Closeness Centrality Measures in Fuzzy Enterprise Technology Innovation Cooperation Networks

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ABSTRACT
Centrality analysis is one of the most important and commonly used tools in social networks. For social networks where edges are just present or absent and have no more information attached, many centrality measures have been presented, such as degree, closeness, betweenness, eigenvector and Laplacian centrality. There has been a growing need to design centrality measures for fuzzy enterprise technology innovation cooperation networks (FETICNs), because FETICNs where edges are attached with fuzzy technical cooperation relation would contain rich information. In this paper, we propose some new centrality measures called fuzzy logarithm attenuation closeness centrality and fuzzy logarithm attenuation closeness centralization which are applicable to the FETICNs. It unveils more structural information about fuzzy technical cooperation relation, attenuation factor, and connectivity of the FETICNs. Furthermore, we investigate the validness of a new centrality measure by illustrating this method to an experimental study and obtain reliable results, which provide strong evidences to the new measure’s utility.

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Fuzzy enterprise technology innovation cooperation network; logarithm attenuation factor; fuzzy logarithm attenuation closeness centrality; fuzzy logarithm attenuation closeness centralization

1. Introduction
Social network analysis is used widely in the social and behavioral sciences, as well as in economics, marketing, and industrial engineering [1]. The social network analysis is an area of study gaining further importance, with a growing number of publications on social influence, disease spread, information communication, citations, co-authorship, international trade, biology and transportation [2–5].

In social network analysis, the problem of determining the importance of actors in a network has been studied for a long time. Centrality measures serve to quantify that in a network some nodes are more important than others [6]. The most commonly used centrality measures are: degree centrality of a node which is the number of other nodes to which it is directly connected [7]; closeness centrality which is based on the distance between a node and every other node in the network [7,8]; betweenness centrality which measures the importance of a node in the connection of other nodes in the network [7,9].

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In recent decades, centrality analysis is used extensively in social and behavioral sciences, as well as in management science, political science, economics, biology, and so on. Bonacich [10] suggested measuring the centrality of different nodes using the eigenvector associated with the largest characteristic eigenvalue of the adjacent matrix. Furthermore, Bonacich and Lloyd [11] presented a principled way of computing eigenvector-like centrality scores when some dyads are not included in the calculations. Kermarrec et al. [12] proposed a novel form of centrality: the second order centrality which can be computed in a distributed manner. Del Pozo et al. [13] defined a family of centrality measures for directed social networks from a game theoretical point of view. Qi et al. [14] proposed a new centrality measure called Laplacian centrality. Laplacian centrality is an intermediate measuring between global and local characterization of the importance of a node. Brandes et al. [15] discussed the duality of closeness and betweenness centrality. It unveils that closeness-as-independence is, in fact, different from closeness-as-efficiency. They proposed a variant notion of distance that maintains the duality of closeness-as-independence with betweenness also on valued relations. Based on three indices, namely, closeness, betweenness, and straightness, in a multiple centrality assessment model, Lin et al. analyzed the location of various retail stores and street centrality in Guangzhou using points of interest and street network data [16]. De Andrade and Rêgo [17] proposed a generalized measure, which they called p-means centrality.

The fuzzy set theory, introduced by Zadeh, is suitable for dealing with the uncertainty and imprecision associated with information concerning various parameters [18,19]. Nair and Sarasamma [20] applied fuzzy set theory to perform social network analysis, defining fuzzy social network as a fuzzy graph with the entities as the nodes or actors and the relations among them as the edges or links. Furthermore, Liao and Hu [21] defined the concept of undirected fuzzy social network and explored some of its basic properties, which provided the theoretical foundation for further study of the undirected fuzzy social network. Nair and Sarasamma [20] suggested centrality measures from social network analysis can be straight away applied to fuzzy social network analysis. Furthermore, Liao et al. [22] extended the notion of centrality to the undirected fuzzy framework, proposed fuzzy degree centrality, fuzzy closeness centrality and fuzzy betweenness centrality. Fan et al. [23,24] discussed structural equivalence and regular equivalence in undirected fuzzy social networks. Liao et al. [25] studied the position and role with the concept of structural equivalence in the fuzzy technology innovation network. Hu et al. [26] proposed some new centrality measures called fuzzy in-degree centrality, fuzzy out-degree centrality, fuzzy in-closeness centrality and fuzzy out-closeness centrality which are applicable to the directed fuzzy social networks.

In the report of the 19th National Congress of the Communist Party of China, General Secretary Xi Jinping emphasizes, ‘Innovation is the primary driving force behind development; it is the strategic underpinning for building a modernized economy.’ After experiencing rapid economic growth and scale expansion relying on the input of resources, capital and labor, the Chinese economy is entering a new normal characterized by speedy change, structural optimization and power transformation. Innovation is becoming a decisive factor in driving and maintaining economic sustainable development [27,28]. Theoretical and practical research shows that the technical cooperation behavior between enterprises is a fuzzy relationship. It directly affects the innovation ability of
enterprises. In this context, we propose fuzzy enterprise technology innovation cooperation network (FETICN), and discuss centrality measures in the FETICN. In the FETICN, the more actors between \( v_i \) and \( v_j \), the technical cooperation behavior will decrease more quickly. How to calculate the fuzzy closeness centrality in FETICN based on attenuation factor? It has not been considered formally in the literature until now, to the best of our knowledge.

The organization of this paper is as follows. Section 2 contains the notation and some preliminary concepts. In Section 3, we propose fuzzy logarithm attenuation intensity, fuzzy logarithm attenuation connected intensity, fuzzy logarithm attenuation closeness centrality, and discuss fuzzy group closeness centralization based on logarithm attenuation factor in the FETICN. In Section 4, we present the data of FETICN (twelve enterprises, nine universities, and one research institute) of Luogang Development Zone, and in Section 5, we present experimental results. Finally, a conclusion appears in Section 6.

2. Preliminaries

In social networks, the relations between actors are reduced to ‘1’ and ‘0’. ‘1’ indicates the presence of linkage between actors, and ‘0’ indicates the absence of such a linkage. It cannot make the relation between actors clear. Hence, how to describe the relation between actors has come into greater prominence. Liao and Hu [21] defined fuzzy social network as follows.

**Definition 2.1:** A fuzzy social network is defined as a fuzzy relational structure \( \tilde{G} = (V, \tilde{E}) \) where \( V = \{v_1, v_2, \ldots, v_n\} \) is a non-empty set of actors or nodes, and \( \tilde{E} = \begin{pmatrix} \tilde{e}_{11} & \cdots & \tilde{e}_{1n} \\ \vdots & \ddots & \vdots \\ \tilde{e}_{n1} & \cdots & \tilde{e}_{nn} \end{pmatrix} \) is a fuzzy relation on \( V \).

According to the fuzzy technical cooperation behavior between enterprises, universities, research institutes etc., we define FETICN as follows.

**Definition 2.2:** A fuzzy enterprise technology innovation cooperation network is defined as a fuzzy relational structure \( \tilde{G}_t = (V, \tilde{E}_t) \) where \( V = \{v_1, v_2, \ldots, v_n\} \) is a non-empty set of enterprises, universities, research institutes etc., and \( \tilde{E}_t \) is a set of technical cooperation behaviors between actors.

In definition 2.2, a FETICN is a set of nodes representing enterprises, university, research institute etc., that are connected by links showing fuzzy technical cooperation relations between them.

We now discuss how several of the concepts for social networks are applied to the FETICNs. We will focus on the most important concepts of them including the fuzzy intensity, fuzzy connected intensity and fuzzy connected intensity matrix.

**Definition 2.3:** Assume that \( \tilde{\omega} = v_0 e_1 v_1 e_2 v_2 \ldots, e_k v_k \) is a fuzzy path between \( v_0 \) and \( v_k \) in \( \tilde{G}_t \), then \( \tilde{z}(\tilde{\omega}) = \bigwedge_{i=1}^{k} \mu(e_i) \) is called fuzzy intensity of the path \( \tilde{\omega} \).
Here, $\mu(e_i)$ is a membership function.

**Definition 2.4:** If there are $n$ fuzzy path $\tilde{\omega}_k$ connecting $u$ and $v$ in $\tilde{G}_t$, then $\tilde{s}(u, v) = \bigvee_{k=1}^{n} \tilde{s}(\tilde{\omega}_k)$ is called fuzzy connected intensity between $u$ and $v$.

Here, $\tilde{s}(u, v) = \tilde{s}(v, u), k = 1, 2, \ldots, n$. If there is no fuzzy path between $u$ and $v$, then $\tilde{s}(u, v) = 0$. If $u = v$, then $\tilde{s}(u, v) = 1$.

Further, we can define fuzzy connected intensity matrix $\tilde{R}$ in $\tilde{G}_t$ as follows:

$$
\tilde{R} = \begin{pmatrix}
\tilde{s}_{11} & \cdots & \tilde{s}_{1n} \\
\vdots & \ddots & \vdots \\
\tilde{s}_{n1} & \cdots & \tilde{s}_{nn}
\end{pmatrix}
$$

where, $\tilde{s}_{ij} = \tilde{s}(v_i, v_j) = \tilde{s}(v_j, v_i), (i, j = 1, \ldots, n)$. From fuzzy connected intensity matrix $\tilde{R}$ for $\tilde{G}_t$, we can know the relation between any of the two actors in FETICN.

However, in a specific FETICN, the fuzzy intensity and fuzzy connected intensity between $v_i$ and $v_j$ are related to the total actor numbers between $v_i$ and $v_j$. The more actors between $v_i$ and $v_j$, the fuzzy intensity and fuzzy connected intensity will decrease more quickly. So, we further discuss fuzzy intensity, fuzzy connected intensity, fuzzy connected intensity matrix, fuzzy closeness centrality and fuzzy group closeness centralization based on logarithm attenuation factor in Section 3.

### 3. The Fuzzy Logarithm Attenuation Closeness Centrality Analysis in Fuzzy Enterprise Technology Innovation Cooperation Network

Fuzzy centrality analysis is one of the most important and commonly used tools in the analysis of FETICN. This is a measurement concept which reflects the different positions and advantages between different actors in the FETICN. Generally, based on the local difference and global difference, centrality is classified into local fuzzy centrality and global fuzzy centrality respectively. The former is also known as fuzzy degree centrality and reflects a person’s dominant position in the FETICN. The greater the centrality, that is, more associated with more enterprises, universities, or research institutes, the more they are in the central position. The latter refers to the fuzzy relation between a given actor and the remaining in the whole FETICN. This reflects the closeness between actors, which is measured by the relation between different actors. Fuzzy centralization refers to the overall closeness, rather than the relative importance of certain actors.

**Definition 3.1:** Fuzzy closeness centrality is the sum of fuzzy connected intensity from actor $v_i$ to other $n-1$ actors,

$$
\tilde{C}_C(v_i) = \sum_{j=1}^{n} \tilde{s}(v_i, v_j)
$$

where $\tilde{s}(v_i, v_j)$ is the fuzzy connected intensity between $v_i$ and $v_j$ in $\tilde{G}_t$.

Katz and Powell [29] proposed an ‘attenuation parameter’ $\alpha$ to adjust for the lower ‘effectiveness’ of longer paths in a network. Unfortunately, the parameter $\alpha$ is unknown, and
must be estimated for a given sociomatrix. Hu et al. [30] suggested an ‘inversely attenuation factor’ \( \alpha = 1/k \) to adjust for the attenuation phenomenon of longer paths in a fuzzy social network. However, the inverse attenuation factor decreases too fast. In this paper, we propose logarithm attenuation factor \( \frac{1}{\lg(k+2)/\lg 2} \), to define fuzzy logarithm attenuation intensity, fuzzy logarithm attenuation connected intensity, and fuzzy logarithm attenuation closeness centrality in the FETICN.

**Definition 3.2:** Assume that \( \tilde{\omega} = v_0e_1v_1e_2v_2 \ldots e_kv_k \) is a fuzzy path between \( v_0 \) and \( v_k \) in \( \tilde{G}_t \),

\[
\tilde{s}^f(\omega) = \frac{1}{\lg(k+2)/\lg 2} \left[ \bigwedge_{i=1}^{k} \mu(e_i) \right]
\]

then \( \tilde{s}^f(\omega) \) is called fuzzy logarithm attenuation intensity of path \( \tilde{\omega} \).

In definition 3.2, \( \frac{1}{\lg(k+2)/\lg 2} \) is called logarithm attenuation factor in path \( \omega \).

**Definition 3.3:** If there are \( n \) paths \( \tilde{\omega}_k (k = 1, 2, \ldots, n) \) connecting \( u \) and \( v \), \( k_j + 1 \) actors on \( \tilde{\omega}_k \),

\[
\tilde{s}^l(u, v) = \bigvee_{j=1}^{n} \tilde{s}^f(\tilde{\omega}_k)
\]

then \( \tilde{s}^l(u, v) \) is called fuzzy logarithm attenuation connected intensity between \( u \) and \( v \) in fuzzy enterprise technology innovation cooperation network \( \tilde{G}_t \).

Here, \( \frac{1}{\lg(k_j+2)/\lg 2} \) is called logarithm attenuation factor in path \( \omega_j \).

Further, we can define fuzzy logarithm attenuation connected intensity matrix \( \tilde{R}^l \) in \( \tilde{G}_t \) as follows:

\[
\tilde{R}^l = \begin{pmatrix}
\tilde{s}^E_{11} & \cdots & \tilde{s}^E_{1n} \\
\vdots & \ddots & \vdots \\
\tilde{s}^E_{n1} & \cdots & \tilde{s}^E_{nn}
\end{pmatrix},
\]

where \( \tilde{s}^l_{ij} = \tilde{s}^f(v_i, v_j) = \tilde{s}^l(v_j, v_i) \), \( (i, j = 1, \ldots, n) \). From fuzzy logarithm attenuation connected intensity matrix \( \tilde{R}^l \) for \( \tilde{G}_t \), we can know the relation between any of the two actors in fuzzy enterprise technology innovation cooperation network.

**Definition 3.4:** Fuzzy logarithm attenuation closeness centrality is the sum of fuzzy logarithm attenuation connected intensity from \( v_i \) to other \( n - 1 \) actors,

\[
\tilde{C}^l_c(v_i) = \sum_{j=1}^{n} \tilde{s}^l(v_i, v_j)
\]

where \( \tilde{s}^l(v_i, v_j) \) is the logarithm attenuation connected intensity between \( v_i \) and \( v_j \) in \( \tilde{G}_t \).
\( \tilde{C}_c^L(v_i) \) grows with decreasing relation between \( v_i \) and other actors. Nevertheless, it is a simple measure and, since it is a sum relation based on logarithm attenuation factor, \( \tilde{C}_c^L(v_i) \) has a natural interpretation. It is, of course, only meaningful for a connected FETICN.

This measure is dependent upon the number of actors in the FETICN from which is calculated. We cannot, therefore, compare values of \( \tilde{C}_c^L(v_i) \) for actors drawn from FETICNs of different sizes. So it would be useful to have a measure from which the impact of FETICN size was removed.

In this paper, the relative fuzzy closeness centrality based on logarithm attenuation factor of \( v_i \) is defined as:

\[
\tilde{C}_c^L(v_i) = \frac{\sum_{j=1}^{n} \tilde{s}^L(v_i, v_j)}{n - 1} \tag{7}
\]

The measures \( \tilde{C}_c^L(v_i) \) and \( \tilde{C}_c^L(v_i) \) are both closeness-based indexes of actor centrality in \( \tilde{G}_t \). Either may be used when measures based upon independence or efficiency is desired.

From an alternative view, the centrality of an entire FETICN should index the tendency of a single actor to be more central than all the other actors in the FETICN. Measures of this type are based on differences between the centrality of the most central actor and that of all others. Thus, they are indexes of the fuzzy group closeness centralization based on logarithm attenuation factor of the FETICN. The measure of fuzzy logarithm attenuation group closeness centralization is

\[
\tilde{C}_c^L = \frac{\sum_{i=1}^{n} (\tilde{C}_c^L(v^*) - \tilde{C}_c^L(v_i))}{\max \sum_{i=1}^{n} (\tilde{C}_c^L(v^*) - \tilde{C}_c^L(v_i))} \tag{8}
\]

where, \( \tilde{C}_c^L(v^*) \) = the largest value of \( \tilde{C}_c^L(v_i) \) for any actor in the FETICN, \( \max \sum_{i=1}^{n} (\tilde{C}_c^L(v^*) - \tilde{C}_c^L(v_i)) \) = the maximum possible sum of differences in relative fuzzy closeness centrality based on logarithm attenuation factor for a FETICN of n actors.

4. Data

In this study, we obtain technical cooperation behavior between enterprises through questionnaire survey. Take the high-tech enterprises involving the pharmaceutical, chemical, electronics, materials and other industries in Luogang Development Zone, Guangzhou, Guangdong Province as respondents, 40 copies of questionnaires were sent, and all of them were taken back. Among them, 24 were valid and 16 were deemed invalid for they were incompletely filled in, so the effective response rate was 60%.

The sample is comprised of twelve enterprises, nine universities, and one research institute. Firstly, we present the actors of the FETICN of Luogang Development Zone (see Table 1).

In fact, if the sample size is too large, it becomes a difficult task to distinguish the network structure. On the other hand, if the sample size is too small, the network provides only a little information to explore. In addition, the size of the data set (24 actors) is suitable for analysis. It is not appropriate if the size is either too large or too small.
Table 1. Actors of FETICN of Luogang development zone.

| Code name | Actors                                      | Code name         | Actors                                      |
|-----------|--------------------------------------------|-------------------|--------------------------------------------|
| X1        | Guangzhou Food Industry Research Institute | X13               | Guangzhou Anlang Communication Technology Co., Ltd |
| X2        | Ji’nan University                         | X14               | Guangzhou Tongtian Communication Technology Co., Ltd |
| X3        | Guangdong Pharmaceutical University        | X15               | Guangzhou Kinth Information Technology Service Co., Ltd |
| X4        | GRG Banking                                | X16               | Guangzhou Baiyun Lantian Electronic Technology Co., Ltd |
| X5        | Tsinghua University                       | X17               | Guangzhou Zhiyou Patent & Trademark Agency Co., Ltd |
| X6        | Harbin Institute of Technology             | X18               | Unikbio Biotch (Guangzhou) Ltd             |
| X7        | SUN YAT-SEN University                     | X19               | Zhijiang Beer Group Co., Ltd               |
| X8        | South China University of Technology       | X20               | Fujian Agriculture and Forestry University |
| X9        | Guangzhou Gaolan Energy Conservation Tech Co., Ltd | X21           | Shandong Wonderful Industrial Group Co., Ltd |
| X10       | Wuhan University                           | X22               | Nanfang Lee Kum Kee Co., Ltd               |
| X11       | Guangdong University of Technology         | X23               | Guangzhou Bai Sheng Fitness Facilities Development Co., Ltd |
| X12       | Guangdong E.Trust Information Co., Ltd     | X24               | Guangzhou Leafun Technology for Art Co., Ltd |

Table 2. Fuzzy adjacency matrix of FETICN of Luogang Development Zone.

|   | X1 | X2 | X3 | X4 | X5 |    | X20 | X21 | X22 | X23 | X24 |
|---|----|----|----|----|----|----|-----|-----|-----|-----|-----|
| X1| 1  | 1  | 1  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   |
| X2| 1  | 1  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   |
| X3| 1  | 0  | 1  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   |
| X4| 0  | 0  | 0  | 1  | 0.6| 0  | 0   | 0   | 0   | 0   | 0   |
| X5| 0  | 0  | 0  | 0.6| 1  | 0  | 0   | 0   | 0   | 0   | 0   |
| X6| 0  | 0  | 0  | 0  | 0.6| 0  | 0   | 0   | 0   | 0   | 0   |
| X7| 0  | 0  | 0  | 0  | 0.6| 0  | 0   | 0   | 0   | 0   | 0   |
| X8| 0  | 0  | 0  | 0  | 0.6| 0  | 0   | 0   | 0   | 0   | 0   |
| X9| 0  | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   |
| X10|0  | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   |
| X11|0  | 0  | 0  | 0  | 0.8| 0.8| 0.8 | 0   | 0   | 0   | 0   |
| X12|0  | 0  | 0  | 0  | 0  | 1  | 0   | 0   | 0   | 0   | 0   |
| X13|0  | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 1   | 0   |
| X14|0  | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 1   |
| X15|0  | 0  | 0  | 0  | 0  | 0  | 0   | 0   | 0   | 0   | 0   |

We convert a fuzzy relation data of twelve enterprises, nine universities, and one research institute into fuzzy adjacency matrix (see Table 2), and conduct fuzzy closeness centrality analysis in Section 5.

5. Experimental Results

We used NetDraw in UCINET to draw the FETICN of Luogang Development Zone. Figure 1 depicts a fuzzy enterprise technology innovation network of 24 actors.

Figure 1 shows that among the FETICN in Luogang Development Zone, there is one main subnetwork including 16 actors, two secondary subnetworks including six actors (subnetwork 1: X1, X2, X3; subnetwork 2: X12, X13, X14), and two isolated actors (X23, X24).
The two isolated actors are the enterprises with independent research and development, which have no technical cooperation with others, for which the development zone provides only physical space, while it doesn't provide any support in technical cooperation to other enterprises.

Fuzzy degree centrality reflects the influence degree of actors just from the local actors, i.e. the influence that one actor and others relate directly, therefore, fuzzy closeness centrality must be calculated. Fuzzy closeness centrality not only takes into account the direct fuzzy relation but also an indirect fuzzy relation between actors. However, it does not take the attenuation factor into account. Fuzzy logarithm attenuation closeness centrality not only takes into account the direct fuzzy relation and the indirect fuzzy relation, but also the attenuation factor between actors. Scores of 24 actors of FETICN of Luogang Development Zone based on fuzzy degree centrality, fuzzy closeness centrality and fuzzy logarithm attenuation closeness centrality of each actor are calculated in Table 3.

The scores based on all centrality methods are listed in Table 3. The top two individuals are indicated in bold. As we can see, based on fuzzy logarithm attenuation closeness centrality, Unikbio Biotch (Guangzhou) Ltd. and South China University of Technology (X18 and X8) get the two highest scores as we expect. Furthermore, we also present detailed ranking information of these 16 actors (belong to main subnetwork) based on three centrality measures in Figure 2, where the X-axis represents these 16 actors, and Y-axis corresponds to their scores. We find that the ten actors (X5, X8, X9, X10, X11, X18, X19, X20, X21, X22) get the same highest scores based on fuzzy closeness centrality method and we can’t distinguish which one is the most important. We also find that Unikbio Biotch (Guangzhou) Ltd. (X18) gets the highest scores and South China University of Technology (X8) gets higher scores ranking No. 3, No. 1 and No. 2 based on fuzzy degree centrality, fuzzy closeness centrality

Figure 1. FETICN of Luogang Development Zone.
### Table 3. Scores of 24 actors of FETICN of Luogang Development Zone based on various centrality methods

| Actors | Fuzzy degree centrality | Fuzzy closeness centrality | Fuzzy logarithm attenuation closeness centrality |
|--------|-------------------------|----------------------------|-----------------------------------------------|
| X1     | 2.00                    | –                          | –                                             |
| X2     | 1.00                    | –                          | –                                             |
| X3     | 1.00                    | –                          | –                                             |
| X4     | 2.40                    | 9.00                       | 6.02                                          |
| X5     | 1.40                    | 10.80                      | 6.92                                          |
| X6     | 0.60                    | 9.00                       | 4.76                                          |
| X7     | 1.40                    | 9.00                       | 4.92                                          |
| X8     | 2.80                    | 10.80                      | 7.50                                          |
| X9     | **3.20**                | **10.80**                  | 7.15                                          |
| X10    | 0.80                    | 10.80                      | 5.63                                          |
| X11    | 0.80                    | 10.80                      | 5.63                                          |
| X12    | 1.60                    | –                          | –                                             |
| X13    | 1.00                    | –                          | –                                             |
| X14    | 0.60                    | –                          | –                                             |
| X15    | 0.80                    | 9.00                       | 3.00                                          |
| X16    | 1.4000                  | 9.20                       | 4.84                                          |
| X17    | 0.80                    | 9.20                       | 4.27                                          |
| X18    | **4.00**                | **10.80**                  | 7.60                                          |
| X19    | 0.80                    | 10.80                      | 5.71                                          |
| X20    | 0.80                    | 10.80                      | 5.71                                          |
| X21    | 0.80                    | 10.80                      | 5.71                                          |
| X22    | 0.80                    | **10.80**                  | 5.71                                          |
| X23    | 0.00                    | –                          | –                                             |
| X24    | 0.00                    | –                          | –                                             |

**Figure 2.** Scatter diagram marked with straight lines and data based on all centrality methods for UFETICN of the Luogang Development Zone.

and fuzzy logarithm attenuation closeness centrality method respectively. Both X18 and X8 get higher scores because of their relatively neutral position in FETICN of Luogang Development Zone, and they have many fuzzy relations with other members.

### 6. Conclusions

In this paper, we extend the centraity and centralization theory to the FETICN, and some of its basic properties are explored.
Firstly, we define the concept of fuzzy logarithm attenuation intensity, fuzzy logarithm attenuation connected intensity and fuzzy logarithm attenuation connected intensity matrix in the FETICN. According to the fuzzy logarithm attenuation connected intensity matrix, we can get the fuzzy relation between any of the two actors of the FETICN.

Secondly, we propose new centrality measures: fuzzy logarithm attenuation closeness centrality and fuzzy logarithm attenuation group closeness centralization in this paper, which are applicable to the FETICN, but we have no intention to compete with other existing methods, since for any particular research project we should have to identify which centrality measure is the most meaningful or useful.

Thirdly, fuzzy logarithm attenuation closeness centrality not only takes into account the direct fuzzy relation and indirect fuzzy relation but also the attenuation factor between actors. We apply this measure to the FETICN of Luogang Development Zone. By comparison, we find that based on fuzzy closeness centrality method we get the same top ten actors, and we can’t distinguish which is the most important. We also find that based on fuzzy logarithm attenuation closeness centrality, Unikbio Biotch (Guangzhou) Ltd. and South China University of Technology get the two highest scores, because of their relatively neutral position with three groups, it has many fuzzy relations with other members. This is a more effective method to find out which are the most important actors in the FETICN.

Fuzzy logarithm attenuation closeness centrality analysis is one of the most important and commonly used tools in the FETICN. This is a measurement concept concerning an actor’s central position in the FETICN and it reflects the different positions and advantages between actors. This study gives further supplement to the centrality theory and provides the theoretical foundation for further study of the FETICN.

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**References**

[1] Wasserman S, Faust K. Social network analysis: methods and applications. Vol. 8. Cambridge: Cambridge University Press; 1994.

[2] Girvan M, Newman ME. Community structure in social and biological networks. Proc Natl Acad Sci U S A. 2002;99(12):7821–7826.

[3] Ortizpelaez A, Pfeiffer DU, Soaresmagalhães RJ, et al. Use of social network analysis to characterize the pattern of animal movements in the initial phases of the 2001 foot and mouth disease (FMD) epidemic in the UK. Prev Vet Med. 2006;76(1):40–55.

[4] Maireder A, Weeks BE, Gil de Zúñiga H, et al. Big data and political social networks: introducing audience diversity and communication connector bridging measures in social network theory. Soc Sci Comput Rev. 2017;35(1):126–141.

[5] Peng S, Yu S, Mueller P. Social networking big data: Opportunities, solutions, and challenges. Future Gener Comput Syst. 2018;86:1456–1458.

[6] Crucitti P, Latora V, Porta S. Centrality measures in spatial networks of urban streets. Phys Rev E. 2006;73(3):036125.

[7] Freeman LC. Centrality in social networks conceptual clarification. Soc Networks. 1978;1(3):215–239.

[8] Scott J, Carrington PJ. The SAGE handbook of social network analysis. Thousand Oaks: SAGE Publications; 2011.

[9] Freeman LC. A set of measures of centrality based on betweenness. Sociometry. 1977;40:35–41.

[10] Bonacich P. Power and centrality: a family of measures. AJS. 1987;92(5):1170–1182.

[11] Bonacich P, Lloyd P. Eigenvector centrality and structural zeroes and ones: when is a neighbor not a neighbor? Soc Networks. 2015;43:86–90.

[12] Kermarrec AM, Le Merrer E, Sericola B, et al. Second order centrality: distributed assessment of nodes criticility in complex networks. Comput Commun. 2011;34(5):619–628.
[13] Del Pozo M, Manuel C, González-Arangüena E, et al. Centrality in directed social networks. A game theoretic approach. Soc Networks. 2011;33(3):191-200.

[14] Qi X, Fuller E, Wu Q, et al. Laplacian centrality: a new centrality measure for weighted networks. Inf Sci (Ny). 2012;194(1):240-253.

[15] Brandes U, Borgatti SP, Freeman LC. Maintaining the duality of closeness and betweenness centrality. Soc Networks. 2016;44:153-159.

[16] Lin G, Chen X, Liang Y. The location of retail stores and street centrality in Guangzhou, China. Appl Geogr. 2018;100:12-20.

[17] De Andrade RL, Rêgo LC. p-Means centrality. Commun Nonlinear Sci Numer Simul. 2019;68:41-55.

[18] Zadeh LA. Fuzzy sets. Inf Control. 1965;8(3):338-353.

[19] Zadeh, L. A. (1976). A fuzzy-algorithmic approach to the definition of complex or imprecise concepts. Int J Man Mach Stud, 8(3), 249-291.

[20] Nair PS, Sarasamma ST. Data mining through fuzzy social network analysis. In NAFIPS 2007 Annual Meeting of the North American Fuzzy Information Processing Society, IEEE, 2007. p. 251-255.

[21] Liao LP, Hu RJ. On the definition and property analysis of fuzzy social network based on fuzzy graph. J. Guangdong Univ Technol (Soc Sci Ed). 2012;12(3):46-51.

[22] Liao LP, Hu RJ, Zhang GY. The centrality analysis of fuzzy social networks. Fuzzy Syst Math. 2012;27(2):169-173.

[23] Fan TF, Liau CJ, Lin TY. Positional analysis in fuzzy social networks. In 2007 IEEE International Conference on Granular Computing (GRC 2007). IEEE, 2007. p. 423-423.

[24] Fan TF, Liau CJ, Lin TY. A theoretical investigation of regular equivalences for fuzzy graphs. Int J Approx Reason. 2008;49(3):678-688.

[25] Liao LP, Hu RJ, Zhang GY. The position analysis of the fuzzy technology innovation network. J High Technol Manag Res. 2012b;23(2):83-89.

[26] Hu RJ, Li Q, Zhang GY, et al. Centrality measures in directed fuzzy social networks. Fuzzy Inf Eng. 2015;7(1):115-128.

[27] Mu RP, Fang YG, Wen H. Innovation development: way to build China a major S&T power. Bull Chin Acad Sci. 2017;5:512-520.

[28] Xue L, Weng LF. The policy opportunities and challenges in China’s implementation of 2030 sustainable development goals. China Soft Sci. 2017;1:1-12.

[29] Katz L, Powell JH. A proposed index of the conformity of one sociometric measurement to another. Psychometrika. 1953;18(3):249-256.

[30] Hu RJ, Zhang GY, Liao LP. The closeness centrality analysis of fuzzy social network based on inversely attenuation factor. In: Cao Bing-Yuan, Nasseri Hadi editors. Fuzzy information & engineering and operations research & management. Berlin, Heidelberg: Springer; 2014. p. 457-465.