Fuzzy Min-Max Neural Network With Fuzzy Lattice Inclusion Measure for Agricultural Circular Economy Region Division in Heilongjiang Province in China

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ABSTRACT Applying circular economy into agriculture is one of the most efficient methods to implement agricultural sustainable development. Designing different circular economy modes according to local characteristics of various regions can be more efficient. This paper focuses on agricultural circular economy region division in Heilongjiang province in China. First, the specific index system has been constructed. Then, according to these indexes to divide the regions via a novel but more efficient clustering method called Improved Fuzzy min-max neural network with fuzzy lattice inclusion measure (FL-IFMM) proposed in this paper. Heilongjiang province was divided into four agricultural circular economy regions which are respectively Farming(based on grain crops)-animal husbandry dominant region, Farming(based on rice) - animal husbandry dominant region, Vegetable and edible fungi - melons and fruits - animal husbandry dominant region, and Farming - Forestry - Animal husbandry dominant region. Finally, the circular economy modes fitting each region and some detailed policy suggestions have been proposed to help promote agricultural sustainable development in Heilongjiang province.

INDEX TERMS Agricultural circular economy, clustering, fuzzy min-max neural network, fuzzy lattice inclusion measure, region division.

I. INTRODUCTION
The agriculture in China, as a big agricultural country, plays the most vital role in national economy [1]. With the rapid development of modern industrialization [2], the economic profit is increasing. But more and more pressures have been put on the environment, which caused agricultural environmental pollution. Therefore, implementing agricultural sustainable development, which aims to balance the environmental problems and economic development [3], has been attached importance to in international and national agendas [4], [5]. Heilongjiang province, as an important agricultural province in China [6], also suffers from serious environmental problems [7]. In order to implement agricultural sustainable development in Heilongjiang Province, circular economy, as a sustainable development strategy, was introduced to alleviate the tension relationship between environmental problems and economic development [8]. Core idea of circular economy proposed by Pearce and Turner in 1990 [9] is the cycle of waste and resource [10], which specifically refers to the principles of reduce, reuse, and recycle [8]. However, since there have different agricultural resources and technologies in different region, different agriculture circular economy strategies should be carried out in different regions, which facilitates more efficient implementation of whole agriculture circular economy [11]. In order to effectively carry out different agriculture circular economy strategies in different regions, the first key is region division of agriculture circular economy in Heilongjiang Province. Therefore, this paper focuses on region division of agriculture circular economy in Heilongjiang Province by effective methods.
Region division of agricultural circular economy is generally formulated as clustering problem and most researchers used Hierarchical Clustering. For example, Hu has used Hierarchical Clustering to implement region division of agricultural circular economy in Heilongjiang province which will be compared to results in this paper in later section [12]. Yang focused on region division of agricultural circular economy in Ningxia province in China [13], Zhang focused on region division of agricultural circular economy in Guangxi province in China and so on [14]–[18]. However, Hierarchical Clustering needs to search the total data repeatedly to find the most similar patterns, and then merge them, which may increase the number of scans through the pattern set and the requirement of memory. When the dataset to be clustered is large, the two problems above may have more serious influence on the performance of clustering and should be taken into account [19]. A clustering method called Improved Fuzzy min-max neural network with fuzzy lattice inclusion measure (FL-IFMM) is proposed in this paper. The proposed method using dynamic online learning only needs single pass through the data set which can effectively avoid the two aforementioned problems [20]–[22]. It is an improvement of fuzzy min-max neural network, combined with the definition of inclusion measure in fuzzy lattice framework, which has both the dynamic online learning ability from fuzzy min-max neural network and the better ability to measure similarity between patterns from inclusion measure. This paper aims to use this novel method to effectively deal with agricultural circular economy region division problem in Heilongjiang province.

The remaining paper is structured as follows. Section 2.1 illustrates data acquisition and preprocessing. Section 2.2 describes the specific theory of FL-IFMM clustering model. Section 3.1 will discuss clustering results achieved by FL-IFMM clustering model in detail. According to the discussion in section 3.1, the proper developing mode for each region has been selected and analyzed in Section 3.2. Section 4 gives some policy suggestions. Finally, Section 5 will give conclusion of this paper.

II. MATERIALS AND METHODS

A. REGIONALIZATION INDEX AND DATA ACQUISITION

Heilongjiang province has thirteen administrative regions, including Harbin, Qiqihar, Jixi, Hegang, Shuangyashan, Daqing, Yichun, Jiamusi, Qitaize, Mudanjiang, Heihe, Suihua, Daxinganling. The aim of this paper is to use the data of the regionalization index system introduced in this section, which can reflect the developing situation of these cities to divide them into several agricultural circular economy regions which have great similarity within them and great difference between them. Thus, the mode which is the most suitable for each region can be found.

1) REGIONALIZATION INDEX

It is necessary to determine regionalization index reasonably. In order to achieve reliable region division results, the regionalization indexes must reflect the actual development situation of agricultural circular economy. Several essential aspects which should be covered are as follows: the first are the Resource dosage indexes, which can reflect the utilized resources situation intuitively closely related to the implementation of circular economy; the second are the Economic and Social development indexes, because economy is the basis of development and they can reflect the economic and social profit produced by developing agricultural circular economy; the third are the Area indexes, because land is the basic condition of agricultural production; the fourth are the Population and Labor indexes, because the development of agricultural circular economy relies on population and labor, which can reflect the pressure and support on agricultural development.

Considering the aforementioned four aspects and the real situation of Heilongjiang province, sixteen specific indexes are chosen in this paper to implement region division. The specific index system of agricultural circular economy region division is shown as Table 1.

2) DATA ACQUISITION AND PREPROCESSING

The index system was padded by the data collected from 2018 Heilongjiang Statistical Yearbook. The data was shown in Table 2 completely. Due to the difference among the dimensions of these indexes, data has been normalized according to the following equation before clustering them.

\[
x_{ij} = \frac{x_{ij} - x_{i_{min}}}{x_{i_{max}} - x_{i_{min}}}, \quad X_i = [x_{i1}, x_{i2}, \ldots, x_{in}] \tag{1}
\]

where the \(x_{ij}\) is the normalized value of the \(i_{th}\) variable of \(i_{th}\) index vector, \(x_{ij}\) is the original value of the \(j_{th}\) variable of \(i_{th}\) index vector, \(X_i\) is the \(i_{th}\) index vector, \(n\) is the number of variables of each index vector, \(x_{i_{max}}\) is the maximum value of the \(i_{th}\) index vector and \(x_{i_{min}}\) is the minimum value of the \(i_{th}\) index vector. Thus all the data has been normalized into \([0, 1]\).

B. MODEL METHODS

1) FUZZY LATTICE INCLUSION MEASURE

Inclusion measure has been proved to be an efficient tool for similarity measure as well [23], [24]. Inclusion measure is a specific definition in fuzzy lattice theory. Fuzzy lattice theory is an extension of lattice theory, which is defined by introducing the concept of inclusion measure. In recent years, there are more and more researches about neural computational model based on the lattice theory, because mathematical lattice can cope with disparate data [25].

A lattice is a partly order set any two of whose elements have a greater lower bound (g.l.b.), denoted by \(x \wedge y\), and a least upper bound (l.u.b.), denoted by \(x \lor y\). A lattice \(L\) is complete when each of its subsets \(X\) has a l.u.b. and a g.l.b. in \(L\). Note that the inclusion measure is based on the complete lattice [25].
Definition 1: Let $L$ be a lattice, $S = \{(x, y) : x, y \in L\}$ is the universe of discourse. $\mu_p : S \rightarrow [0, 1]$ is a fuzzy membership function, $(L, \mu_p(x, y))$ is a fuzzy lattice if and only if $x \leq y \Rightarrow \mu_p(x, y) = 1$, where $\mu_p(x, y)$ can be considered as a degree of inclusion of $x$ in $y$.

Definition 2: Let $(L, \leq)$ be a complete lattice, where the $O$ and $I$ denote the minimum and maximum element respectively. An inclusion measure $\sigma$ in $L$ is a map: $\sigma(x, y) : S = \{(x, y) : x, y \in L\} \rightarrow [0, 1]$, such that for $u, w, x \in L$ the following conditions are satisfied:

$$\sigma(x, O) = 0, \quad x \neq O \quad (2)$$

$$\sigma(x, x) = 1, \quad \forall x \in L \quad (3)$$

$$x \wedge y < x \Rightarrow \sigma(x, y) < 1 \quad (4)$$

$$u \leq w \Rightarrow \sigma(x, u) \leq \sigma(x, w) \quad (5)$$

$\sigma(x, y)$ can also be denoted by $\sigma(x \leq y)$. In order to qualify the definition inclusion measure, a real positive-valued function $h$ is defined:

Definition 3: A positive valuation function $h, h : L \rightarrow R$ on a complete lattice $L$ satisfies the following three properties:

$$h(O) = 0 \quad (6)$$

$$u < w \Rightarrow h(u) < h(w) \quad (7)$$

$$u \leq w \Rightarrow h(x \vee w) - h(x \vee u) \leq h(w) - h(u) \quad (8)$$

The positive valuation function $h$ does not necessarily exist, if it exists, the $\sigma(x, y) = h(y)/h(x \vee y), x, y \in L$ can be an inclusion measure defined by function $h$ on the lattice $L$. On the other hand, $x \leq u \Rightarrow u = x \vee u \Rightarrow \sigma(x \leq u) = h(u)/h(x \vee u) = 1$, so the $(L, \sigma(x \leq u))$ is proved to be a fuzzy lattice according to the Definition 1. In this paper, the function $h$ is defined as $x$ [22]. If $L$ is Cartesian product of $N$ lattices, $L = L_1 \times L_2 \times \ldots \times L_N$, the partial order relationship of $L$ is defined as:

$$(x_1, \ldots, x_N) \leq (y_1, \ldots, y_N) \Leftrightarrow x_1 \leq y_1, \ldots, x_N \leq y_N \quad (9)$$

Function $h$ on $L$ can be defined by function $h_i$ on each constitute lattice:

$$h(x_1, \ldots, x_N) = h(x_1) + \ldots + h(x_N) \quad (10)$$

However, the aforementioned definitions are defined on the conventional lattice, they can not applied in the lattice of intervals. Suppose that $L$ is a totally ordered lattice, the lattice of intervals $V_L = \{[a, b] : a, b \in L\}$ is a lattice as well. The meet and join operations are defined as below:

$$[a, b] \land [c, d] = [a \land c, b \land d] \quad (11)$$

$$[a, b] \lor [c, d] = [a \lor c, b \lor d] \quad (12)$$

The corresponding partial order relationship in $V_L$ is defined as: if $[a, b] \leq [c, d]$, then $a \leq c$ and $b \leq d$. In order to define an inclusion measure on $V_L$, a positive valuation function $h$ should be defined first. Therefore, an isomorphic function $\theta : L^\delta \rightarrow L$, where $L^\delta$ is the dual of $L$, is introduced, in which the partial order relationship is opposite to that in $L$ (i.e. $a \leq b$ in $L \Leftrightarrow b \leq a$ in $L^\delta$) And $\theta$ satisfies the condition that $x \leq y \Leftrightarrow \theta(x) \geq \theta(y)$. In this paper, $\theta = 1 - x$. Meanwhile, a mapping $\phi : [a, b] \in V_L \rightarrow (\theta(a), b) \in L^\delta \times L$ is defined. Thus the positive evaluation function can be defined by:

$$h([a, b]) = h(\theta(a), b) = h(\theta(a)) + h(b), \quad \forall [a, b] \in V_L \quad (13)$$

The meet and join operations in $L^\delta \times L$ are defined as below:

$$(a, b) \land (c, d) = (a \land c, b \land d) \quad (14)$$

$$(a, b) \lor (c, d) = (a \lor c, b \lor d) \quad (15)$$
TABLE 2. Data for index system of agricultural circular economic region division in Heilongjiang Province.

| Specific indicator number | Harbin | Qiqihar | Jixi | Hegang | Shuangyashan | Daqing | Yichang | Jiamusi | Qitaihe | Mudanjiang | Heihe | Suibai | Daxinganling |
|---------------------------|--------|---------|------|--------|--------------|--------|---------|---------|---------|------------|-------|--------|-------------|
| 1                         | 447623 | 305720  | 494  | 02     | 43389        | 67949  | 134123  | 23156   | 233928  | 34465      | 87667 | 13387  | 36788       |
| 2                         | 588    | 375     | 279  | 513    | 383          | 469    | 302     | 475     | 323     | 295        | 505   | 97     |
| 3                         | 112324 | 5341759 | 165  | 955    | 250579       | 1275430.00 | 392127  | 159016  | 3765925 | 463857.00  | 3151142.00 | 27353  | 90991  | 927988.68  |
| 4                         | 665173 | 2866460 | 103  | 078    | 350795       | 878646.00 | 170713  | 888322  | 2373315 | 234492     | 2297605.00 | 20128  | 49701  | 471761.63  |
| 5                         | 302931 | 80458.0 | 756  | 06     | 15378        | 37687  | 66220   | 293500  | 103097  | 397080     | 41756  | 20481  | 77558       |
| 6                         | 375932 | 2266963 | 434  | 30     | 133401       | 336504.00 | 198009  | 36413   | 1205465 | 158635     | 659655.00 | 35891  | 36813  | 118906.40  |
| 7                         | 179402 | 103615. | 659  | 97.0   | 13923.00     | 16433.00 | 147907  | 5887.00 | 74349.00 | 7973.00    | 25010.00 | 26624  | 22537  | 1982.76    |
| 8                         | 15557.0| 13965.0 | 168  | 08.0   | 13967.00     | 13882.00 | 14757.0 | 13725.00 | 14872.00 | 12169.00  | 16896.00  | 14007.00 | 12831.00 | 12098.00   |
| 9                         | 53076.4| 42255.4 | 94.4 | 01     | 14656.00     | 22051.13 | 21204.00 | 32800.20 | 32469.90 | 6190.09   | 38827.19  | 60861.00 | 34873.00 | 64768.44   |
| 10                        | 191579 | 2241627 | 438  | 96.4   | 188283       | 401210.57 | 71259.01 | 21557.4 | 1054845 | 180353.00 | 656102.97 | 11121.00 | 18487    | 155056.67  |
| 11                        | 182300 | 2184861 | 421  | 64     | 186653       | 385554.57 | 651008  | 208652.0 | 1021711 | 160195.00 | 505489.97 | 10763.00 | 17623.00 | 159030.67  |
| 12                        | 542208 | 353131. | 147.0| 68     | 99853.00     | 86742.99  | 116010  | 391839  | 404734.00 | 19615.80  | 401534.99 | 14051.00 | 34804.00 | 14.00       |
| 13                        | 54137.0| 15604.0 | 241  | 73     | 884.00       | 8237.00   | 18718.0 | 2579.00 | 13204.00 | 15201.00  | 31974.00  | 6380.00  | 33419.00 | 1568.00    |
| 14                        | 9777.00| 4873.00 | 757  | 00     | 199.00       | 5366.00   | 8709.0  | 421.00  | 4907.00  | 2102.00   | 5695.00   | 425.00   | 8977.00  | 336.00     |
| 15                        | 954.99 | 533.68  | 175  | 0.05   | 100.95       | 142.29    | 277.80  | 115.93  | 226.21   | 78.60     | 247.78    | 160.51   | 527.56   | 43.93       |
| 16                        | 133182 | 1176492 | 224  | 00     | 8841.00      | 153583.00 | 479988  | 61405.00 | 455388.00 | 108523.00 | 403196.00 | 21889.00 | 14347.00 | 16854.00   |

where $a, b, c, d \in L^\delta \times L$. According to the aforementioned definitions, the relation $[a, b] \leq [c, d] \Rightarrow a \geq c, b \leq d$ can make the relation $(\theta(a), b) \leq (\theta(c), d)$ true and the inclusion measure on $V_L$ can be defined as:

$$
\sigma([a, b] \leq [c, d]) = \frac{h(\theta(a), b)}{h(\theta(a), b) \lor (\theta(c), d)} + \frac{h(b \land d)}{h(\theta(c) \lor \theta(c)) + h(b \lor d)}
$$

(16)

2) IMPROVED FUZZY MIN-MAX NEURAL NETWORK WITH FUZZY LATTICE INCLUSION MEASURE (FL-IFMM)

Fuzzy min-max neural network (FMM) was proposed by P. K. Simpson and combined the neural network with the fuzzy set, which can not only be used to cluster but also to classify [26]. The learning method used by FMM is dynamic online learning, which need not determine the number of clusters in advance like many other models and only need single pass through the dataset. In the fuzzy min-max neural network clustering model, the expansion condition in it will increase the overlapping areas, and overlap test rules cannot recognize all overlapping area. On the other hand, due to the dependence of contraction rules used to eliminate overlapping areas on the overlap test rules, the contraction rules need to be improved as well. To overcome the aforementioned shortcomings, this paper formulated a new expansion condition which can test every dimension separately and alleviate the appearance of overlapping area, and proposed ten new cases to cover more circumstances of overlapping and eliminate them. Simultaneously, using inclusion measure in fuzzy lattice framework to better measure the similarity between the fundamental element called hyperbox in Fuzzy min-max neural network.

The fundamental element hyperbox in FL-IFMM is just fuzzy set. The basic idea of fuzzy set theory is to extend the membership relation in the classical set, so as to generalize the degree of membership to any value between [0, 1]. Thus the fuzziness of object can be depicted quantitatively. The min and max points are utilized to define the hyperbox fuzzy set and the corresponding membership function in FL-IFMM. Note that, each single data point can be considered as a
hyperbox whose min and max points are equal to itself. A hyperbox fuzzy set \( B_j \) can be defined as below:

\[
B_j = \{ A_h, V_j, B_j(A_h, V_j) \} \quad \forall A_h \in I^n
\]

where \( V_j = (V_{j1}, V_{j2}, \ldots, V_{jn}) \) is the minimum point, \( W_j = (W_{j1}, W_{j2}, \ldots, W_{jn}) \) is the maximum point of \( B_j \), \( A_h = (A_{h1}, A_{h2}, \ldots, A_{hn}) \) is the input data sample within the unit hypercube \( I^n \). \( B_j \) is the membership function. In the aspect of membership function, it can be considered as a kind of similarity measure in Fuzzy min-max neural network. In this paper, the inclusion measure in fuzzy lattice framework which can also be considered as another kind of similarity measure was introduced to replace the membership function in original Fuzzy min-max neural network. As illustrated before, the minimum point and the maximum point are utilized to represent the hyperbox in FL-IFMM. They can be transformed into the form of interval in the fuzzy lattice framework easily. For example, a hyperbox with minimum point \( V_j = [0.2, 0.3] \) and maximum point \( W_j = [0.5, 0.8] \) in the two-dimensional space can be denoted in the form of interval as \([0.2, 0.5, 0.3, 0.8]\) in the fuzzy lattice framework. Thus, (16) can be used. However, the inclusion measure was based on complete lattice, once the set of hyperbox fuzzy sets is proved to be a complete lattice, the inclusion measure can be applied in it to measure the similarity. In order to prove the rigorousness and feasibility of the FL-IFMM model proposed in this paper. The related proof is presented as follows.

**Proof:** Hyperbox represents an area in the \( n \)-dimensional mode space. All patterns contained in hyperbox are completely subject to a category.

Set vector \( x = (x_1, x_2, \ldots, x_n), y = (y_1, y_2, \ldots, y_n), z = (z_1, z_2, \ldots, z_n) \) is the three points in space. Definition of partial order relation between them is:

\[
x \leq y = (x_1 \leq y_1) \& (x_2 \leq y_2) \& \cdots \& (x_n \leq y_n)
\]

\[
y \leq z = (y_1 \leq z_1) \& (y_2 \leq z_2) \& \cdots \& (y_n \leq z_n)
\]

\[
x \leq z = (x_1 \leq z_1) \& (x_2 \leq z_2) \& \cdots \& (x_n \leq z_n)
\]

where \( \leq \) represents the relationship between vectors; \( \leq \) represents the relationship between components. If \( x \leq y \), the hyperbox determined by \( x, y \) is represented as \( G(x, y) \), thus \( G(y, z), G(x, z) \) can be defined similarly. If a partial order set satisfies the following four laws, it can also be defined as a lattice.

1. **Idempotent law:** \( x \lor x = x \), \( x \land x = x \)

2. **Commutative law:**

   \[
   \begin{align*}
   x \lor y &= y \quad \Rightarrow \quad x \lor y = y \lor x, \\
   y \lor x &= y \\
   x \land y &= x \\
   y \land x &= x
   \end{align*}
   \]

3. **Combination law:**

   \[
   \begin{align*}
   (x \lor y) \lor z &= y \lor z \Rightarrow (x \lor y) \lor z &= x \lor (y \lor z) \\
   x \lor (y \lor z) &= x \lor z \\
   (x \land y) \land z &= x \land z \Rightarrow (x \land y) \land z &= x \land (y \land z) \\
   x \land (y \land z) &= x \land y = x
   \end{align*}
   \]

4. **Absorption law:**

\[
\begin{align*}
(x \lor y) \land x &= y \land x = x \\
(x \land y) \lor z &= z \lor x = x
\end{align*}
\]

\( G \) satisfies the above four laws, so it can be called as a lattice. Where the operation relationship \( \land \), \( \lor \) is \( x \land y = \text{Inf} \{x, y\}, x \lor y = \text{Sup} \{x, y\} \).

Because \( G(x, y) \) is a hyperbox defined by \( x, y \). And \( G(x, y) \) is a non-empty subset in space. Let \( a \) be a point in and lower bound. In summary, \( G \) is a complete lattice. In other words, the set of hyperbox fuzzy sets were proved to be a complete lattice successfully, which verified the feasibility of this combination as well.

The concrete steps of FL-IFMM learning phase are shown as follows. First is initialization, the hyperboxes will be divided into two sets, one is the set of uncommitted hyperboxes whose min and max points are still not be adjusted, and the other is committed hyperboxes whose min and max points of them have been adjusted. Before training, there has no committed hyperboxes and arbitrary number of uncommitted hyperboxes. Initialize the minimum points, \( V_j = (V_{j1}, V_{j2}, \ldots, V_{jn}) \) and the maximum points \( W_j = (W_{j1}, W_{j2}, \ldots, W_{jn}) \) of uncommitted hyperboxes, set the each element of the minimum points as 1, set the each element of the maximum points as 0. Thus, the first committed hyperbox can be ensured to be equal to the first input point, that is \( V_j = W_j = A_h \), according to the following updated rules of min and max points.

Second is the step of expansion, when fed into new data samples, the FL-IFMM creates new hyperbox and consider it as new cluster or expand the hyperbox of existing clusters according to some rules without retraining. After given a new data sample, check if the existing committed hyperbox which has the max membership degree with it meets the expansion condition below:

\[
\text{Max}_n(W_{ji}, A_{hi}) - \text{Min}_n(V_{ji}, A_{hi})) \leq \eta
\]

where \( \eta \) is a user-defined expansion coefficient, \( 0 \leq \eta \leq 1 \). If the condition is satisfied, the min and max points will be updated as follows:

\[
V_{ji}^{\text{new}} = \min(V_{ji}^{\text{old}}, A_{hi}) \quad \forall i = 1, 2, \ldots, n,
\]

\[
W_{ji}^{\text{new}} = \max(W_{ji}^{\text{old}}, A_{hi}) \quad \forall i = 1, 2, \ldots, n
\]

If find no eligible hyperbox, choose an uncommitted hyperbox and perform the above two operations on it, consider it as new cluster.

Third is the step of overlap test and eliminate overlapping areas. One pattern can have different membership degree with different hyperbox, but it cannot fully belong to more than one hyperbox at the same time. Therefore, the overlapping areas which will lead to this kind of confusion should be tested and eliminated. The overlap test rules and corresponding contraction operations to eliminate overlapping areas are as
follows (Case 1 and Case 2 have already existed in original FMM):

If Case $1V_{ji} < V_{ki} < W_{ji} < W_{ki}$:

$$V_{ki}^{\text{new}} = W_{ki}^{\text{new}} = \frac{V_{ki}^{\text{old}} + W_{ki}^{\text{old}}}{2}$$

If Case $2V_{ki} < V_{ji} < W_{ki} < W_{ji}$:

$$V_{ji}^{\text{new}} = W_{ji}^{\text{new}} = \frac{V_{ji}^{\text{old}} + W_{ji}^{\text{old}}}{2}$$

If Case $3V_{ji} = V_{ki} < W_{ji} < W_{ki}$:

$$V_{ji}^{\text{new}} = W_{ji}^{\text{old}}$$

If Case $4V_{ji} < V_{ki} < W_{ji} = W_{ki}$:

$$W_{ji}^{\text{new}} = V_{ki}^{\text{old}}$$

If Case $5V_{ki} = V_{ji} < W_{ki} < W_{ji}$:

$$V_{ji}^{\text{new}} = W_{ji}^{\text{old}}$$

If Case $6V_{ki} < V_{ji} < W_{ki} = W_{ji}$:

$$W_{ji}^{\text{new}} = V_{ji}^{\text{old}}$$

If Case $7V_{ji} < V_{ki} \leq W_{ki} < W_{ji}$ and $(W_{ki} - V_{ji}) < (W_{ji} - V_{ki})$:

$$V_{ji}^{\text{new}} = W_{ji}^{\text{old}}$$

If Case $8V_{ji} < V_{ki} \leq W_{ki} < W_{ji}$ and $(W_{ki} - V_{ji}) > (W_{ji} - V_{ki})$:

$$W_{ji}^{\text{new}} = V_{ji}^{\text{old}}$$

If Case $9V_{ki} < V_{ji} \leq W_{ji} < W_{ki}$ and $(W_{ki} - V_{ji}) < (W_{ji} - V_{ki})$:

$$W_{ki}^{\text{new}} = V_{ji}^{\text{old}}$$

If Case $10V_{ki} < V_{ji} \leq W_{ji} < W_{ki}$ and $(W_{ki} - V_{ji}) > (W_{ji} - V_{ki})$:

$$V_{ki}^{\text{new}} = W_{ji}^{\text{old}}$$

If Case $11V_{ji} = V_{ki} < W_{ji} = W_{ki}$:

$$W_{ji}^{\text{new}} = V_{ki}^{\text{old}} = \frac{W_{ji}^{\text{old}} + V_{ki}^{\text{old}}}{2}$$

If Case $12V_{ji} = V_{ki} < W_{ki} = W_{ji}$:

$$W_{ki}^{\text{new}} = V_{ji}^{\text{old}} = \frac{W_{ki}^{\text{old}} + V_{ji}^{\text{old}}}{2}$$

Repeat the aforementioned three steps until all training data has been presented over. Thus, arbitrary number of clusters consisted with hyperbox fuzzy sets have been established and the rest data can be clustered by calculating the highest membership degree which the data fits in the existing hyperboxes. The procedure of FL-IFMM is shown in Table 3.

## III. REGION DIVISION RESULTS AND MODE SELECTION

### A. AGRICULTURAL CIRCULAR ECONOMY REGION DIVISION RESULT AND DISCUSSION

After applying the FL-IFMM model whose parameter $\eta$ was set as 0.8 into the data collected as Table 2. Heilongjiang province was divided into four regions of agricultural circular economy. The concrete region division result is shown in Table 4.

Table 5 shows the comparison among the different regions in the aspects of distribution of grain crops, rice, vegetable and edible fungi, melons and fruits, and the developing situation of farming, forestry, animal husbandry, and fishery. Referring related researches [15], [18] and considering actual situation in Heilongjiang Province, the aforementioned eight aspects were selected. The proportion of each crop and industry in each region were used to show the distribution situation.

The proportion of each crop can be calculated as follows:

$$P_{ij} = \frac{S_{ij}}{S_i} \quad (22)$$

where $P_{ij}$ is the proportion of the $j_{th}$ crop in $i_{th}$ region, $S_{ij}$ is the sown area of $j_{th}$ crop in $i_{th}$ region, $S_i$ is the total sown area of $i_{th}$ region.

The proportion of each industry can be calculated as follows:

$$P_{ij} = \frac{O_{ij}}{O_i} \quad (23)$$

where $P_{ij}$ is the proportion of the $j_{th}$ industry in $i_{th}$ region, $O_{ij}$ is the output value of $j_{th}$ industry in $i_{th}$ region, $O_i$ is the total output value of $i_{th}$ region.

The cities in Region 1 are all have higher economic statuses in Heilongjiang province. However, as is indicated in Table 2, the Chemical fertilizer input (the amount of effective components) of these cities are higher. This possibly due to the ignorance of reduction use of resource when developing the economy, to which should be paid more attention in the agricultural circular economy. As is shown in Table 5, the output value of animal husbandry has achieved 34.56% of the total output value in Region 1. According to the 2018 Heilongjiang Statistical Yearbook and taking the number of hogs for sale for example, Harbin occupies 17%, Qiqihar occupies 16%, Suihua occupies 26%, Jiamusi occupies 10% within the whole province, which are the top four cities. The sown area of grain crops has achieved the 96.52% of the total sown area, which indicates that the grain crop is the focus of the agricultural production in this region. Therefore, region 1 should be considered as Farming(based on grain crops)-animal husbandry dominant region.

The cities in Region 2 are famous “coal cities” in Heilongjiang Province. This region is based on resources to a great extent, which needs transformation urgently. Developing agriculture greatly can be considered as an efficient method to adjust the industrial structure which is needed in these cities [27]. The “coal cities” have natural advantages to develop sustainable agriculture. For example, the water
TABLE 3. The procedure of FL-IFMM.

| Training phase: |
|-----------------|
| Consider all training data as uncommitted hyperboxes, initialize them by \( V_{ji} = 1 \) and \( W_{ji} = 0 \). |
| For \( i = 1 \) to \( i = n \), where \( n \) is the number of total training data: |
| **Input** \( A_h \) which is in the set of uncommitted hyperboxes. |
| **If** there is no hyperbox: |
| \( V_j = W_j = A_h \) and consider it as committed hyperbox. |
| **Else** Calculate the inclusion degree of \( A_h \) within the committed hyperboxes according to inclusion measure (16) |
| **If** there exists committed hyperbox which has max inclusion degree and fits the expansion condition \( \max_n (W_{ji}, A_{hi}) - \min_n (V_{ji}, A_{hi}) \leq \eta \): |
| Adjust the hyperbox according to \( V_{ji}^{new} = \min(V_{ji}^{old}, A_{hi}), W_{ji}^{new} = \max(W_{ji}^{old}, A_{hi}) \). |
| **Else** Select a hyperbox from uncommitted hyperboxes and apply \( V_{ji}^{new} = \min(V_{ji}^{old}, A_{hi}) \) |
| **Then** execute the overlapping test rules |
| **If** exists overlapping areas: |
| Execute the contraction operation according to the corresponding rules. |
| **Endif** |
| **Endfor** |

Testing phase

**Input** \( A_h \)

Calculate the inclusion degree of the \( A_h \) within the set of committed hyperboxes.

Consider the cluster which has maximum inclusion degree as the cluster of \( A_h \).

TABLE 4. Agricultural circular economic region division result.

| Region 1 | Region 2 | Region 3 | Region 4 |
|----------|----------|----------|----------|
| Name of city | Harbin, Qiqihar, Xuhua, Jiamusi | Jixi, Hegang, Shuangyashan, Qitaibe | Daqing, Mudanjiang, Yichun, Daxinganling | Heihe, |

resources of subsidence area in this region can be fully utilized to develop rice or other crop types, which can be proved by the result that the sown area of rice occupies 31.41% of this region which is the highest among the four regions. The sown area of grain crops has achieved the 95.89% of the total sown area and the output value of farming has achieved 63.61%. It is obviously that farming is the focus of agricultural development in region 2. Although the proportion of the output of animal husbandry is lower than that in region 1, it is significantly higher than the other industries in the same region. Therefore, region 2 should be considered as the Farming(based on rice)-animal husbandry dominant region.

In Region 3, Daqing has abundant grassland resources and the total area of grassland ranks first in Heilongjiang province. Favorable natural conditions ensure the flourishing development of animal husbandry. As is indicated in Table 5, the proportion of animal husbandry output value 37.32% is
the highest. For example, in terms of number of hogs for sale, Daqing occupies 8%, Mudanjiang occupies 6% within the whole province, which are higher than the other cities except the four cities in region 1, all the other cities together occupy the rest 17%. The Chemical fertilizer input (the amount of effective components) of the two cities are higher than most cities except for cities in region 1. Reduction use of resource should be emphasized. The proportion of sown area of grain crops in this region is 84.36% which is the lowest value compared to the other three regions. Note that, the proportions of sown area of vegetable and edible fungi and melons and fruits in this region are the highest. Therefore, region 3 should be considered as Vegetable and edible fungi - melons and fruits - animal husbandry dominant region.

The cities in Region 4 are the economic core of the Daxinganling and Xiaoxinganling forest region in Heilongjiang province. They all have higher forestry output value. They take forestry as the key industry, however, the sown area of grain crops in this region also achieved 96.65% and the farming output value occupies 64.2% of the total output value, which indicate that farming is also the main industry of this region. In terms of animal husbandry, the proportion of animal husbandry output value shows the minimum as 17.19% when compared to the other three regions, but the animal husbandry industry occupies larger than the other industries in this region. Therefore, region 4 should be considered as Farming - Forestry - Animal husbandry dominant region.

| Region | Grain crops | Rice | Vegetable and edible fungi | Melons and fruits | Farming | Forestry | Animal husbandry | Fishery |
|--------|-------------|------|----------------------------|------------------|---------|----------|-----------------|---------|
| Region 1 | 96.52%      | 24.22% | 1.57%                      | 0.37%            | 58.13%  | 3.54%    | 34.56%          | 1.69%   |
| Region 2 | 95.89%      | 31.41% | 2.22%                      | 0.68%            | 63.61%  | 4.55%    | 27.63%          | 2.66%   |
| Region 3 | 84.36%      | 11.00% | 3.70%                      | 1.05%            | 56.62%  | 1.67%    | 37.32%          | 2.45%   |
| Region 4 | 96.65%      | 3.59%  | 0.71%                      | 0.08%            | 64.20%  | 15.35%   | 17.19%          | 0.66%   |

There also exists other researches about the agricultural circular economy region division in Heilongjiang province. For example, in Hu’s research [8], Heilongjiang province was divided into three regions: region 1 includes Harbin, Qiqihar, Suihua; region 2 includes Daqing, Jiamusi, Mudanjiang, Heihe; region 3 includes Jixi, Hegang, Shuangyashan, Qitaihe, Yichun, Daxinganling. Comparing it with the result of this paper, it can be obviously seen that the result of this paper is more reasonable. Mainly embodies in the following aspects: First, the result of this paper better guaranteed the similarity of natural conditions within each region. For example, in Hu’s research, Jixi, Hegang, Shuangyashan, Qitaihe, Yichun, Daxinganling were clustered together, however, Jixi, Hegang, Shuangyashan, Qitaihe are famous “coal cities”, Yichun, Daxinganling are famous “forest cities”, which are supposed to be divided due to significant differences of natural resources and agricultural conditions among them. On the other hand, Heihe as one of the main cities in Daxinganling and Xiaoxinganling forest region in Heilongjiang province should be clustered together with Yichun and Daxinganling. Second, the result of this paper better guaranteed the similarity of agricultural production structure within each region. For example, in terms of animal husbandry, there is a wide gap between Heihe and the other cities in region 2 in Hu’s research. But it can be seen from the result discussion of this paper that the region division here is more in detail and the cities of each region all have similar agricultural production structure which is more beneficial to the establishment of agricultural circular economy modes. In order to quantitatively analyze the results, the silhouette coefficients of them were calculated as follows:

Silhouette coefficient of $i_{th}$ sample is denoted by:

$$SC(i) = \frac{b(i) - a(i)}{\max \{a(i), b(i)\}}$$  \hspace{1cm} (24)

where $a(i)$ is the average distance of the $i_{th}$ sample to all other sample in the cluster which $i_{th}$ sample belongs to. $b(i)$ is the minimum of vector, which is generated by the average distance of the $i_{th}$ sample to all sample in another each cluster.

The total silhouette coefficient of clusters is denoted by:

$$SC = \frac{1}{K} \sum_{i=1}^{K} SC(i)$$  \hspace{1cm} (25)

The closer the value of the silhouette coefficient (between $[-1, 1]$) is to 1, the better the cohesion and resolution are, and the better the algorithm is. The silhouette coefficient of Hu’s result is 0.187, however, that of the result in this
paper is 0.215 which quantitatively proves the superiority of FL-IFMM and reasonability of the result.

B. SELECTION AND ANALYSIS OF AGRICULTURAL CIRCULAR ECONOMY MODES IN EACH REGION

In the above paragraphs, the emphasis of developing direction of each region has been proposed according to the realistic local situation. Selection and analysis of mode which fits each region will be discussed in detail in this section.

1) REGION 1: FARMING(BASED ON GRAIN CROPS)-ANIMAL HUSBANDRY DOMINANT REGION

Recycling use mode of agricultural by-products which considers biogas as link is selected for region 1. Farming has close relationship with animal-husbandry which mainly embodies in that farming provides feed and straw for animal husbandry and animal husbandry provides fertilizer for farming conversely. The biogas is one of the most efficient and renewable resource, which can be made by fermentation of the straw and excrement of livestock. Biogas can be used as fuel and fertilizer and the by-product of the process of making biogas are effective materials to improve soil and environment-friendly fertilizer to reduce fertilizer and pesticide input as well, such as biogas slurry and biogas residues. From animal husbandry to farming, the management of excrement of livestock and the straw returned to field after eating to made biogas should be strengthened. From farming to animal husbandry, extend technologies such as corn straw silage to provide feed for animal husbandry can solve the scarcity of forage in cold season of northern region. In addition, the processed straw have higher nutritional components than fresh straw.

2) REGION 2: FARMING(BASED ON RICE)-ANIMAL HUSBANDRY DOMINANT REGION

Recycling mode of agricultural product deeply processing is selected for region 2. The relationship between farming and animal-husbandry has been illustrated in previous section. This mode is similar to the last mode, however, agricultural product deep processing is introduced to this region considering the characteristic that rice is the main crop in this region. Many complementary product can be produced through the deep processing of rice, such as rice bran and rice husk. Rice bran can be used to make rice bran oil with high nutrition value. Rice husk can be burnt to generate electricity and the rice husk ash obtained after the burning of rice husk can be used to generate biological fertilizer which has lighter burden on the environment. Deeply processing of rice can prolong industry chain and increase added value of rice and the economic benefit is also improved. Meanwhile, ducks can be fed in the rice field which can help rice prevent disease and weed conversely. According to the local characteristics, the fly ash produced during industrial production can be utilized to improve the quality of land or make biological fertilizer which can promote the development of farming consequently [28].

3) REGION 3: VEGETABLE AND EDIBLE FUNGI - MELONS AND FRUITS - ANIMAL HUSBANDRY DOMINANT REGION

Recycling use mode of agricultural by-products which considers edible fungi as link is selected for region 3. Region 3 has developed husbandry industry and farming is also one of main industries, which will produce much agricultural by-products every year. The agricultural by-products include excrement, straw and so on. They are good materials for edible fungi cultivation. Developing animal husbandry to generate organic fertilizer and organic fertilizer not only can promote pollution-free production of vegetables and fruits but also can be directly applied into cultivating edible fungi. Branches of fruit trees can be used to cultivate edible fungi as well. Waste material after the cultivation of edible fungi can be added into the feed for animal to help develop animal husbandry or applied into the production of grain crops whose straw can be used to cultivate edible fungi. For example, fungi chaff is the waste culture medium transformed from excrement and straw after cultivating edible fungi by them. Fungi chaff itself is efficient organic fertilizer, and the above transformation can increase the use efficiency of excrement and straw. Thus, reuse and recycle of agricultural organics have been achieved successfully.

4) REGION 4: FARMING - FORESTRY- ANIMAL HUSBANDRY DOMINANT REGION

Two modes can be applied into region 4:

(1) Complex recycling mode of farming, forestry and animal husbandry Region 4 is located in Daxinganling and Xiaoxinganling forest region in Heilongjiang province. Due to excess deforestation, resources were exhausted and forest ecological function reduced. Different combination methods of farming, forestry and animal husbandry may provide various ideas to solve problems. For example, developing undergrowth husbandry or grass planting. The excrement of livestock or poultry can be used as organic fertilizer to support the growth of trees and planting grass can increase the vegetation coverage and help the soil and water conservation. Establishing eco-agricultural gardens combining farming and husbandry is another method, which is based on the mountain forest. It develops farming to provide feed for animal and then using the excrement of them to make biogas which is beneficial to forestry.

(2) Eco-agricultural tourism mode As mentioned above, the three cities of this region have abundant forest resources. Therefore, eco-agricultural tourism mode is proposed for this region specifically. Heilongjiang province has several natural advantages to develop forest tourism: first, natural forest takes a large proportion which will be more attractive to visitors; second, the species of forest are various, meanwhile, there are also many precious wild animals and plants in forest, such as amur tiger, pilose antler and so on; third, Heilongjiang province as a famous northeastern province, winter tourism industry is popular. The forest in winter shows unique and irreplaceable scene which is a great characteristic of this region.
IV. POLICY SUGGESTIONS

A. CONSTRUCT REGIONAL AGRICULTURAL CIRCULAR ECONOMY SYSTEM

It can be indicated from the results of this paper that regional policies are very necessary for efficient development of agricultural circular economy. Regional policies can give full play to the advantages of each region, which can make full use of local resources. If applying uniform policy into different regions, not only will not achieve any profit, but also will destruct local natural environment and make large loss. On the other hand, regional policies will be more suitable for the agricultural production ideas of local agricultural labors which can easily obtain support of them. Their support to policies is very important for the execution of policies established by government.

B. CONSTRUCT AGRICULTURAL CIRCULAR ECONOMY TECHNOLOGY AND SERVICE SYSTEM

Developing agricultural circular economy should be based on technology. Financial support is necessary, so government should provide more fund for researches of advanced technologies. On the other hand, talent introduction is needed to promote these researches. Corresponding welfare policies and reasonable mechanism of talent should be established to attract and retain talent. In addition to supporting the innovation of advanced technologies, the generalization of them also should be taken into account. Information service platform is an effective method to generalize novel technologies. Integrating useful information in time and put them onto the international platform to facilitate agricultural labors to know the latest information which can guide their production.

C. COMPLETE RELATED LAWS AND REGULATIONS

The specific laws and regulations about agricultural circular economy are not complete. There are no explicit laws to regulate the behaviors of people, which means there may not exist proper punishment corresponding to some behaviors polluting environment. The awareness of sustainable development is not strong enough in some agriculture labors’ mind. They used to insist their traditional methods. They should be regulated mandatory by strict laws, meanwhile, some awarding policies should be established which can stimulate the enthusiasm of agriculture labors. The establishment of responsibility system is also necessary to ensure the implementation of other policies.

V. CONCLUSION

This paper focused on proposing Improved Fuzzy min-max neural network with fuzzy lattice inclusion measure (FL-IFMM) to divide Heilongjiang province into four regions on agricultural circular economy. In this paper, region division of agricultural circular economy is regarded as a clustering problem, so this paper proposed a novel clustering method called Improved Fuzzy min-max neural network with fuzzy lattice inclusion measure (FL-IFMM) to deal with the task of agricultural circular economy region division in Heilongjiang province. Data about four aspects of indexes including Resource dosage indexes, Economic and Social development indexes, Area index, Population and Labor index was mainly used to implement agricultural circular economy region division in Heilongjiang province. Heilongjiang province was divided into four agricultural circular economy regions in this paper. Region 1 focused on farming (based on grain crops) and animal husbandry. Region 2 focused on farming (based on rice) and animal husbandry. Region 3 focused on vegetable and edible fungi, melons and fruits, and animal husbandry. Region 4 focused on farming, forestry and animal husbandry. It can be indicated from the discussion of region division results that the clustering results achieved by FL-IFMM have high reliability which embodies in that many factors affecting agricultural production and economic development such as resources, land, economic status are similar within each region. This is mainly due to the outstanding ability of FL-IFMM to measure similarity among patterns. Meanwhile, this novel method needs less memory and less times of searching patterns set which is more suitable for such lager datasets. The region division results in this paper have the immensely guiding role for sustainable development in Heilongjiang province. Finally, some detailed policy suggestions are proposed which provide ideas for government. On the other hand, this paper not only offered references for the field of agricultural circular economy region division, the FL-IFMM model proposed in this paper can also be generalized to any clustering problems.

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