The overall accuracy and kappa coefficient of the LCZ classifications were 87.37% and 86.59%, respectively, which indicates that the classification results are satisfactory.
Figure 2. Local climate zone mapping of Shenyang with 100 m resolution–filtered.

Figure 3. Land use planning map of downtown Shenyang.
Table 1. Confusion matrix for LCZ classification of Shenyang, China.

| CLASS | LCZ 1 | LCZ 2 | LCZ 3 | LCZ 4 | LCZ 5 | LCZ 6 | LCZ 7 | LCZ 8 | LCZ 9 | LCZ 10 | LCZ A | LCZ B | LCZ C | LCZ D | LCZ E | LCZ F | LCZ G |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| User  | 537   | 2     | 31    | 6     | 20    | 6     | 0     | 0     | 0     | 0     | 27    | 0     | 0     | 32    | 9     | 670   |
| accuracy |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| Reference |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| LCZ 1 classification output |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |       |
| LCZ 2 | 47 | 269 | 0 | 13 | 0 | 0 | 0 | 0 | 0 | 4 | 0 | 51 | 8 | 0 | 0 | 0 | 0 | 2 | 394 | 68.2741 |
| LCZ 3 | 15 | 0 | 272 | 15 | 1 | 28 | 19 | 0 | 42 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 1 | 453 | 71.0817 |
| LCZ 4 | 62 | 3 | 0 | 265 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 20 | 0 | 0 | 0 | 0 | 0 | 0 | 353 | 75.0708 |
| LCZ 5 | 12 | 11 | 387 | 10 | 3 | 0 | 0 | 0 | 12 | 0 | 6 | 0 | 0 | 14 | 29 | 35 | 584 | 66.2671 |
| LCZ 6 | 0 | 0 | 0 | 0 | 583 | 0 | 0 | 0 | 0 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 589 | 98.9813 |
| LCZ 7 | 0 | 0 | 0 | 0 | 0 | 193 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 7 | 200 | 96.5 |
| LCZ 8 | 32 | 0 | 73 | 0 | 0 | 2 | 22 | 529 | 0 | 0 | 1 | 1 | 0 | 1 | 2 | 3 | 666 | 79.4294 |
| LCZ 9 | 4 | 0 | 1 | 0 | 0 | 13 | 1 | 0 | 320 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 11 | 6 | 356 | 89.8876 |
| LCZ 10 | 24 | 0 | 0 | 0 | 0 | 14 | 0 | 0 | 0 | 334 | 0 | 31 | 4 | 0 | 5 | 0 | 0 | 1 | 412 | 81.0679 |
| LCZ A | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 19 | 0 | 173 | 56 | 0 | 0 | 0 | 23 | 1831 | 94.6477 |
| LCZ B | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 571 | 97.8984 |
| LCZ C | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 31 | 92.8571 |
| LCZ D | 2 | 0 | 36 | 0 | 0 | 0 | 1 | 6 | 81 | 0 | 0 | 0 | 0 | 1 | 704 | 7 | 13 | 856 | 82.243 |
| LCZ E | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 230 | 99.5671 |
| LCZ F | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 532 | 98.3364 |
| LCZ G | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 627 | 97.6636 |
| Sum column | 732 | 332 | 475 | 319 | 408 | 660 | 239 | 538 | 469 | 350 | 1733 | 755 | 609 | 704 | 250 | 656 | 736 |
| Output accurate | 73.3607 | 81.0241 | 67.7895 | 83.0721 | 94.8529 | 88.3333 | 80.7531 | 98.3271 | 68.2303 | 95.4286 | 100 | 74.0397 | 93.92447 | 100 | 92 | 81.0976 | 85.1902 |
| Overall accuracy | 87.3658 |
| Kappa coefficient | 86.5877 |
Energy simulation

DeST-h is a specific energy consumption simulation analysis software developed for residential buildings (Liu, 2013). Compared with EnergyPlus and DOE-2, its data settings, including temperature and humidity, building envelope structure parameters, air conditioning operating conditions, personnel, equipment, lighting, are more suitable for simulation of energy consumption in residential buildings in China (Zhu et al., 2012). Meanwhile, factors such as shading, ventilation, and sky background radiation are also considered, making the simulation of energy consumption closer to the actual situation (Jian, 2007).

This study is based on the LCZ mapping of Shenyang. DeST-h was used to construct a compact high-rise (LCZ 1), compact mid-rise (LCZ 2), compact low-rise (LCZ 3), open high-rise (LCZ 4), open mid-rise (LCZ 5), open low-rise (LCZ 6), and six typical residential buildings for architectural modeling. Shenyang city energy consumption simulation workflow is presented in Figure 4. The construction area was set to 400 m² for a total of 4 households. The shape factor and window-to-wall area ratio of residential buildings in Shenyang is set in strict accordance with JGJ 26–2010 “Design Standards for Energy Efficiency in Residential Buildings in Frigid and Cold Regions” (Table 2). The heat transfer coefficient of the thermal performance of the residential building in Shenyang is shown in Table 3. By setting the number of people in the building and the hourly schedule throughout the year, the air-conditioning equipment is operated hourly and the lighting and electrical appliances are simulated throughout the year. After the modeling is completed for residential temperature load analysis, special attention should be focused on the LCZ1, LCZ2, and LCZ3 compact buildings considering sunshine shade. Finally, the annual cold and heat load statistical reports of the building are generated and exported.

This study uses typical annual meteorological data from Shenyang to set the building’s winter heating from November 1 to March 31. Summer air conditioning starts from June 1 to August 31. Finally, the annual total cold and heat load value of a single building is obtained (Figure 5), and then the annual total cumulative load value of a single building can be obtained (Figure 6).

The building height (BH), building surface fraction (BSF), and other attributes of the LCZ scheme set in this study are constructed based on the average of the attribute tables.
data provided by Stewart and Oke (2012). Based on the “Shenyang Residential Building Spacing and Residential Sunshine Management Regulations,” the spacing of different building types for X-axis and Y-axis spacing of the residential building LCZ 1 – 6 in Shenyang is set in Table 4. Therefore, the number of different types of buildings per square kilometer can be calculated to obtain the annual total load value per square kilometer (Figure 7).
Results and analysis

According to the classification and statistical results of LCZ maps in Shenyang, we identified 17 LCZ-type training zone samples within the study area on Google Earth (Table 5), specifically, 10 built types (LCZ 1-LCZ 10) and 7 land cover types (LCZ A-LCZ G). The area of Shenyang that this study focused on is 3601.26 Km², of which the built area covers 1,438.34 Km², accounting for 39.94%, and land cover types cover 2,162.92 Km², accounting for 60.06%. According to the fan-shaped statistical chart of the local climate zoning in Shenyang, the local climate zoning type has the highest proportion of 24.10%. A bare rock or paved (LCZ E) has the lowest proportion of 1.32%, and the rest of the local climate zoning types are shown in Figure 8. It shows that the current status of the built types in Shenyang’s LCZ is significantly lower than the land cover types.

Table 4. Setting of X-axis distance and Y-axis distance for LCZ 1- LCZ 6 of residential buildings in Shenyang.

| LCZ    | Length × width × height (m)/number of layers | X-axis building spacing (m) | Y-axis building spacing (m) | Number of X-axis buildings | Number of Y-axis buildings | Total number of buildings per square kilometer |
|--------|-----------------------------------------------|----------------------------|-----------------------------|----------------------------|----------------------------|-----------------------------------------------|
| LCZ 1  | 20 × 20 × 3/12                                | 13                         | 47                          | 30                         | 15                         | 450                                           |
| LCZ 2  | 20 × 20 × 3/6                                 | 8                          | 27                          | 36                         | 21                         | 756                                           |
| LCZ 3  | 20 × 20 × 3/3                                 | 15                         | 30                          | 28                         | 14                         | 392                                           |
| LCZ 4  | 20 × 20 × 13/12                               | 10                         | 33                          | 22                         | 10                         | 660                                           |
| LCZ 5  | 20 × 20 × 3/3                                 | 10                         | 17                          | 33                         | 27                         | 891                                           |

Note: In a two-dimensional plane, with (0,0) as the origin, the horizontal 1000m is the X axis, and the vertical 1000m is the Y axis.
Figure 5 shows that the cumulative annual heat load value of a single building in Shenyang is approximately twice that of the total annual cooling load value. This indicates that the energy consumption for heating during winter in severely cold areas is much greater than that for cooling during summer.

Figure 6 shows that the cumulative total load value of a compact single building is approximately 1 MW-h lower than that of a spacious single building, and its energy consumption is approximately 1000 kW-h.

Figure 7 presents the cumulative total load per square kilometer for the whole year: compact high-rise (LCZ 1) > open high-rise (LCZ 4) > compact mid-rise (LCZ 2) > open mid-rise (LCZ 5) > compact low-rise (LCZ 3) > open low-rise (LCZ 6). The compact high-rise (LCZ 1) buildings have the highest energy consumption, with an annual energy consumption of 123,771.150 MW-h/km², which is equivalent to 41,257 tons of standard coal combustion power generation. Open low-rise (LCZ 6) buildings have the lowest energy consumption, with an annual energy consumption of 5,529.526 MW-h/km², which is equivalent to 1,843.175 tons of standard coal combustion power generation.

The different values are distinguished on the LCZ map with different shades of color. Finally, the energy consumption distribution map of civil buildings (LCZ 1-LCZ 6) in the concentrated residential area of Shenyang is shown in Figure 9; high energy consumption areas are mainly distributed in the main urban area of the city center, including Shenbei New District, Hunnan New District, and Sujiatun District. This energy consumption distribution map can provide a scientific basis and theoretical guidance for urban planning and energy-saving transformation of Shenyang City from the perspective of alleviating the urban heat island effect.

Discussion

In this study, we explored the workflow for using DeST-h to simulate urban energy consumption and combine the LCZ scheme with the DeST-h model. The resolution of the LCZ
Table 5. Samples of the LCZs 1~10 and LCZs A~G images of the Shenyang local climate zones training area taken on Google Earth.

| Built types       | Land cover types       |
|-------------------|------------------------|
| LCZ 1 compact high-rise | LCZ A dense trees      |
| LCZ 2 compact mid-rise   | LCZ B scattered trees  |
| LCZ 3 compact low-rise    | LCZ C bush, scrub      |
| LCZ 4 open high-rise    | LCZ D low plants       |
| LCZ 5 open mid-rise    | LCZ E bare rock or paved|
| LCZ 6 open low-rise     | LCZ F bare soil or sand|
| LCZ 7 lightweight low-rise | LCZ G water          |

(continued)
Table 5. Continued.

| Built types             | Land cover types |
|------------------------|------------------|
| LCZ 8 large low-rise    |                  |
| LCZ 9 sparsely built   |                  |
| LCZ 10 heavy industry  |                  |

Note: The picture on the left is a top view, and the picture on the right is a perspective view.

Figure 8. Local climate zones pie diagram of Shenyang city.
is 100 m, and a high accuracy is the advantage of this study. Specifically, the accuracy of the LCZ map of Shenyang City is based on the application of the real situation of land use. Twenty to twenty-five polygons larger than 1 km² are selected, trained, applied, and evaluated on Google Earth. Each category uses 50% polygons as the samples in the training area, and the remaining 50% of the polygons are tested as independent reference polygons. The overall accuracy of the LCZ map in Shenyang was 87.37% and the kappa coefficient was 86.59%. Generally, the accuracy of the LCZ map in Shenyang is relatively high when applied to actual research. The city energy consumption simulation workflow proposed in this study requires further exploration and verification to achieve the energy consumption simulation that is significantly close to the actual situation.

**Conclusion**

1. The downtown area of Shenyang belongs to the old region. Compact mid-rise (LCZ 2) and open high-rise (LCZ 4) buildings are dominant. This area has a high heat island intensity trend, and should be used as an emergency relief for urban heat island intensity. The typical mid-rise buildings were compact and intricate, indicating that the compact mid-rise is the core area of the city. The focus of urban construction is on the energy-saving renovation of old cities and improvement of infrastructure.

2. Shenbei New District and Hunnan New District, as well as the newly incorporated compact high-rise (LCZ 1) and open mid-rise (LCZ 5) buildings in Sujiatun District, which is newly incorporated into the Shenyang territory. This distribution trend demonstrates the development pattern of Shenyang cities in recent years. The city’s periphery, which includes the suburbs and surrounding villages, is dominated by compact low-rise
(LCZ 3) and open low-rise (LCZ 6) buildings. Owing to rapid urbanization, the construction of low-rise buildings around the city will show a trend of gradual decrease.

3. The high energy consumption areas of Shenyang are mainly in the city center, Shenbei New District, and Hunnan New District. Shenyang is located in a severely cold area, and the annual energy consumption for heating is approximately twice that for cooling. The total energy consumption of open-separated single buildings is higher than that of compactly distributed single buildings. However, the cumulative total energy consumption per square kilometer of the compact distribution area is higher than that of the open distribution area. Particularly, the compact high-rise buildings (LCZ 1) have the highest energy consumption, with a unit annual energy consumption of 123,771.150 MW·h, which is equivalent to 41,257 tons of standard coal combustion power generation.

From the perspective of energy consumption in residential buildings, large-scale high-rise buildings in the core area of Shenyang and compact mid-rise buildings in the downtown area are high-energy consumption areas. In future urban planning, it will be necessary to focus on design strategies such as energy-saving renovation and energy planning. This research provides a scientific basis and theoretical support for reducing building energy consumption, alleviating the urban heat island effect, and modern urban planning development.

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