Diffusion Paths and Guiding Policy for Urban Residents’ Carbon Identification Capability: Simulation Analysis from the Perspective of Relation Strength and Personal Carbon Trading

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Abstract: On the consumption side, the key to carbon emission reduction is urban residents’ carbon capability. As it is the main bottleneck hindering carbon capability enhancement, the promotion of carbon identification capability is very important. This study establishes diffusion models of carbon identification capability from the perspectives of relation strength and personal carbon trading through weighted small-world theory, and it takes Chinese urban residents as the research object to make a simulation analysis. The results show that, at the initial stage, using a knowledge priority strategy to determine the sender of capability can bring about a higher capability growth rate for individuals, and the capability diffusion equilibrium of the network is also the highest. However, in the entire diffusion process, the strength priority model is the best to make the network reach the equilibrium quickly. After the introduction of personal carbon trading, the growth rate of the carbon identification capability increases significantly, and the network equilibrium becomes higher synchronously. More egoistic nodes and fewer altruistic nodes in the network are more favorable for the capability diffusion in the network, but they may bring about the risk that the network equilibrium becomes lower. Finally, the study puts forward suggestions to help with the improvement of residents’ carbon identification capability.

Keywords: urban residents; carbon capability; carbon identification capability; relation strength; personal carbon trading

1. Introduction

Environmental issues have become a major global problem in the 21st century, especially carbon emissions associated with energy consumption. As the world’s largest developing country, China’s total primary energy consumption and its carbon emissions are growing rapidly along with its GDP. China’s carbon emissions overtook those of the United States in 2006 and are now the highest in the world [1]. In such circumstances, there is no doubt that China needs to shoulder the responsibility of reducing its carbon emissions [2,3]. In the process of exploring the feasible paths for carbon emission reduction, scholars have come to realize that applying only supply-side measures of carbon emission reduction, such as technological advances and improved energy efficiency, could lead to a “rebound effect” and higher carbon emissions [4–6]. Therefore, we need to start from the consumption side to change consumption patterns and promote low-carbon lifestyles to fundamentally...
achieve carbon emission reduction [7]. China is currently undergoing rapid industrialization and urbanization. With continuous economic growth and the improvement in urban residents’ living standards, the structure of energy consumption for urban residents is improving, and the possession and usage of energy-consuming products such as home appliances and cars will continue to increase. These factors will inevitably lead to the rapid growth of urban residents’ living energy consumption and carbon emissions [8]. Urban residents’ energy consumption will become the major source of carbon emissions, and the key to consumption-side carbon emission reduction will be the residents’ carbon capability [9–12]. The carbon capability of urban residents can be described as a capability collection that shows a continually changing trend from the establishment of low carbon values, obtaining low carbon identification skills, and making wise low carbon choices to taking effective low carbon actions and having a low carbon influence in the whole process. The conceptual structure of the whole carbon capability process mainly includes five dimensions: carbon values, carbon identification ability, carbon selection ability, carbon action ability, and carbon influence ability [13,14]. In reality, urban residents in China already have certain low-carbon values, so this provides an inherent possibility and value basis for low-carbon practices [13–15]. However, sustained and stable low-carbon behaviors require not only a stable low-carbon value foundation but also an effective low-carbon cognitive foundation, and both are indispensable. The effective low-carbon cognitive foundation is carbon identification capability.

Carbon identification capability (CIC) is one of the core dimensions of carbon capability, and the essential condition for individuals to implement low carbon emission reduction behavior [9–11,13]. CIC refers to the ability of urban residents to know about relevant low-carbon policies, master low-carbon knowledge and skills, and make wise judgements about whether an action can be low carbon [13,14]. Two typical large-scale questionnaire-based studies on CIC were conducted in which all data were collected through a combination of an internet-based investigation and a field investigation. The first investigation was launched between January and March 2015 and covered cities in northern, central, and southern Jiangsu Province in China. Of the 1153 samples that were issued, 890 valid samples were recovered [13]. The second investigation was conducted from November 2016 to February 2017 and involved about 10 provinces and cities in eastern China. A total of 2056 valid questionnaires were recovered, with an effective recovery rate of 84.15% [14]. The two investigations found that the CIC averaged less than 3 points (total score of 5 points), which is far below the other links of carbon capabilities. This research shows that a poor capability for carbon identification is the main capability factor that hinders carbon capability improvement [13,14]. We find that many people in their daily lives occasionally or unconsciously adopt low-carbon behaviors, but such behaviors are not stable in the long term, so they cannot bring long-term significance to improving the environment. This is due to their weak inherent cognition, which means that, even if residents have a certain value foundation and behaviors, the behaviors, which lack intrinsic and accurate low-carbon cognition, cannot stabilize themselves in the long run and cannot continuously and steadily promote the overall carbon capability. Thus, to enhance carbon capability, there is an urgent need to improve the CIC.

To improve the CIC, we need to pay attention to not only the autonomous promotion of residents’ individual capability but also the permeability enhancement effect caused by the interaction among residents as social beings. CIC is advanced knowledge. Thus, the interactive influence of CIC among individuals is mainly realized through the diffusion of low-carbon knowledge. Knowledge diffusion generally refers to knowledge flow and transfers within and across the organizations through various channels. The exchange is based on the purpose of fully acquiring and utilizing the knowledge value foundation [16]. Knowledge diffusion is embodied in the process of knowledge sharing and communication among different individuals, and it often requires the help of various relations. As an important carrier of knowledge diffusion in groups and society, informal relations are of great significance to the system underlying the diffusion of knowledge among the entire group, organization, and even the society as a whole [17–19]. Relevant studies on knowledge diffusion based on informal relations among individuals have found that the factors influencing the diffusion of such knowledge are mainly classified into the following three categories. The first is the characteristics of
individuals, such as their basic personal information, social position, and the individuals’ knowledge reserves. The second is the characteristics of knowledge, such as the type and the coding degree of knowledge. The third is the relations between individuals, such as the relation strength [20] and relation attributes (cooperation and competition). In this study, there is no special distinction between the basic characteristics of the individual residents. The characteristics of knowledge mainly refer to the knowledge of low-carbon identification, and the relations among individuals are mainly shown through the relation strength among the residents.

At the same time, it needs to be emphasized that CIC is not only advanced knowledge but also special advanced knowledge, and it is special because of the low-carbon guiding characteristics in the capability. The study found that, to form low-carbon lifestyles and consumption patterns, means such as government propaganda and guidance are not enough [21,22]. It also requires improving consumers’ carbon values and encouraging them to identify low carbon and develop their carbon knowledge, supplemented by the corresponding market or economic means [23]. Therefore, while carbon values and CIC are taken as the foundation to realize low carbon, it is necessary to introduce a market mechanism to guide a low-carbon life for residents, and personal carbon trading (PCT) is considered to be a good option [24,25]. Although PCT has not yet been implemented in any country or region, there is no doubt that it plays a positive role in guiding consumers’ low-carbon behavior [26]. In the PCT system, consumers are given the same carbon emission rights. Although each consumer has equal carbon emissions, it does not mean that each consumer has the same carbon emissions. Because of the differences in each consumer’s consumption habits and patterns, each consumer can gain a certain benefit from the allotted carbon emission right or pay a certain price [27]. In short, as a market-oriented approach to environmental regulation, PCT can improve consumers’ perception of carbon, enhance carbon visibility, and strengthen consumers’ carbon concepts and thereby guide consumers to gradually change their way of living and consumption into a low-carbon lifestyle [28,29]. Accordingly, when individuals can trade their own carbon allowance and gain a certain income, to effectively change their behavior, we need to consider whether they will increase their cognitive learning of low carbon and develop and enhance their CIC. To investigate this question, this study uses the MATLAB simulation platform to explore the change rules of CIC from the perspective of PCT. It is assumed that all individuals are in the carbon trading market, and under this mechanism individuals can freely and openly trade their own carbon allowances, so different individuals can have a different willingness and demand for a CIC.

Based on the foregoing analysis, this study, from the perspectives of relation strength and PCT, explores the diffusion rules of CIC in groups and the effective paths for CIC diffusion to enhance urban residents’ CIC and thereby provide a reference basis for consumption-side carbon emission reduction.

2. Theoretical Basis

Capability is the stable psychological structure of a person. It refers to the possibility of the individual completing various tasks. Knowledge is an important carrier of the ability to display capability. In fields such as psychology, organizational behavior, and philosophy, it is believed that capability must be connected with specific task activities, and that no activity or task can be carried out smoothly. In addition, competence motivation theory (CMT) postulates that people will tend to engage in certain behaviors if they believe they are capable of executing those behaviors successfully [30,31]. Although knowledge is not a direct influence factor on behavior, its effect on behavior cannot be ignored [32]. In conclusion, capability is an essential condition for an individual to complete all kinds of behaviors. Lack of capability could directly lead to the nonoccurrence of effective behavior, which excludes some random or accidental behaviors. CIC is one of the core dimensions of carbon capability. Lack of CIC could lead to unsuccessful low carbon behavior [9–11,13]. Thus, to enhance carbon capability and promote carbon emission reduction for urban residents on the consumption side, there is an urgent need to improve the CIC. Based on these principles, CIC was chosen as our starting point and the center of our research.
The essence of CIC diffusion is the diffusion of knowledge. There is no universal definition of knowledge diffusion in respect of the informal relations among individuals. Allen believed that informal knowledge diffusion among individuals was private behavior and did not necessarily have to do with the organization it belonged to and the related policies [33]. To summarize previous researchers' viewpoints, knowledge diffusion among individuals is "private knowledge assistance" [34]. In the related knowledge diffusion research, the small-world network has been applied the most, and the theory is more mature. Many scholars believe that the small-world network is the most effective and fair network structure in knowledge diffusion [35–37]. The WS small-world network model (traditional small-world network) was first proposed by Watts and Strogatz, and in the model the relations between the two nodes are defined only by yes and no (1 represents "yes", 0 represents "no"). However, it should not be overlooked that, in the real world, the connection between different nodes is not so simple. The relations involve not only "yes" or "no" but also "strong" or "weak", and the "strong" and "weak" embodies the difference between "strong relations" and "weak relations". In other words, if the relations between nodes are strong, there are strong relations, and if the relations are relatively alienated, the relations are weak. Based on this the weighted small-world network is widely used in which weights are given to the relations among nodes. The weights represent the relation strength between two nodes or the difficulty of the knowledge diffusion between the nodes. Therefore, this study selects the weighted small-world network to study the diffusion of CIC among individuals.

At present scholars regard the social exchange theory, economic exchange theory, and social-economic exchange theory as the theoretical basis for studying knowledge diffusion. The economic exchange theory is based on the hypothesis of the "economic being". Under this theory, we assume that the subject of knowledge is selfish, and individuals are willing to take part in knowledge diffusion because this behavior is beneficial to themselves and their interests, which basically refer to their economic interests. The social exchange theory is based on the hypothesis of the "social being". The social exchange theory is based on the hypothesis of the "social being". The knowledge diffusion among the social beings depends more on the trust and familiarity among individuals rather than solely on their economic interests [38]. With the social-economic exchange theory, after integrating the two theories, the study puts forward the notion that the subject of knowledge is both an economic being and a social being, and the two attributes are indivisible. This idea is based on the hypothesis of the "complex being" [39], so it needs to be considered comprehensively in the study.

The essence of CIC diffusion is the diffusion of low-carbon knowledge. In the studies on knowledge diffusion, the two mechanisms proposed by Cowan et al. are widely identified, and these studies mainly divide knowledge diffusion into an altruistic type and egoistic type [40]. Altruistic diffusion mainly manifests as the free diffusion of knowledge. The theoretical basis of this diffusion is the social exchange theory; that is, the subject of knowledge is a social being, all its attributes are embedded in the social relation structure, and knowledge is diffused based on the social attributes. Egoistic-type diffusion manifests itself as knowledge exchange and transfer, which is based on the economic exchange theory. It means that the subject of knowledge is the economic being. When it diffuses knowledge, it gains interests, and the interests are economic interests in most cases.

This study, which is based on the social exchange theory, economic exchange theory, and social-economic exchange theory, establishes models of CIC by comprehensively taking into consideration the altruistic- and egoistic-type capability diffusion mechanisms and adopting a weighted small-world network. On this basis, it continues to explore the diffusion paths of CIC in the regulation of individual carbon trading through simulation analysis with the Matlab software.

3. Materials and Methods

3.1. Construction of Individual CIC Network

The weighted small-world network needs to focus on the relation strength between the nodes, and it can reflect the interaction emotion, affinity, and reciprocity between individuals [11]. The relation strength between the subjects of knowledge will change with time [41]. In general, it mainly shows
that strong relations will become stronger. Moreover, compared with weak relations, strong relations will bring about more individual interests [42]. The weighted small-world network is used to construct knowledge network \( K \), and \( K = (N, S, R) \). In the formula, \( N = (1,2,3 \cdots n) \) represents a set of all nodes in the network, and \( N \) is the number of nodes. \( S = \{ S(i) | i \in N \} \) represents a set of all the edges in the network. \( R = \{ r_{ij} | i, j \in N \} \) is a set of the relation strength in the network. \( r_{ij} \) represents the relation strength between individuals \( i \) and \( j \). If there are no relations between two nodes, \( r_{ij} = 0 \), and no connection exists between the two nodes. In the study we assume that the relation strength between two nodes is symmetrical, namely \( r_{ij} = r_{ji} \).

In addition, in the CIC network, each node has various low-carbon knowledge, and it is able to identify whether a kind of product or service is low-carbon. In the aforementioned research questionnaire, the CIC involves eight items to measure eight aspects of low-carbon knowledge. Based on this, the study assumes that each node in the CIC network can only have eight different types of low-carbon knowledge. The double dimensional array \( v[i,c] \) represents the level of each knowledge subject in the eight types of knowledge, where, \( i \) is an individual node with \( i = 1,2,3 \cdots n. \ c \) is the type of knowledge with \( c \in [1,8] \). \( v[i,c] \) represents the level of node \( i \) in \( c \) level of knowledge. Greater values of \( v[i,c] \) represent higher CIC of node \( i \) in the \( c \) level of knowledge. Node \( i \) in the network equals the average value of the eight types of foregoing knowledge, and the formula is as follows.

\[
v_i(t) = \frac{1}{8} \sum_{c=1}^{8} a_c \cdot v[i,c], \quad \sum_{c=1}^{8} a_c = 1, \quad 0 < a_c < 1
\]

3.2. Construction of CIC Diffusion Model Based on Relation Strength

3.2.1. Determination of Diffusion Targets

The diffusion targets of CIC are mainly divided into the sender and demander of the CIC (hereinafter referred to as the sender and demander). In the diffusion process of CIC, the sender and demander both have certain selection strategies. Different diffusion strategies lead to different diffusion efficiencies and effects, and they affect the diffusion equilibrium of the entire network. To facilitate comparison and analysis, this study sets the CIC as the following three types [27].

**Random model:** In the entire diffusion process of CIC, the demander randomly selects a node in the neighboring node set meeting the basic condition of the “difference of CIC” as the sender. In other words, the basic condition for the diffusion of any demander node \( j \) and its neighboring node \( i \) in the CIC network is the existence of a type of low-carbon knowledge \( c \), and \( c \) can make the CIC of node \( i \) in \( c \) low carbon knowledge greater than that of node \( j \); that is, \( v[i,c] > v[j,c] \).

**Strength priority model:** In the entire diffusion process of CIC, the demander, based on the principle of “relation strength priority”, selects a node with the strongest relation strength in the set of neighboring nodes meeting the basic condition of “difference of CIC” as the sender. This means that the condition of CIC diffusion between the demander \( j \) and the sender \( i \) is \( v[i,c] > v[j,c] \) and \( r_{ij} = \text{Max}\{r_{ij}\} \).

**Knowledge priority model:** In the entire process of diffusion, the demander, based on the principle of “knowledge priority”, selects a node with the biggest difference from the low-carbon knowledge it needs in the set of neighboring nodes meeting the basic condition of “difference of CIC” as the sender. The condition of CIC diffusion between the demander \( j \) and the sender \( i \) is \( v[i,c] > v[j,c] \) and \( v[i,c] = \text{Max}\{v[i,c]\} \). The above setting only analyzes the diffusion sender’s three strategies and does not pay attention to the demander. In fact, the demander is the initiator of the entire process of diffusion in the network, and different node strengths may influence its choice on strategies. In this study, the demander mainly selects the sender randomly. In other words, in each process of CIC diffusion, a node randomly selected from the nodes meeting the condition of “difference of CIC” is taken as the demander, and the demander’s CIC must be lower than that of the sender.
3.2.2. Capability Growth Mechanism and Relation Strength Change Mechanism of the Nodes of CIC Diffusion

- Capability growth mechanism of nodes of CIC diffusion

In this section, we mainly focus on the CIC diffusion paths influenced by the relation strength without considering the trading conditions. Thus, CIC diffusion is a free diffusion method, namely, altruistic diffusion. It means that one side is willing to diffuse relevant low-carbon knowledge for the other side for free.

In each simulation step (denoted by \( t \)) of CIC diffusion in the network, the growth patterns of the CIC of the demander \( j \) and the sender \( i \) are shown in Formulas (2) and (3).

\[
v[j, c](t+1) = v[j, c](t) + \varphi[j] \times r_{ij} \times \{v[i, c](t) - v[j, c](t)\} \\
v[i, c](t+1) = v[i, c](t)
\]

where \( \varphi[j] \) is the absorption coefficient of the CIC of the node \( j \), and it is assigned as a random number in \((0, 0.02)\). \( r_{ij} \) is the relation strength between the nodes of CIC diffusion, and it is assigned as a random number in \((0, 1)\). Since the relation strength \( r_{ij} \) affects not only the sender’s effort degree in CIC diffusion but also the demander’s acceptance degree, it is included in the formula measuring the growth of the CIC.

- The relation strength change of the node

After a diffusion process of CIC, the relation strength between the demander and its neighboring node changes. Because of the CIC diffusion between the two sides of the diffusion, the connection between the two sides is closer and the relation strength is stronger. When the individual \( i \) is the sender, the change of the relation strength \( r_{ij}(t) \) is shown in Formula (4):

\[
r_{ij}(t+1) = r_{ij} + \omega
\]

where the small positive number \( \omega \) is the changing value of the relation strength, and it is assigned as 0.05. To balance the relation strength between the nodes in the network, the relation strength between a node \( k \) in the demander’s neighboring nodes and the demander \( j \) is randomly reduced. The change is shown in Formula (5):

\[
r_{kj}(t+1) = r_{kj} - \omega
\]

- Measuring diffusion CIC performance

The faster growth of the average CIC of all individuals in the network means there will be a higher level of efficiency of CIC diffusion. To measure the rate of the CIC diffusion of all nodes in the network, this study defines the average CIC of all nodes at \( t \) moment as the average value of CIC of all nodes at \( t \) moment in the network. This is shown in Formula (6), where \( n \) is the total number of nodes in the network of CIC diffusion.

\[
u(t) = \frac{1}{n} \sum_{i=1}^{n} v_i(t)
\]

The equilibrium of the CIC diffusion of all nodes in the network can be measured through the variance of the CIC of all the nodes. The higher the variance values of the CIC of all nodes, the lower the equilibrium of the CIC diffusion of all nodes in the network, which means that the individual’s level of CIC is more deviant from the average of all the individuals. Conversely, the lower the variance values of the CIC of all the nodes in the network, the higher the equilibrium of the CIC diffusion of all nodes in the network. It is important to note that when the variance value is 0, the equilibrium of all nodes in the network is the highest. At this time, the CIC of all individuals in the network is the same, and the diffusion process of the CIC can be ended accordingly. The calculation for the variance of the
CIC of all the individual nodes in the network at moment is set out in Formula (7), where \( n \) is the total number of nodes in the network of CIC diffusion.

\[
\sigma^2(t) = \frac{1}{n} \sum_{i=1}^{n} \sigma_i^2(t) - \sigma(t)^2
\]  
(7)

### 3.3. Construction of Diffusion Model of CIC from Perspective of PCT

The diffusion targets of the CIC are mainly divided into the sender and demander of the CIC. In the CIC diffusion process, the sender and the demander both have certain selection strategies. Different diffusion strategies lead to different diffusion efficiencies and effects, which affect the diffusion equilibrium of the entire network. Individuals would fully consider their own economic interests in the CIC diffusion process, and this is mainly based on the social-economic exchange theory. In other words, in the CIC diffusion process, individuals do not always conduct diffusion for free. From the foregoing analysis, we can see that the capability diffusion can be divided into egoistic type and altruistic type. Among them, the free diffusion of CIC is altruistic diffusion, and such nodes continue to maximize their collective interests (i.e., the overall interests of the CIC network). The exchange diffusion of CIC is egoistic-type diffusion, and such nodes also focus on their maximized interests. Thus, in this section we divide the nodes into altruistic and egoistic types to distinguish the attitudes of different nodes towards the diffusion of CIC.

In this section, we aim to examine the influence of the diffusion attitudes of nodes on the CIC diffusion in the network from the PCT perspective. To exclude the interference of the relation strength, this section only explores the CIC diffusion influenced by the diffusion attitude of the nodes.

Based on the foregoing analysis, this study assumes that, when the sender is an egoistic-type node, the CIC will be diffused in an exchange way. When the sender is an altruistic-type node, the CIC will be diffused in a free way. From the PCT perspective, egoistic nodes aim to maximize their own interests and altruistic nodes aim to optimize the overall interests in the network, so the willingness of both sides of the CIC diffusion to send and demand the capability will increase. In the CIC network, \( P = \{ P(i) | i \in N \} \) represents a set of diffusion ways of all nodes in the network, where \( P(i) = 0 \) means egoistic nodes, and \( P(i) = 1 \) means altruistic nodes. The diffusion attitude of the nodes to the diffusion of the CIC is an inherent and stable attribute, so it is assumed that the diffusion attitudes will remain constant throughout the CIC diffusion process.

Assuming that the relation strength between nodes in the network is unchanged, we only consider the influence of the diffusion attitude of the nodes on the CIC diffusion in the network. Based on the diffusion condition of the CIC of different nodes in the CIC network, the two sides of the CIC diffusion generate different capability growth ways and processes.

#### 3.3.1. Knowledge Transfer with PCT

Without a mechanism for carbon trading in the market, all nodes in the network are not simulated by the external economy, and the demand of all nodes to CIC tends to stabilize in the long run, which means that the willingness of both sides to send and demand identification capability is stable; that is, without obvious changes. In the following section, the sender of the CIC is divided into egoistic and altruistic nodes, and the growth of the CIC is analyzed.

- When the sender of the CIC is an egoistic-type node, the CIC is diffused in an exchange way.

\[
\begin{align*}
\mathcal{v}[j,c_1](t+1) &= \mathcal{v}[j,c_1](t) + \varphi[j] \times \{ \mathcal{v}[i,c_1](t) - \mathcal{v}[j,c_1](t) \}, \mathcal{v}[i,c_1](t+1) = \mathcal{v}[i,c_1](t) \\
\mathcal{v}[i,c_2](t+1) &= \mathcal{v}[i,c_2](t) + \varphi[i] \times \{ \mathcal{v}[i,c_2](t) - \mathcal{v}[i,c_2](t) \}, \mathcal{v}[j,c_2](t+1) = \mathcal{v}[j,c_2](t)
\end{align*}
\]  
(8)

(9)
When the sender of the carbon identification is an altruistic-type node, the CIC is diffused in a free way among the nodes. The diffusion mechanism of the CIC is shown in Formula (10):

$$v[j, c](t + 1) = v[j, c](t) + \phi[j] \times (v[i, c_1](t) - v[j, c](t)), \quad v[i, c_1](t + 1) = v[i, c_1](t)$$

(10)

where $c_1$ is the low-carbon knowledge needed by the demander $j$; $c_2$ is the low-carbon knowledge compensation to the sender $i$ provided by the demander $j$; $\phi[j]$ is the low-carbon knowledge absorption coefficient of the demander $j$; and $\phi[i]$ is the low-carbon knowledge absorption coefficient of the sender $i$. The values are the random numbers in $[0,0.2]$.

3.3.2. CIC Diffusion from Perspective of PCT

• When the sender is an egoistic-type node, the CIC is diffused in an exchange way among the nodes. The CIC diffusion mechanism is shown in Formulas (11) and (12):

$$v[j, c_1](t + 1) = v[j, c_1](t) + \phi[j] \times (1 + z_i) \times (v[i, c_1](t) - v[j, c_1](t)), \quad v[i, c_1](t + 1) = v[i, c_1](t)$$

(11)

$$v[i, c_2](t + 1) = v[i, c_2](t) + \phi[i] \times (1 + z_i) \times (v[i, c_2](t) - v[i, c_2](t)), \quad v[j, c_2](t + 1) = v[j, c_2](t)$$

(12)

where $z_j$ is the growth value of the demand willingness intensity of the CIC diffusion of the nodes in the carbon trading market, and $z_i$ is a random number in $[0,1]$. $z_i$ is the growth value of the sending willingness intensity of the CIC diffusion of the nodes in the carbon trading market, and $z_i$ is a random number in $[0,1]$.

• When the sender is an altruistic node, the CIC is diffused in a free way among the nodes. The diffusion mechanism of the CIC is shown in Formula (13):

$$v[j, c](t + 1) = v[j, c](t) + \phi[j] \times (1 + z_j) \times (1 + z_i) \times (v[i, c](t) - v[j, c](t)), \quad v[i, c](t + 1) = v[i, c](t)$$

(13)

• The change of sending and accepting willingness of nodes

After a process of knowledge diffusion, the sending willingness of the egoistic nodes will change. The egoistic nodes are diffused in an exchange way, so after obtaining new low-carbon knowledge, the overall level of the nodes will improve and the sending willingness will weaken.

$$z_i(t + 1) = (1 + z_i) - \delta_i$$

(14)

The altruistic nodes are diffused in free way, so after a process of capability diffusion, their sending willingness will remain unchanged, whereas the demander’s demand willingness will weaken after obtaining new low-carbon knowledge, as shown in Formula (15), where the small positive numbers $\delta_i$ and $\delta_j$ are the changing values of the willingness, 0.05.

$$z_j(t + 1) = (1 + z_j) - \delta_j$$

(15)

3.4. Simulation Process

The study uses Matlab7.6 (2008a) software to simulate the CIC diffusion based on a knowledge network, and the process of system simulation is as follows.

Step 1. Create a CIC network. According to the network generation algorithm in Section 3.1, we produce the CIC network in the following ways. The number of adjacency points in the network is $N$ and $N = 500$ in this study. The number of adjacency points in the network is $k$, which is a constant. If there are no special instructions in the following simulation, $k = 8$. The disconnect and reconnect
probability of the neighboring nodes is $p$, and $p = 0.09$ when creating the small-world network. According to the network generated by the aforementioned parameters, the adjacency relation between the nodes is stored in matrix $A$. For the random nodes $i$ and $j$, $A[i, j] = 1$ indicates a direct connection between nodes $i$ and $j$ in the network; that is, they are related. $A[i, j] = 0$ indicates no indirect connection between nodes $i$ and $j$ in the network; that is, they are unrelated.

Step 2. Initialize the CIC network. Each node is set to have eight different types of relevant low-carbon knowledge in the network, so it needs $B$, a matrix of $500 \times 8$, to store the CIC levels of the nodes in each knowledge type. For a random node $i, (i \in [1, 1500])$ and random knowledge type $c (c \in [1, 8]), B(c)$ is randomly generated and the knowledge level is $d (d \in [1, 5])$.

Step 3. Determine the simulation step size $T$. This study is set to 200,000 times, and the current simulation step size is 1.

Step 4. If the current simulation step size is less than or equal to the total simulation step size $T$, go to Step 5, otherwise go to Step 9.

Step 5. Select a node $j$ as the initiating node ($j$ is the demander) of the CIC diffusion based on the different demander determination methods. Randomly select a knowledge type $c$ as the low-carbon knowledge type for node $j$ to learn through CIC diffusion.

Step 6. Look for all nodes directly connected with $j$ in the adjacency matrix $A$ of node $j$. For all the nodes found, if node $i$ makes $B[i, c] > B[j, c]$, go to Step 7, otherwise go to Step 4.

Step 7. Select the sender based on the different determination methods for the diffusion objects of CIC.

- Random selection: Randomly select a node from the nodes found as the sender $i$.
- Strength priority: Select the node with the highest strength of the demander in all the nodes found as the sender $i$.
- Knowledge priority: Select the node with the highest knowledge level in type $c$ from all nodes found as the sender $i$.

Step 8. Formulas (2)–(5) are used to achieve the growth of the CIC of nodes $j$ and $i$ and the relation strength change between node $j$ and its adjacent node.

Step 9. Add one to the simulation step size, then go to Step 4.

Step 10. The simulation ends; output the result.

The above process is a diffusion analysis based on the relation strength. In the analysis of the intervention of PCT, the knowledge priority is mainly taken to select the sender; that is, only one step is conducted in Step 7.

4. Results and Discussion

4.1. Results Analysis Based on Relation Strength

In reality, the relation strength of the nodes in the network is complex, and the relation strength is different among the nodes. In the study, when the relation strength between the nodes in the network is in $(0, 1)$, the relation is defined as random. If the relation strength is in $[0.7, 0.9]$, the relation is defined as strong, and if the relation strength is in $[0.1, 0.3]$, the relation is weak. This section analyzes the diffusion paths of the CIC where the relations are defined as random, weak, and strong, respectively.

- Network of random relation strength

To show more clearly the influence of the relation strength between the nodes on CIC diffusion in different sending ways, all of the relation strengths between the nodes in the network are set as random numbers in $(0, 1)$, which means that the network is a random relation network. The average carbon capability of all the individuals in the network is shown in Figure 1a, and the simulation results of the carbon capability variance are shown in Figure 1b.
The influence of the knowledge priority model is close to that of the strength priority model in the initial period of simulation, but it is still significantly higher than that of the random model (Figure 1). The knowledge priority model brings about such a growth tendency because the demander absorbs the difference of the CIC between it and the sender. As a result the advantage of the difference of the CIC continuously reduces to the influence of the strength priority model. In addition, in the strength priority model, with the increase of the simulation step size the knowledge variance of the individuals in the network decreases gradually; that is, the knowledge transfer between the individuals in the network tends to be balanced. Through a comprehensive analysis of the growth rate of the CIC and network equilibrium, in the individual CIC network of the weighted small-world network, we can give preference to a sender diffusing capability to the demander based on the relation strength. Such a sender will increase the average CIC of all the individuals in the network and first optimize the network equilibrium.

- **Network of weak relations**

The relation strength of the nodes in the network is defined as a random number in [0.1, 0.3], which represents the weak relations between the nodes, and the simulation results are shown in Figure 2.

![Figure 1](image1.png)

**Figure 1.** Changing tendency of the CIC in different sending ways: (a) the average CIC level of all individuals in the network (random relation strength); and (b) the CIC variance of all individuals in the network (random relation strength).

![Figure 2](image2.png)

**Figure 2.** Influence of weak relations network on CIC diffusion: (a) the average CIC level of all individuals in the network (weak relations); and (b) the CIC variance of all individuals in the network (weak relations).
In the entire process of the simulation, the node CIC grows slowest in the random model (Figure 2). In the early stage of the simulation, the node CIC of the knowledge priority model has the fastest growth rate, followed by the knowledge priority model. After the simulation enters the middle and later stages, the advantages of the knowledge priority model gradually decrease, whereas the node CIC in the strength priority model grows the fastest, and the variance of the node CIC in this model is the smallest. This means that the equilibrium of the CIC diffusion in the network is the highest, whereas the equilibrium of the network capability diffusion in the random model is the lowest.

- Network of strong relations

The relation strength of the nodes in the CIC network is defined as a random number in [0.7, 0.9], which represents the strong relations between the nodes, and the simulation results are shown in Figure 3.

In Figure 3, we can see that, in the entire simulation process, the knowledge priority model has a distinct advantage in the strong relations network. This is mainly because the growth rate of the CIC in this model is obviously higher than those in the strength priority model and random model, and in the middle and early stages, the network has the highest equilibrium.

4.2. Results Analysis Based on PCT Intervention

In this study, two kinds of PCT schemes were conducted: one was an optional scheme and the other was a mandatory scheme. They were analyzed at the same time to compare the differences between the two schemes and find the optimal one. Sections 4.2.1 and 4.2.2 reflect the results of the optional PCT scheme, and compare the difference of CIC with the intervention of PCT. Section 4.2.3 shows the results of the mandatory PCT scheme. The basic assumption of this section is that all individuals in the network must carry out this scheme. The different diffusion attitudes of the nodes (egoistic nodes and altruistic nodes) in the network could lead to differences in the growth rates of CIC.

4.2.1. CIC Diffusion in the Intervention of the PCT

First, the diffusion paths of the CIC of all nodes in the network without and with a carbon trading market are examined, and the simulation results are shown in Figure 4.
were nearly 1:1 (50%). In particular, if the samples were divided into different groups by region, gender, and (b) the CIC variance of all individuals in the network.

Generally speaking, it is unrealistic to measure the diffusion attitudes of all individuals, but we can obtain the distribution characteristics data through representative samples. Based on the previous research results [14], the distribution ratio of egocentric and altruistic individuals in the whole sample were nearly 1:1 (50%). In particular, if the samples were divided into different groups by region, gender,
age, and other characteristics, there was no uniform trend in the proportion of individuals; that is, in reality, the diffusion attitudes of all the individuals was not evenly distributed 1:1 in the groups. They could be 3:7, 1:9, 5:5, etc. To describe the population differences and compare the influence of the different distributions on CIC diffusion, this study established the distribution of two kinds of nodes based on the above thinking to make the simulation analysis. When the diffusion attitude of the nodes in the network was distributed in a certain proportion, the growth of the CIC of all nodes and the simulation results of the network capability diffusion equilibrium without PCT were as shown in Figure 6.

![Figure 6](image)

**Figure 6.** Influence of diffusion attitudes of nodes on the CIC (T = 200,000): (a) the average CIC level of all individuals in the network (without PCT); and (b) the CIC variance of all individuals in the network (without PCT).

As the proportion of egoistic nodes in the network increases, the proportion of altruistic nodes gradually reduces, and the average growth rate of the knowledge level of the nodes gradually increases (Figure 6). This is mainly because each phase of capability diffusion of the egoistic nodes triggers two diffusion processes, which results in a rapid increase in the average value of the network as a whole. In addition, the average variance of the CIC reflects the equilibrium of the capability diffusion in the CIC network. The figure shows that during the entire simulation process, as the simulation step size increases, the average variance of the carbon capability of the nodes in the network fluctuates significantly in the early stage, and it is has a significant downward tendency in the middle and later stages. It is worth noting that the lower proportion of egoistic nodes does not mean there is a higher equilibrium of the network capability diffusion. In the middle and later stages of the simulation, the equilibrium of the network capability diffusion is highest with 30% egoistic nodes and 70% altruistic nodes.

To more clearly demonstrate the changing tendency of the CIC in the early stage of the simulation, the simulation step size is set as 10,000 steps, as shown in Figure 7.

As the proportion of the egoistic nodes in the network changed from 10% to 90%, the average CIC of the nodes in the network gradually increased at an accelerated speed (Figure 7). This is mainly because of the difference in the egoistic and altruistic nodes in the mechanism of capability diffusion and the required conditions. For the egoistic nodes, in a successful process of capability diffusion the capability diffusion manifests as exchange diffusion, and the overall growth rate of the network capability is great. At the same time, compared to the egoistic nodes, the capability growth of the altruistic nodes resulting from time of knowledge diffusion is lower. Therefore, there being more egoistic nodes means fewer altruistic nodes in the network. With the increase of the simulation step size, the advantage of the knowledge diffusion of the egoistic nodes is increasingly
prominent, and the capability increase from it is much more than that from the altruistic nodes. Thus, there being more egoistic nodes means fewer altruistic nodes and greater efficiency of the CIC diffusion. However, in terms of the equilibrium of the capability diffusion in the network, despite the increase in the efficiency of the capability diffusion from the more egoistic nodes, the network is at risk of lower equilibrium.

4.2.3. The Influence of Diffusion Attitudes of Nodes on CIC Diffusion from the PCT Perspective

With regard to the CIC diffusion paths of from the PCT perspective, the diffusion attitudes of the nodes in the network are distributed in different proportions, and the average CIC of all the nodes and the simulation results of the variance are shown in Figure 8. Similar to the case where there is no introduction of a carbon market trading mechanism, as the proportion of egoistic nodes in the network increases from 10% to 90%, the average CIC of the nodes gradually increases at an accelerated speed (Figure 8).

Figure 7. Influence of diffusion attitudes of nodes on the CIC (T = 10,000): (a) the average CIC level of all individuals in the network (without PCT); and (b) the CIC variance of all individuals in the network (without PCT).

Figure 8. Influence of diffusion attitudes of nodes on the CIC from perspective of the PCT (T = 200,000): (a) the average CIC level of all individuals in the network (with PCT); and (b) the CIC variance of all individuals in the network (with PCT).
Further, to more clearly demonstrate the changing tendency of the CIC in the early stage of the simulation, the simulation step size is set as 10,000 steps and the results are shown in Figure 9.

Figure 8. Influence of diffusion attitudes of nodes on the CIC from perspective of the PCT (T = 200,000): (a) the average CIC level of all individuals in the network (with PCT); and (b) the CIC variance of all individuals in the network (with the PCT).

Figure 9. Influence of diffusion attitudes of nodes on the CIC from the perspective of the PCT (T = 10,000): (a) the average CIC level of all individuals in the network (with PCT); and (b) the CIC variance of all individuals in the network (with the PCT).

With the carbon market trading mechanism, the average growth rate of the CIC of the nodes in the network has increased significantly (Figure 9). When the simulation step size is 10,000 steps, the average CIC value in the network is close to 4.2, which is much higher than the average value of the CIC for the same step size without a carbon trading mechanism. The entire simulation process shows that the lower proportion of egoistic nodes means a higher equilibrium of the diffusion capability of the network.

5. Conclusions and Policy Implications

First, this study explores the influence of relation strength on CIC diffusion. Second, it compares and analyzes the influence of a personal trading market on CIC diffusion, it clarifies the positive influence of PCT on the improvement of CIC, and it further explores the influence of the diffusion attitudes of nodes (egoistic and altruistic) on CIC diffusion. Finally, it explores an optimal distribution of the diffusion attitudes that can trigger a high level of efficiency of capability diffusion. The conclusions are summarized as follows.

- In the weighted small-world network structure with random relation strength, the determination of the sender of CIC through a knowledge priority strategy in the process of capability diffusion enables an increase in the capability growth rate of the nodes in the individual network and makes the equilibrium of the capability diffusion the highest in the whole network in the early stage of the simulation. However, in the middle and later stages of the simulation, the advantage of the difference of the CIC fades, whereas the advantage of the strength priority model stands out, and the equilibrium of the capability diffusion in the entire network is the highest. In the weak relations network, the determination of the sender through knowledge priority and private strength results in a small difference in the capability growth rate of the nodes, but the equilibrium of the CIC of the nodes in the network of strength priority is obviously higher than that of knowledge priority in the network. In the strong relations network, the determination of the sender through knowledge priority makes the growth rate of the CIC of the nodes significantly higher than that through strength priority and a random model; the network equilibrium is the highest and the advantage continues until the middle and later stages of the simulation.
• Without a carbon trading market, having more egoistic nodes in the network is more conducive to the efficiency of capability diffusion, but there is a need to assume the risk of a low equilibrium of the capability diffusion in the CIC network.

• With the mechanism of a carbon trading market, the CIC growth significantly increases. In the early stage of the simulation, the average value and variance of the CIC increases rapidly in the short term, and the network equilibrium is lower. However, with an increase in the simulation step size, the equilibrium became gradually higher, and as a whole it is a better model than the network without the mechanism of a carbon trading market. Having more egoistic nodes in the network means fewer altruistic nodes and a higher level of efficiency of the CIC diffusion, but there is a risk of lower network equilibrium.

Based on the research results, the following suggestions are made.

• The authorities should improve the education mechanism. The public low carbon education should be taken as the basis link for the cultivation of the CIC, as it provides the foundation and supplement for other guiding policies. Basic education and low-carbon education should be treated as equal, and a new low-carbon diffusion method should be proposed. The government should improve the democratic dialogue mechanisms among the government, news media, and residents and promote the widespread dissemination of low carbon news among the residents. It should be noted that the promotion of specific and targeted low-carbon knowledge would bring about more pronounced results.

• Based on the simulation results, we should select a sender through the knowledge priority strategy in the process of capability diffusion. Together with the strength priority, the knowledge priority can quickly promote the average CIC of urban residents and increasingly reduce the gap in CIC among residents. As the main body of capability diffusion, the sender plays a great role in improving the diffusion efficiency by improving their own condition and capability diffusion situation. Therefore, idols with good carbon identification capabilities should be cultivated as the senders of capability diffusion, and activities should be organized regularly to provide low-carbon knowledge to residents with poor carbon identification capabilities. The results showed that the relation strength affected not only the seriousness of the sender but also the effort degree of the demander in receiving capability. Therefore, the low-carbon community and idols could constantly narrow the distance from other residents and improve the relation strength and trust to disseminate the CIC effectively. The following recommendations are made for the low carbon community and models with high levels of CIC: (1) Promote their learning initiative to master the different kinds of low carbon knowledge to improve their own low carbon knowledge reserve and low carbon knowledge supply ability. (2) Establish effective communication mechanisms to improve the absorption efficiency of low carbon knowledge. The sender of capability needs to continuously strengthen their coding ability of low carbon knowledge to reduce the difficulty of knowledge diffusion and guarantee that the knowledge transferred is easy to understand for other urban residents. At the same time, different ways should be used to do this because of the different classifications of the simple or complex low carbon knowledge. For example, knowledge about the purchase and use of low carbon products needs to be spread through several professional tips, and the far-reaching effects of carbon emissions can be transferred through the mass media like TV, newspapers, radio, networks, and outdoor media. (3) Widely disseminate knowledge to realize a knowledge “win–win” for all the urban residents. Try to avoid the one-to-one ability diffusion pattern, which can raise the efficiency level of CIC diffusion. Many forms can be taken, such as theme education, knowledge competitions, visits and interviews, class education, and community consultation to give urban residents a multifaceted education about resource conservation and low-carbon knowledge.

• The simulation results show that, with a PCT mechanism, the CIC growth has been significantly improved, and the overall equilibrium of residents’ CIC is also higher than that without the
carbon market trading mechanism. Even though China has not implemented a PCT scheme, the mechanism should be considered in the promotion of carbon capability in the future. At the beginning of the implementation, it could be set as an optional scheme that asks for interested residents or families to participate in a pilot project. After continuous revision and improvement of the PCT scheme according to the actual situation in China, the mandatory PCT scheme would be a good one.

- In reality, the CIC level of Chinese urban residents is generally low. That is, most urban residents are the demanders of CIC. The above research shows that the demander is the key trigger of CIC diffusion, and the higher quest for knowledge of the demanders can bring a higher degree of diffusion of CIC. It should be noted that the simulation results show that more egoistic nodes in the network mean a higher efficiency level of CIC diffusion. Thus, the government and related departments should first let residents know that low carbon can have a positive impact on the economy as well as the residents’ emotional and physical health. Various measures should be adopted to inspire residents’ demand for low-carbon knowledge and make them actively learn, exchange, and share low-carbon knowledge through various ways. The following suggestions are proposed for urban residents who need to improve their CIC. They should maintain their social networks system, strengthen their awareness of resource maintenance, and expand their channels for CIC diffusion. They should also enhance their interaction with relatives, friends, and colleagues, get beneficial low carbon knowledge from different groups, and improve their learning efficiency. If the residents cannot initially master the new knowledge, they should actively improve their absorption of the new knowledge through various channels; for example, they should make full use of the existing communication platforms, such as salons, social networks, and BBS, to facilitate their communication with other residents.

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Abbreviations

The following abbreviations are used in this manuscript:

- CIC Carbon identification capability
- PCT Personal carbon trading

References


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