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Research on the Influencing Factors of Carbon Emissions in Low-carbon Communities based on Complex Network Theory

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Abstract: Achieving carbon peak before 2030 and carbon neutrality before 2060 is a solemn commitment made by China to address global climate change, and is also one of the main goals for economic and social development in the 14th Five Year Plan and the 2035 vision period. The changes in carbon emissions are directly related to the progress of China's "carbon peak" and "carbon neutrality" goals. Therefore, in-depth research on the influencing factors of carbon emissions has become a key link in promoting the achievement of this goal. In the existing research on carbon emission influencing factors, countries mainly focus on macro scale low-carbon urban carbon emission influencing factors and micro scale low-carbon building full life cycle carbon emission influencing factors. However, there is relatively little research on the influencing factors of carbon emissions in low-carbon communities of urban micro units, and there is still considerable research space. This study conducted an in-depth analysis of the influencing factors of carbon emissions in low-carbon communities using complex network methods. By constructing a complex network model of factors affecting carbon emissions, we identified key nodes and pathways, and explored their interrelationships. The results indicate that factors such as energy structure, resident behavior, building design, and policy implementation play an important role in carbon emissions in low-carbon communities.

Keywords: Low-carbon Community; Carbon Emissions; Influencing Factors; Complex Network Theory.

1. Introduction

AllAs the problem of global warming becomes more and more serious, reducing carbon emissions and realizing low-carbon development have become the focus of general attention of the international community. As the core unit of people's lives, communities play a pivotal role in addressing these challenges. The construction of low-carbon communities not only helps to reduce urban carbon emissions, but also is an effective way to promote green living and realize sustainable development. However, the influencing factors of carbon emissions in low-carbon communities are complex and diverse, and need to be studied and analyzed systematically. Therefore, it is crucial to conduct an in-depth study on the influencing factors of low-carbon communities, which is of great significance for reducing community carbon emissions and realizing the goal of energy conservation and emission reduction in cities.

At present, scholars at home and abroad have conducted a large number of studies on the influencing factors of carbon emissions, involving multiple levels such as national, regional and industry. However, most of these studies focus on the macro-scale carbon emission influencing factors of low-carbon cities and the micro-scale carbon emission influencing factors of the whole life cycle of low-carbon buildings, and the research on the community carbon emission influencing factors of urban micro-units is still insufficient. Rui Qi [1], in China's carbon emission influencing factors and scenario prediction, utilized the STIRPAT model, combined with the GA-BP model to analyze the factors and scenario prediction of carbon emissions in 30 regions in China. Fu Jingyuan et al [2], in the analysis of carbon emission influencing factors in Gansu Province, studied the key influencing factors by constructing an econometric model, and finally put forward the corresponding suggestions. Zhang Yan et al [3] studied the influencing factors of heating energy consumption and carbon emission of traditional residential houses in Ganzi. The article simulated the energy consumption and carbon emission of traditional residential houses in Ganzi Prefecture, a Tibetan area on the Western Sichuan Plateau, based on the DesignBuilder software, focusing on analyzing the influence of the availability of sunlight intervals on the building's energy consumption, and the influence of different exterior wall materials as well as thermal insulation on the heating energy consumption and carbon emission. However, as the basis of urban carbon emission, the reduction of community carbon emission is of vital significance to the carbon reduction of the whole city. Therefore, in the context of the current "dual-carbon" strategy, it is particularly important to study the influencing factors of carbon emissions in low-carbon communities.

This thesis aims to analyze the influencing factors of community carbon emissions through the complex network approach, to reveal the complex relationship between the factors, and to provide a new perspective for the study of carbon emissions in low-carbon communities. At the same time, we expect to propose practical community carbon reduction and carbon mitigation strategies through this research, and contribute to building a low-carbon and sustainable community.

2. Scoping of Carbon Emissions in Low-carbon Communities

2.1. Definition of Low-carbon Communities

A low-carbon community is a community that upholds the concept of low-carbon living and a code of conduct, and is committed to achieving a reduction in the consumption of energy resources and low carbon emissions through the careful creation of climate-friendly natural environments, buildings and infrastructure, and the promotion of healthy lifestyles and management modes.

Its core objective is to reduce carbon dioxide emissions and bring the community's carbon emissions to a lower level, or even pursue the ideal of zero carbon emissions, by changing the community's production and living patterns, reducing dependence on fossil fuels, and enhancing the efficiency of energy use within the framework of a low-carbon economy. This community model not only helps to promote the sustainable development of society, but also has far-reaching strategic significance in realizing the ambitious goals of carbon peaking and carbon neutrality [4].

2.2. Scoping of Carbon Emissions in Low-carbon Communities

Defining the scope of carbon emissions in a low-carbon community primarily involves greenhouse gas emissions generated by various activities within the community. Specifically, it encompasses the following aspects:

(1) Building and Industrial Carbon Emissions: This includes carbon emissions from energy activities in public buildings within the community (especially those with a single building area of 5,000 square meters or more), industrial facilities, and energy centers (if any).

(2) Transportation Carbon Emissions: This primarily concerns carbon emissions generated by private cars, connecting transportation, etc., within the community. As transportation is an integral part of daily life in the community, its carbon emissions are also considerable.

(3) Municipal Infrastructure Carbon Emissions: Municipal infrastructure such as road lighting systems also generates certain carbon emissions during operation.

(4) Carbon Sink: While carbon sink primarily refers to the process by which plants absorb carbon dioxide through photosynthesis, when defining the scope of carbon emissions in a low-carbon community, it is necessary to consider the carbon reduction capacity of plant carbon sinks within the community to comprehensively assess the carbon balance of the community.

In addition, some indirect emissions also need to be considered, such as indirect emissions from the purchase of energy including electricity, steam, heating, and cooling, as well as all indirect emissions occurring in the community's value chain.

In summary, the scope of carbon emissions in a low-carbon community is a comprehensive concept that involves not only direct emissions but also indirect emissions and carbon sinks. Therefore, when defining the scope of carbon emissions in a low-carbon community, it is necessary to comprehensively consider various activities and facilities within the community to ensure the accuracy and integrity of the assessment results.

3. Complex Network Theory and Metrics

3.1. Complex Network Theory

Complex network theory is based on graph theory, using nodes and edges to describe the subjects in the system and the internal evolution process, in order to study complex systems and their topology. Therefore, the identified factors can be regarded as the "nodes" of the network, and the interaction and mutual influence between each factor can be regarded as the "edges", which can be used as the basis to construct the complex network model [5].

3.2. Statistical Indicators Related to Complex Networks

(1) Degree of a node. The number of edges of a node i in a complex network that are connected to other nodes in the network is called the degree of the node. When the total degree of a node is larger, it means that the node is more important, and it also indicates that the influences represented by this node are more critical.

(2) Proximity centrality. Proximity centrality measures the average distance of a node to all other nodes in the network. The higher the proximity centrality of a node indicates that its average distance to other nodes is shorter and thus the more reachable it is in the network.

(3) Mediated Centrality. The mediated centrality of a node refers to the percentage of the number of each shortest path in the network that passes through that node, reflecting the function and status of the corresponding node in the entire network.

(4) Clustering coefficient. The clustering coefficient is a localized indicator that the nodes in the network tend to cluster in one place, indicating the aggregation status among the nodes in the network.

4. Network Construction of Carbon Emission Influencing Factors in Low-Carbon Communities

4.1. Data Collection and Collation

Table 1. Factors affecting carbon emissions in low-carbon communities

Classify	Factors affecting	Numble
Building Carbon Emissions	Construction Materials	X1
	Construction Equipment	X2
	Building Operation	X3
	Building Design	X4
	Building Waste Disposal	X5
	Building Maintenance and Remodeling	X6
Household Carbon Emissions	Transportation	X7
	Resident Behavior	X8
	Household Size	X9
	Household Direct Energy Consumption	X10
	Household Indirect Energy Consumption	X11
	Age structure of household population	X12
Community Environmental Carbon Emissions	Green area	X13
	Energy structure	X14
	Spatial Planning	X15
	Policy Implementation	X16
	Domestic Waste Disposal	X17
	Transportation Facilities Planning	X18

Since the carbon emission influencing factors have the complexity of space and time dimensions, and change dynamically with space and time, this paper constructs an evaluation index system that is more in line with the current low-carbon community through the study of carbon emission influencing factors in low-carbon community [6]. With "community carbon emission influencing factors" as the search formula in CNKI for literature search, a total of 119 highly relevant literature retrieved with the theme, the use of correlation analysis to extract the impact of low-carbon community carbon emissions of 18 factors and according to the building carbon emissions, residents of the household carbon emissions, community environmental carbon emissions for sorting and categorization, as shown in Table 1.

4.2. Network Construction of Carbon Emission Influencing Factors in Low-Carbon Communities

When studying the influencing factors of carbon emissions in low-carbon communities, if each identified factor is regarded as a "node" and the interactions and influences between each factor are seen as "edges," it can be viewed as a complex network composed of many interrelated influencing factors. By using the method of adjacency matrix, the relationship between node i and node j can be defined as Xij. If there is a connection between node i and node j, then Xij=1 (indicating that there is a certain relationship between influencing factors i and j), otherwise Xij=0. Define L as the reduction of carbon emissions [7]. By establishing a complete adjacency matrix in the database, as shown in Table 1, and utilizing Gephi to draw the network model, a risk network model consisting of 18 nodes and 148 edges was ultimately constructed.

4.2.1. Relationship Analysis of Factors Affecting Carbon Emissions

The relationships among influencing factors of carbon emissions in low-carbon communities are intricate and complex. These influencing factors interact and influence each other. Through literature review and investigation, 18 carbon emission influencing factors within low-carbon communities were identified. By expert analysis and field surveys, the connections between each factor were established, and the final result of comprehensive mutual influences of influencing factors was used to establish propagation paths of mutual influences among factors, connecting all paths through certain key nodes to form a complex network. As the influencing factors have mutual interactions, an undirected network is constructed.

For example, changes in building design (X4) in building carbon emissions not only affect the carbon emissions of building materials (X1), building operation (X3), and building waste treatment (X5), but also impact energy consumption structure (X14) and energy indirect consumption (X11). The population size of households (X9) in household carbon emissions also influences community environmental carbon emissions, such as the effects of resident behavior (X8) and community spatial planning (X15). In addition, transportation facility planning (X18) affects the carbon emissions resulting from community residents' travel (X7).

Therefore, when formulating carbon emission reduction policies, it is necessary to comprehensively consider the relationships among these influencing factors and take comprehensive measures to reduce carbon emissions.

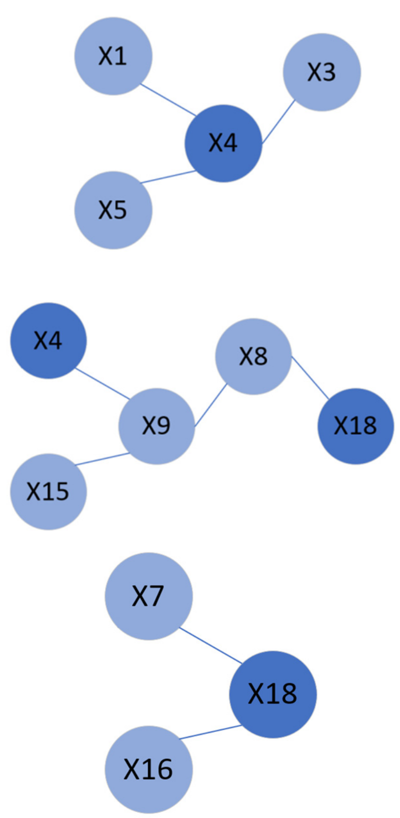

Fig 1. Map of carbon emission impact factor dissemination pathways (partial)

4.2.2. Complex Network Construction

Taking the key nodes on the path of carbon emission influencing factors as a link, the summarized path diagrams are connected to form a connected path diagram of influencing factors, and the path diagrams shown in Fig. 1 are connected and integrated to obtain Fig. 2 Connected path diagram of carbon emission influencing factors.

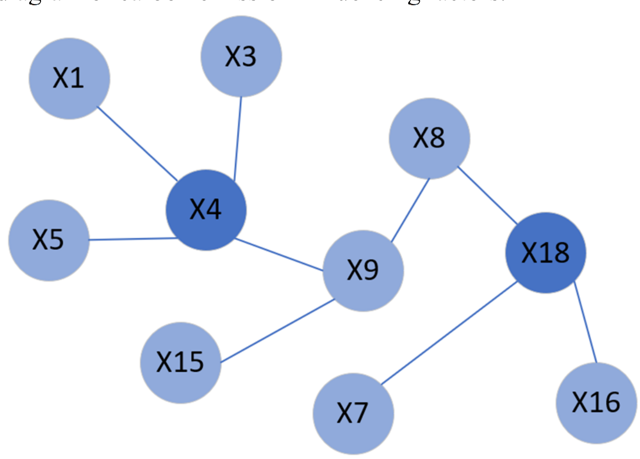

Fig 2. Pathway map for the dissemination of factors influencing carbon emissions in the Link (partial)

Taking the 18 low-carbon community carbon emission influencing factors extracted in Table 1 as nodes, analyzing the other nodes associated with each influencing factor, expressing the relationship between the influencing factors with 0 and 1, and writing the corresponding matrices, and finally writing an 18×18 adjacency matrix, the network model was drawn using Gephi, as shown in Fig. 3 [9].

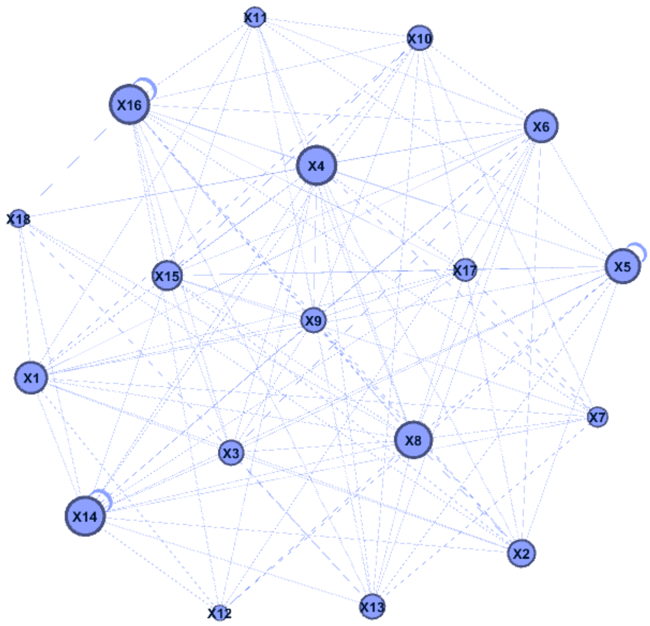

Fig 3. Network Modeling of Carbon Emission Influencing Factors in Low Carbon Communities

4.3. Nodal Indicator Analysis of Key Influencing Factors on Carbon Emissions in Low Carbon Communities

4.3.1. Network Overview

(1) Network Average Degree

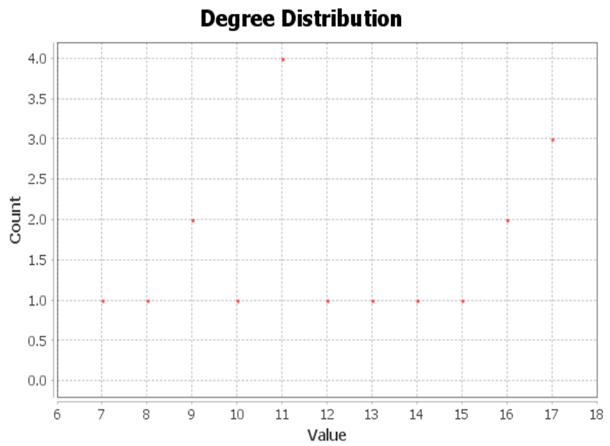

Fig 4. Average degree

In complex network theory, the Average Degree of a network (Average Degree) is an important measure of how closely the nodes in a network are connected. It is defined as the average of the degrees of all the nodes in the network, where the degree (Degree) of a node is the number of edges directly connected to that node. The average degree of this network is 12.444.

(2) Average clustering coefficient

The clustering coefficient reflects the density of connections between a node and its neighboring nodes in the network, i.e., the ratio of the number of connections that actually exist among a node's neighboring nodes to the maximum number of connections that could exist. The higher the clustering coefficient, the closer the nodes are to each other, i.e., the higher the degree of local aggregation [10].

The average clustering coefficient of this network is 0.759. a clustering coefficient close to 1 indicates that the nodes in the network tend to form a tight community structure, i.e., the neighboring nodes of a node are also connected to each other. This shows that the mutual influence relationship between the factors influencing community carbon emissions is extremely close.

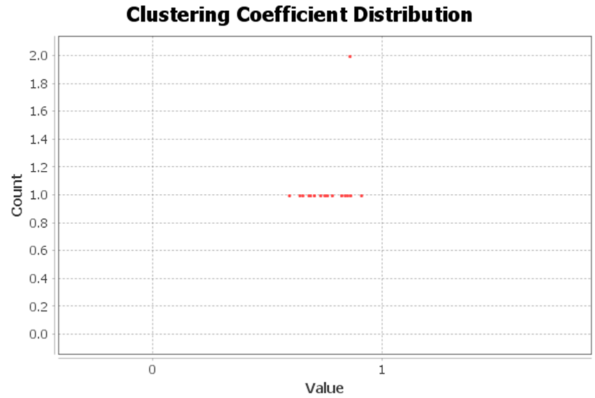

Fig 5. Average clustering coefficient

(3) Intermediary centrality

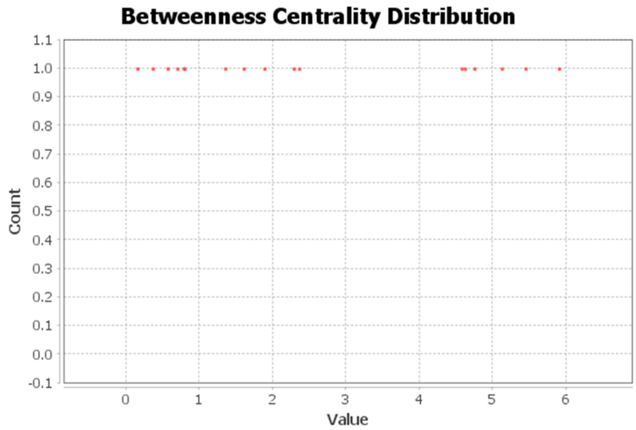

Fig 6. Intermediary centrality

The average mediated centrality of this network is 1.288. In complex networks, nodes with high mediated centrality are often key nodes for information dissemination, and they are able to control or influence the flow of information. For example, in a network of carbon emission influencing factors, influencing factors with high mediated centrality may be key node factors because they have large carbon emission values.

4.3.2. Analysis of Indicators

By using Matlab software to calculate the proximity centrality, mediated centrality and clustering coefficients of each influencing factor node, the risk nodes with the top six values are shown in Table 2.

Table 2. Indicator Analysis of Carbon Emission Influencing Factors

Ordering	Influence nodes	Proximity centrality	Cluster coefficients	Mediated Centrality
1	X14	0.6042	0.898	1.569
2	X8	0.5686	0.887	1.5440
3	X16	0.5179	0.845	1.5111
4	X4	0.5088	0.832	1.4446
5	X6	0.5088	0.811	1.4393
6	X5	0.4833	0.793	1.4165

The level of each index in Table 2 indicates the importance of each node's influencing factors, for example, X14's proximity to centrality, clustering coefficient, and intermediary centrality are all ranked high, which indicates that X14 has more influence in the network of carbon emission influencing factors and is an important influencing factor affecting carbon emissions, and that the energy structure (X14) affects other nodes to a greater extent, and at the same time, X14 is in the shortest path between many pairs of nodes. paths between many node pairs [11].

5. Conclusion

In this study, we conducted a systematic research on the factors affecting carbon emissions in communities and analyzed the data on the factors affecting carbon emissions in low-carbon communities based on complex network theory. By analyzing the results of the study, the following conclusions were drawn:

First, community carbon emissions are influenced by a variety of factors, including energy use patterns, transportation patterns and demand, waste disposal methods, land use and cover, buildings and infrastructure, resident lifestyles, and policy and management measures. These factors interact with each other to determine the level of community carbon emissions.

Second, the analysis of the factors influencing carbon emissions in low-carbon communities based on the complex network-related statistical indicators concludes that different factors contribute to carbon emissions to varying degrees. Among them, building design (X4), residents' behavior (X8), energy structure (X14) and policy implementation (X16) play an important role in the carbon emissions of low-carbon communities.

Finally, in order to effectively reduce community carbon emissions, we should take comprehensive measures, including promoting energy-saving and emission reduction technologies, optimizing transportation organization and planning, and enhancing waste treatment and resource recovery. At the same time, government departments should increase policy support and guide residents to change their lifestyles in a concerted effort to achieve carbon neutrality and sustainable development goals.

In summary, this study is of great significance in gaining a deeper understanding of the factors influencing community carbon emissions and their weight distribution, and provides theoretical support and practical guidance for future emission reduction efforts.

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