Selecting Evaluation Indices for Cleaner Production of Plantation Logging in Southern China with Fuzzy Clustering Methods

Aihua Yu, Tom Gallagher, Chen Zhao, Yao Zhao

Abstract

Over the years, China has shown a significant reduction in natural forest resources, while the increasing area of plantations has made greater contributions to the huge demand for wood. In southern China, these new plantations have produced some problems such as environmental hazards of logging operations and the most reasonable use of forest resources. A new management process called »cleaner production« is defined as reducing pollution from its source, increasing the rate of utilization of resources, and preventing the generation of pollutants in the production of services and products. In recent years, cleaner production has been widely applied to industrial processes such as agriculture and other environmental industries. In order to make rational use of plantation resources, to achieve maximum economic efficiency and to reduce or remove the environmental hazards of logging operations, it is necessary to carry out an in-depth study of cleaner production on the process of logging operations. This paper aims to establish an index system for cleaner production evaluation of plantation logging. The fuzzy clustering method was used to initially screen twenty-nine indices. After screening by the fuzzy clustering method, six first-grade indices and twelve second-grade important indices were selected as formal evaluation indices. The six first-grade indices are 1) cutting area design index, 2) logging operation techniques index, 3) ecological environmental impact index, 4) utilization of resource and energy index, 5) sustainable development index, and 6) safety production management and protection index. A maximum and minimum matrix method and a correlation coefficient matrix method were used to establish the similar matrix in the fuzzy clustering method. The screening results were then compared. The comparison shows that out of the twelve second-grade indices, ten are similar and two are different. The results suggest that the fuzzy clustering method is reliable for screening indices.

*Keywords: plantation, logging operation, cleaner production (*CP*), evaluation indices, fuzzy clustering method.*

1. Introduction

With a sharp reduction in the natural forest over the past decade in China, a greater emphasis has been put on plantations to meet lumber demand. The recently completed Eighth National Forest Inventory supports this assumption. Specifically, the proportion of plantation harvesting has increased from 39% to 46%, and plantation harvesting has increased to 155 million cubic meters annually (the results of the eighth national forest resources inventory in China (2009–2013). While the additional plantation harvesting has many economic benefits, it has also produced some new problems in southern China, such as soil erosion and waste timber in the land. Some criteria needed to be developed to measure what is important in the performance of these plantations. This paper focuses on the index system for cleaner production (*CP*), which is an evaluation of plantation logging in order to rationally use plantation resources, achieve the maximum economic benefit, and reduce the effects of logging on the environment.

CP has been defined in »The Law of the People's Republic of China on Promotion of Cleaner Production« by continuously adopting measures to improve design, use cleaner energy and raw materials, introduce advanced techniques and equipment, improve management and make comprehensive use of resources as well as other measures. *CP* is also defined by reducing pollution from its source, increasing the utilization ratio of resources, and reducing or preventing the generation and discharge of pollutants during production and in providing services. The goal is to alleviate or eliminate harm to human health and the environment (Zhao and Zhang 2003). This not only applies to industrial processes, but also to agriculture, planning, construction, and services as this is a general issue.

Based on the industry definition of *CP* and the characteristics of plantation logging, *CP* involves improving cutting area design with the local conditions, using cleaner energy, developing reasonable logging technologies and equipment, improving management practices, minimizing pollution, saving, and protecting the forestry environment and workers. The results should be to achieve sustainable plantations. The methodology is to produce a model for plantation resources by using a whole environmental strategy for the processes and productions of plantation logging in order to reduce or eliminate harm to human health and the environment while fully satisfying human needs. *CP* in plantation logging is an important means for achieving sustainability of plantations. The final goal is to maximize the balance between natural resources, energy use and economic benefits and minimize the harm to humans and the environment, all in order to save resources, reduce waste and protect the environment while harvesting timber.

2. Contents of *CP* evaluation for plantation logging

Cutting area design, logging technology, ecological environment impact, resource and energy use, and sustainable businesses of forest protection and management for workers, all contribute to the *CP* evaluation for plantation logging. So the evaluation not only considers the longevity, gradualness, and complexity of the impacts of logging on forest ecological systems, but also the method and intensity of logging, scale of production, and the stability and recovery of the ecological environment.

2.1 Evaluations for cutting area design

CP for cutting area design should include the following: designing energy saving processes, promoting low-energy techniques, shortening the working time, simplifying equipment, and paying attention to energy management. In addition, using logging equipment to benefit the ecological environment, reducing logging waste and combustible materials of forest fires, and improving the benefits of logging by-products were also considered when evaluating the importance of *CP*.

In designing of an index for *CP*, the following should be considered: the rationality of logging processes (including the type of logging system, index of logging intensity, index of outturn percentage and output, index of road design, index of bucking, index of skidding and transportation, organization of logging team and so on), advancement of logging technology, reliability of preventative measures for cutting renewable areas, and operation management considerations.

2.2 Evaluation of logging technology

Cutting, skidding, and transportation are three important processes in timber production technology in a logging operation. Various working methods and equipment types are used in each process, so that many different timber production models and economic benefits can be compared. Based on the investigation of plantation logging in the Fujian Province, clear-cutting was the main type of cutting method with the exception of the cases provided in »Regulation of Forest Harvesting and Renew«. Chainsaw operation was the main equipment method of felling. Angular saw was only used in a few China fir collective forest areas with mostly small diameter logs (diameter <8 cm). Methods of skidding included aerial cableway, walking tractor, push cart, dirt chute, and manpower. Transportation included truck, farm vehicle, shipping, and rafting (manpower) (Zhang et al. 2008). *CP* of logging mainly reflected the interference and acceptability to the environment. Reduced Impact Logging (*RIL*) was based on principles of science and engineering and a combination of education and training (Dykstra 2001). *RIL* required specific forest investigation procedures before logging, including a plan and construction of logging roads and landings, reliable ways for cutting and bucking, skidding felled timbers along skid roads, skidding systems for protecting soil and vegetation, and evaluation after logging. In addition, *RIL* also included the impacts of logging on landscapes, biodiversity, vegetation, water, and soil (Long 2006).

Evaluation for logging mainly includes the following items: advance of technology, rationality of logging processes, coordination, economic benefits, security and work efficiencies of a human-equipment-environment system. The economic benefit was based on reducing working costs while not destroying the forested ecological environment.

2.3 Evaluation for ecological environment impacts

For a small cutting area, soil and vegetation in the ecological environment were the most directly impacted. When evaluating logging practices such as cutting, skidding, and transportation, it becomes increasingly important to always consider the effects on the ecological environment.

The unreasonable cutting, skidding and ground disturbance impact many parts of the ecological environment when logging, including the effects on soil, reserve, rivers, biodiversity, loads of CO_2 in air, landscape, and regional climate. Therefore, a cleaner logging model must minimize the above effects, in order to maximize the ecological environmental benefits of logging in the forest.

2.4 Evaluation for resources and energy use

Plantations were resource used for an evaluation of logging. The forest resource in China is considered a scarce raw material when evaluating its biological and economic benefit. So, in order to save on the use of raw materials as well as maintain higher working ability and level, larger outputs and fewer resource wastes should be expectated of plantation logging.

Energy use in the logging processes mainly means that fuel and lubricants were consumed by equipment that was used in cutting, skidding and transportation. So, low-energy and clean energy equipment should be used. Also, the index of evaluation for resource and energy use included standing tree utilization, volume of waste timber in cutting area, volume of waste timber in loading bay, logging slash utilization, and the fuel consumption of equipment used during logging.

2.5 Evaluation for sustainable businesses of plantation

China has implemented new practices in forestry development, though mostly for afforestation, because of many factors. These factors include harvesting in areas where forest harvesting has followed the traditional methods and patterns. It can be said that in these areas we do not see the forest for the trees. In afforestation areas, some areas were deforested without reforestation and had false reporting, which led to inaccurate forest resource database. These factors have led to low-quality afforestation, reforestation missing from the forest each year, and an increased impact to the environment and ecological balance, which have caused irreversible damage to woodland sites. Logging has an important effect on the ecological environment, such as reducing the depth of litter fall and destroying the surface soil. Especially in spring and summer, increased surface runoff usually results in heavy soil erosion. Moreover, pushing timber by skidding equipment negatively impacted the surface soil and damaged the young trees and reserves (Wang 1997).

Evaluation of plantations for sustainable businesses included the utilization rate of wood, renewable rate of cutover land, and the survival rate of regeneration. The aim of *CP* for plantation logging was sustainable businesses.

2.6 Evaluation of safety production management and protection

To make plantation logging cleaner, production must be cleaner first. This includes cleaner awareness and action of the producers. This was particularly reflected in the aspects of safety on production and protection. So, better education of workers was the basis for achieving *CP*. If working conditions were improved, employees could benefit from increased safety and a better overall working environment.

CP could minimize the injury rate of operators in working processes. Meanwhile, *CP* was also found to ensure worker rights and safety. Only labor protection was able to become the essence of *CP*. So for evaluation of safety production, one aspect of the evaluated content consisted of reducing operation damage of workers and ensuring worker rights and safety.

3. Evaluation indices

3.1 The principles for determining evaluation indices

The index system for *CP* evaluation of plantation logging consists of many structured and graduated indices that connect and complement each other. It is a combination of the evaluation of sustainable and high efficient utilization levels of resources and its index, and how it directly affects the results of forest resources management and utilization levels. Correctly implemented, the result is an accurate representation of *CP* for plantation logging. Sustainable development theory and ecology-economy-society theory were the guides for setting up the index system for the *CP* evaluation of plantation logging, and they were also based on the following five principles:

1) Methods combined qualitative and quantitative analysis. In order to ensure the accuracy and scientific nature of the results for evaluating the *CP* of plantations, the quantity index should be selected to set up a quantitatively evaluable model. On the other hand, the evaluated objects were completed production processes that involved various quarters. Therefore, the index system of *CP* was a completed and intrinsic closed contact system. Absolute quantity, relative quantity, averages and other indices could be used, and some indices could also be used as quality if they could not be managed by quantitative analysis.

2) Independence: the status of the system could be described by a number of indices, but intercrossing of information always occurs. In order to establish an index system, representative and independent indices must be selected using the scientific method to improve its accuracy and scientific nature.

3) Evaluation through the whole process: the index system not only includes the whole production process, but also the product itself. In other words, *CP* evaluations of plantation logging aimed to analyze and evaluate the raw material and energy consumption, as well as pollutant creation and its toxicity in the whole process of design, production, storage, and transportation.

4) Improving sustainability: *CP* is a sustainable improving process, and it requires the company to continuously achieve higher environmental objectives on the basis of existing economic, technological, and environmental indices. Therefore, for the purpose of promoting *CP*, different *CP* objectives should be selected to promote sustainable development on the basis of the existing situation.

5) Simple and focused: the index system for *CP* could not cover all the processes in the plantation logging. Generally, the most simple and focused indices are implemented effectively.

3.2 Selection of the evaluation index

The process begins with selecting some evaluation indices on the basis of contents and principles (as shown in Table 1) (Yu et al. 2009). Such indices should not be combined together directly because of information interference and the fact that this could have an impact on the evaluation results (Chen 2003).

Cluster analysis divides data into groups (clusters) such that similar data objects belong to the same cluster and dissimilar data objects to different clusters. The resulting data partition improves data understanding and reveals its internal structure. Partitional clustering algorithms divide up a data set into clusters or classes, where similar data objects are assigned to the same cluster, whereas dissimilar data objects should belong to different clusters. In real applications, there is very often no sharp boundary between clusters so that fuzzy clustering is often better suited for the data. Membership degrees between zero and one are used in fuzzy clustering instead of crisp assignments of the data to clusters. Fuzzy clustering is the method that can capture the uncertainty situation of real data and it is well known that the fuzzy clustering can obtain a robust result as compared with conventional hard clustering (Silviu 2013). Conventional clustering means classifying the given observation as exclusive clusters. It can be clearly seen whether an object belongs to a cluster or not. However, such a partition is insufficient to represent many real situations. Therefore, a fuzzy clustering method is offered to construct clusters with uncertain boundaries, so this method allows that one object belongs to some overlapping clusters to some degree. In others words, the essence of fuzzy clustering is to consider not only the belonging status to clusters, but also to consider to what degree the objects belong to the clusters (Sato-Ilic et al. 2006). One of the main advantages of fuzzy clustering is the ability to express ambiguity in an assignment of objects to clusters (Silviu 2013). A corresponding fuzzy set was used to describe the uncertainties (Han et al. 2011). However, apart from this, experimental results prove that fuzzy clustering seems also to be more robust in terms of local minima of the objective function (Klawonn 2004). Another distinct advantage of fuzzy clustering over its crisp counterpart is that the continuous range of the combinatorial functions turns into smooth functions. This makes it possible to design algorithms that are more likely to attain a global solution, whereas crisp techniques often wind up in the local solution. (Rousseeuw 1995). The fuzzy relation between samples is quantified in fuzzy cluster, so fuzzy cluster is more objective and accurate (Yang 2011).

In recent years, the fuzzy clustering has been widely studied and applied in a variety of key areas (Wang and Zhang 2011) such as in data mining, economic analysis, and selection evaluation indices (Xu et al. 2005). Li et al. (2008) used this method to select the evaluation indices of stock investment value, providing an empirical basis for artificial intelligence methods in the stock value of investment. Guan et al. (2009) applied the fuzzy clustering approach in constructing the evaluation index system of core competence of

Table 1 *CP* evaluation indicators system for forest plantation loggi

Primary index system for cp evaluation of plantation logging	First level index	Second level index
	Cutting area design	Cutting area division (x_1)
		Cutting area survey (x_2)
		Engineering design (x_3)
		Production process design (x_4)
	Logging technology	Rationality of operation process (x_5)
		Advanced of operation technology (x_6)
		Efficiency (x_7)
		Human-machine-environment harmony (x_8)
		Economics and safety of ways to work (x_9)
	Impacts on ecological environment	Soil physical properties (x_{10})
		Soil chemical properties (x_{11})
		Soil and water conservation (x_{12})
		Injury rate of retention tree in slash (x_{13})
		Average wind speed and temperature (x_{14})
		Biomass (x_{15})
		Biodiversity (x_{16})
		The rate of slash soil erosion area (x_{17})
	Resources and energy use	The number of discarded wood in cutting area (x_{18})
		Utilization rate of wood (x_{19})
		Utilization rate of slash (x_{20})
		The number of discarded wood in the landing place (x_{21})
		Logging equipment fuel consumption (x_{22})
	Sustainable development	Survival ratio of renew (x_{23})
		Renew ratio of cutting area (x_{24})
		Wood renewal utilization (x_{25})
	Improvement of safety and management	Safety management (x_{26})
		Equipment safety (x_{27})
		Labor protection (x_{28})
		Labor intensity (x_{29})

corporation and achieved very good results. Yan et al. (2008) forecasted the heavy rainstorm based on the fuzzy cluster type in Jiangsu province and reduced the storm empty reported rates. Chiba et al. (2012) analyzed the web survey data with the similarity fuzzy cluster and showed a better performance by using numerical examples.

A secondary selection should be used by the fuzzy cluster method. The basic idea of fuzzy cluster was to construct the fuzzy matrix according to attributes of a research object, and on this basis the clustering relation was determined according to certain subordinate relations (Peng 2003).

The process of the fuzzy cluster method is described by the following 3 steps:

1) Set up a fuzzy similarity matrix by calculating similar coefficients between samples and variables.
2) Transform the fuzzy similarity matrix into a fuzzy equivalence matrix with the help of fuzzy operation.
3) Classify the fuzzy equivalence matrix according to a different fuzzy graph λ.

3.3 Data processing

The fuzzy cluster process begins by setting n items as a classification, the indicator set $X = \{X_1, X_2, \ldots, X_n\}$, with available m-dimensional vector describing the sample, $X_i = \{X_{1i}, X_{2i}, \ldots, X_{mi}\}$, $i = 1,2,\ldots, n$. As there were some qualitative analysis indices in *CP* evaluation of plantation harvesting, this paper used a five grade Likert scale to evaluate indices, ranging from »very important (5)« to »not care (1)«, to determine a better measure of each index.

The membership function was then defined: t was the number of classifications of certain properties, Cp for p class, x was an attribute value of Cp, $u(x) = N(Cp)$ m, $p = 1,2,\ldots, t$. $N(Cp)$ was the number of attribute values included in the class Cp. Following the above process, data matrix was initialized, if y_{ij} represents the property value of the i^{th} row and column j, then $0 \le y_{ij} \le 1$, and y_{ij} size reflects the dependence of the property value for the property.

Establishing the fuzzy similar matrix: The domain $U = \{y_1, y_2, \ldots, y_n\}$ was concerned, y_i, y_j relationship was described by $R(y_i, y_j)$. There were many methods to help set up a fuzzy similarity matrix, such as the distance method, correlation coefficient method, and maximum and minimum method. Both the maximum and minimum method and correlation coefficient method were used in this paper to set up a fuzzy similarity matrix for the *CP* evaluation of plantation logging, and also to compare the difference between them.

(1) Maximum and minimum method

A value is calculated by the eq. (1):

$$R\left(y_{\mathrm{i}}, y_{\mathrm{j}}\right) = \left\{ \begin{array}{c} 1, i = j \\ \dfrac{\sum_{\mathrm{k}=1}^{\mathrm{m}} \min\left(y_{\mathrm{ik}}, y_{\mathrm{jk}}\right)}{\sum_{\mathrm{k}=1}^{\mathrm{m}} \max\left(y_{\mathrm{ik}}, y_{\mathrm{jk}}\right)}, i \neq j \end{array} \right\} \quad (1)$$

Where, y_{ik} was the attribute value of row i column k; y_{jk} was the attribute value of row j column k.

A fuzzy similarity matrix *R* was set up as follows:

$$R=\begin{pmatrix} R(y_1,y_1) & R(y_1,y_2)\dots & R(y_1,y_\mathrm{n}) \\ R(y_2,y_1) & R(y_2,y_2)\dots & R(y_2,y_\mathrm{n}) \\ \vdots & \vdots & \vdots \\ R(y_\mathrm{n},y_1) & R(y_\mathrm{n},y_2) & R(y_\mathrm{n},y_\mathrm{n}) \end{pmatrix} \tag{2}$$

As shown in the above matrix, reflexivity and symmetry are satisfied due to $R(y_\mathrm{i},\ y_\mathrm{i})=1$; $R(y_\mathrm{i},\ y_\mathrm{j})=R(y_\mathrm{j},\ y_\mathrm{i})$, but do not meet the transitivity. Therefore, the values cannot be classified directly.

Squares method was used to calculate transitive closure of the fuzzy matrix, so that a fuzzy equivalence matrix was set up from the fuzzy similarity matrix *R* (as shown below).

$$R^{\rightarrow}R^{2\rightarrow}R^{4\rightarrow}\cdots R^{2\mathrm{k}\rightarrow} \tag{3}$$

R^k was the transitive closure of the fuzzy matrix when $R^{\mathrm{k}0}\,R^\mathrm{k}=R^{2\mathrm{k}}$. In other words, R^k was the fuzzy equivalence matrix. The cube operation was calculated as follows:

$$A=R^0R\leftrightarrow A_\mathrm{ij}=\overset{\mathrm{k}=1}{\underset{\mathrm{m}}{\vee}}\left(R_\mathrm{ik}\wedge R_\mathrm{jk}\right) \tag{4}$$

λ was the fuzzy graph:

$$R=\left(r_\mathrm{ij}\right)_{\mathrm{n}\times\mathrm{n}}\ \forall\lambda\in\left[0,1\right]R_\lambda=(r_\mathrm{ij}\left(\lambda\right))_{\mathrm{n}\times\mathrm{n}} \tag{5}$$

where:

$r_\mathrm{ij}\left(\lambda\right)=\begin{cases}1,r_\mathrm{ij}\geq\lambda\\0,r_\mathrm{ij}<\lambda\end{cases}$, so R_λ was the fuzzy graph of matrix R_o.

Different values would be assigned to λ from large to small after the fuzzy equivalence matrix was set up, and different classifications would be gained by calculating λ. In other words, λ was assigned by the actual needs, and classification was selected by λ (Li et al. 2003).

A representative index was selected from each classification as the typical index after classifying. The specific method was the following: first, correlation coefficients of each classification were calculated; then, the averages of the squares of the correlation coefficient between one index and the other were calculated, and the maximum was the typical index. The index could be put into the index set, if only one index was classified and one index of two indices existed in classification (Sârbu and Einax 2008).

The main factors that impacted the *CP* of plantation logging would be the index of cluster on the basis of literature review and investigations. We designed the questionnaire according to the content and features of cleaner production in plantation logging, issued over 100 questionnaires to almost twenty forestry companies or universities by email, including colleges of forestry, forestry research institutes, forest engineering enterprise and so on, and recovered 30 valid questionnaires. A five grade Likert scale was used to evaluate indices. All thirty samples were used for the analysis and the raw data is shown in Table 2.

The membership function was calculated from the definition itself, and an initialization process was used for these data. According to the raw data, membership function of each attribute is calculated and shown in Table 3. In the first attribute, x_1 means the first index (cutting area division); {1–5} means the important degree (from »very important {5}« to »not care {1}«); 0.37, 0.40, 0.23 were the proportion of rating {4}, {5} and {3} in 30 samples, respectively. After mapping each membership function, the resulting initialized data is presented in Table 4.

According to the eq. (1) and combining the initialized data, fuzzy similar matrices *R* were established. Matrices of cutting area design (6), logging technology (7), impacts on ecological environment (8), resources and energy use (9), sustainable development and safety production (10), and labor protection (11) were calculated with the maximum and minimum method, as shown in eq. (6)–(11). In these similar matrices, each value means the correlation of two indices; the higher value has the stronger correlation, thus value 1 means fully correlated. For example, in matrix (6), the first row, the values 1, 0.6693, 0.8085, 0.7380 mean the correlation between index of the first and first, the first and the second, the first and the third, the first and the fourth, respectively. In the first column, the values meaning as the first row, and so on.

$$\begin{vmatrix} 1.0000 & 0.6693 & 0.8085 & 0.7380 \\ 0.6693 & 1.0000 & 0.6904 & 0.6544 \\ 0.8085 & 0.6904 & 1.0000 & 0.6791 \\ 0.7380 & 0.6544 & 0.6791 & 1.0000 \end{vmatrix} \tag{6}$$

$$\begin{vmatrix} 1.0000 & 0.7408 & 0.6813 & 0.5171 & 0.6441 \\ 0.7408 & 1.0000 & 0.6429 & 0.6699 & 0.6103 \\ 0.6813 & 0.6429 & 1.0000 & 0.5211 & 0.5203 \\ 0.5171 & 0.6699 & 0.5211 & 1.0000 & 0.5413 \\ 0.6441 & 0.6103 & 0.5203 & 0.5413 & 1.0000 \end{vmatrix} \tag{7}$$

$$\begin{vmatrix} 1.0000 & 0.5125 & 0.6285 & 0.5227 & 0.6466 & 0.6667 & 0.7293 & 0.6033 \\ 0.5125 & 1.0000 & 0.6384 & 0.5586 & 0.5472 & 0.5206 & 0.5145 & 0.5269 \\ 0.6285 & 0.6384 & 1.0000 & 0.6522 & 0.6209 & 0.6831 & 0.6486 & 0.6603 \\ 0.5227 & 0.5586 & 0.6522 & 1.0000 & 0.5283 & 0.5560 & 0.5443 & 0.5731 \\ 0.6466 & 0.5472 & 0.6209 & 0.5283 & 1.0000 & 0.7061 & 0.6879 & 0.6177 \\ 0.6667 & 0.5206 & 0.6831 & 0.5560 & 0.7061 & 1.0000 & 0.7221 & 0.6731 \\ 0.7293 & 0.5145 & 0.6486 & 0.5443 & 0.6879 & 0.7221 & 1.0000 & 0.6522 \\ 0.6033 & 0.5269 & 0.6603 & 0.5731 & 0.6177 & 0.6731 & 0.6522 & 1.0000 \end{vmatrix} \tag{8}$$

Table 2 Raw data from the questionnaire

Index	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}	R_{11}	R_{12}	R_{13}	R_{14}	R_{15}	R_{16}	R_{17}	R_{18}	R_{19}	R_{20}	R_{21}	R_{22}	R_{23}	R_{24}	R_{25}	R_{26}	R_{27}	R_{28}	R_{29}	R_{30}
X_1	4	4	5	4	4	5	3	5	5	4	3	5	3	5	4	5	5	5	3	4	4	5	5	5	4	3	4	3	3	4
X_2	2	3	3	4	4	3	4	3	4	4	3	2	2	3	3	1	1	5	2	3	4	4	5	5	3	3	2	3	4	3
X_3	3	3	3	4	5	5	5	3	5	5	4	4	3	5	4	4	3	4	5	4	4	5	5	5	4	4	3	4	4	5
X_4	2	4	4	2	4	4	3	4	3	4	2	2	4	2	2	2	4	4	4	3	4	5	5	5	3	3	3	2	5	3
X_5	5	3	3	4	5	3	4	5	4	4	4	5	5	5	4	4	5	5	5	5	4	5	5	5	4	4	4	4	4	5
X_6	4	5	5	3	4	3	4	3	3	4	4	3	3	4	5	4	5	5	4	3	4	3	5	4	3	5	4	3	5	3
X_7	5	3	5	4	4	5	4	5	3	4	5	4	3	4	5	4	5	3	4	4	3	2	4	3	4	4	4	4	4	4
X_8	2	5	4	3	5	3	5	3	3	4	2	3	1	3	3	2	1	5	4	5	3	4	5	5	2	3	2	2	4	3
X_9	3	2	3	3	4	5	5	4	3	3	5	5	3	2	3	3	3	4	2	4	3	3	4	3	4	3	3	2	5	3
X_{10}	4	4	4	5	4	3	2	4	3	1	2	4	4	1	3	3	2	3	2	4	4	4	5	5	3	3	2	2	3	4
X_{11}	4	4	3	5	4	4	4	5	4	4	4	5	4	3	5	5	5	5	4	3	3	5	3	4	4	4	4	4	4	4
X_{12}	4	5	5	3	4	3	4	4	4	3	4	5	5	3	4	3	4	4	4	4	3	5	5	5	4	3	3	3	4	3
X_{13}	4	2	4	3	1	3	5	3	1	3	3	4	4	4	3	3	2	3	3	4	3	2	5	3	2	2	2	3	3	3
X_{14}	5	3	2	4	4	1	3	5	2	3	2	4	2	3	3	4	3	5	4	5	1	2	5	4	2	2	2	2	2	2
X_{15}	5	4	3	3	4	1	4	4	3	4	4	4	3	3	3	2	2	3	3	3	5	2	5	5	4	3	2	2	3	2
X_{16}	3	3	4	1	4	5	5	4	2	4	2	3	2	3	2	4	3	1	4	3	2	4	5	5	2	2	3	2	4	3
X_{17}	4	1	1	4	3	1	4	1	2	3	4	1	3	3	3	5	4	1	3	1	3	4	4	3	3	3	2	3	5	2
X_{18}	5	4	4	5	5	5	5	4	4	5	3	4	5	3	5	4	4	3	3	5	3	3	4	4	3	4	4	4	4	3
X_{19}	5	4	4	3	5	5	4	4	5	5	4	5	4	3	4	5	3	5	5	5	3	3	4	4	3	4	4	4	5	4
X_{20}	5	4	4	4	3	3	5	1	2	3	4	4	3	4	3	4	2	4	4	5	2	3	4	4	3	3	2	2	4	4
X_{21}	5	3	5	5	4	3	4	3	4	5	4	3	5	5	4	3	3	4	3	5	3	3	4	4	4	3	4	4	5	4
X_{22}	2	4	4	4	4	4	5	4	3	3	4	3	2	5	3	5	5	2	4	5	1	3	5	4	2	2	2	2	4	2
X_{23}	4	5	5	5	5	5	5	3	3	4	5	3	5	4	4	3	5	4	4	3	1	2	5	4	4	4	4	3	5	3
X_{24}	2	2	2	2	4	2	4	1	2	1	2	3	5	1	2	1	2	3	4	4	3	2	5	5	3	2	2	2	4	2
X_{25}	3	2	4	4	4	4	5	3	1	3	1	4	4	3	3	3	2	5	2	4	3	2	5	5	3	2	2	2	4	2
X_{26}	4	5	5	4	5	3	4	5	4	5	3	4	4	4	4	5	3	5	5	5	3	2	5	5	3	3	3	3	3	2
X_{27}	5	4	4	4	4	5	5	4	3	5	5	4	4	4	5	4	3	5	3	4	2	3	4	4	4	4	4	4	4	3
X_{28}	4	2	4	1	3	2	3	2	1	5	4	4	1	4	4	3	3	2	4	4	3	3	4	3	4	4	4	3	4	4
X_{29}	5	2	4	3	3	2	3	3	3	2	4	5	4	2	5	3	4	4	2	4	3	3	3	4	3	3	2	3	3	3

Table 3 Membership function of each attribute

$u(x_1)=\begin{cases}0.37\ldots x_1\in\{4\}\\0.40\ldots x_1\in\{5\}\\0.23\ldots x_1\in\{3\}\end{cases}$	$u(x_2)=\begin{cases}0.07\ldots x_2\in\{1\}\\0.17\ldots x_2\in\{2\}\\0.40\ldots x_2\in\{3\}\\0.27\ldots x_2\in\{4\}\\0.10\ldots x_2\in\{5\}\end{cases}$	$u(x_3)=\begin{cases}0.23\ldots x_3\in\{3\}\\0.40\ldots x_3\in\{4\}\\0.37\ldots x_3\in\{5\}\end{cases}$	$u(x_4)=\begin{cases}0.27\ldots x_4\in\{2\}\\0.23\ldots x_4\in\{3\}\\0.37\ldots x_4\in\{4\}\\0.13\ldots x_4\in\{5\}\end{cases}$
$u(x_5)=\begin{cases}0.10\ldots x_5\in\{3\}\\0.43\ldots x_5\in\{4\}\\0.47\ldots x_5\in\{5\}\end{cases}$	$u(x_6)=\begin{cases}0.37\ldots x_6\in\{3\}\\0.37\ldots x_6\in\{4\}\\0.27\ldots x_6\in\{5\}\end{cases}$	$u(x_7)=\begin{cases}0.03\ldots x_7\in\{2\}\\0.20\ldots x_7\in\{3\}\\0.53\ldots x_7\in\{4\}\\0.23\ldots x_7\in\{5\}\end{cases}$	$u(x_8)=\begin{cases}0.07\ldots x_8\in\{1\}\\0.20\ldots x_8\in\{2\}\\0.33\ldots x_8\in\{3\}\\0.17\ldots x_8\in\{4\}\\0.23\ldots x_8\in\{5\}\end{cases}$
$u(x_9)=\begin{cases}0.13\ldots x_9\in\{2\}\\0.50\ldots x_9\in\{3\}\\0.20\ldots x_9\in\{4\}\\0.17\ldots x_9\in\{5\}\end{cases}$	$u(x_{10})=\begin{cases}0.07\ldots x_{10}\in\{1\}\\0.20\ldots x_{10}\in\{2\}\\0.27\ldots x_{10}\in\{3\}\\0.37\ldots x_{10}\in\{4\}\\0.10\ldots x_{10}\in\{5\}\end{cases}$	$u(x_{11})=\begin{cases}0.17\ldots x_{11}\in\{3\}\\0.57\ldots x_{11}\in\{4\}\\0.26\ldots x_{11}\in\{5\}\end{cases}$	$u(x_{12})=\begin{cases}0.33\ldots x_{12}\in\{3\}\\0.43\ldots x_{12}\in\{4\}\\0.24\ldots x_{12}\in\{5\}\end{cases}$
$u(x_{13})=\begin{cases}0.07\ldots x_{13}\in\{2,5\}\\0.20\ldots x_{13}\in\{2,4\}\\0.47\ldots x_{13}\in\{3\}\end{cases}$	$u(x_{15})=\begin{cases}0.03\ldots x_{15}\in\{1\}\\0.20\ldots x_{15}\in\{2\}\\0.37\ldots x_{15}\in\{3\}\\0.27\ldots x_{15}\in\{4\}\\0.13\ldots x_{15}\in\{5\}\end{cases}$	$u(x_{16})=\begin{cases}0.07\ldots x_{16}\in\{1\}\\0.27\ldots x_{16}\in\{2,3,4\}\\0.13\ldots x_{16}\in\{5\}\end{cases}$	$u(x_{17})=\begin{cases}0.23\ldots x_{17}\in\{1,4\}\\0.10\ldots x_{17}\in\{2\}\\0.37\ldots x_{17}\in\{3\}\\0.07\ldots x_{17}\in\{5\}\end{cases}$
$u(x_{18})=\begin{cases}0.27\ldots x_{18}\in\{3\}\\0.43\ldots x_{18}\in\{4\}\\0.30\ldots x_{18}\in\{5\}\end{cases}$	$u(x_{19})=\begin{cases}0.20\ldots x_{19}\in\{3\}\\0.43\ldots x_{19}\in\{4\}\\0.27\ldots x_{19}\in\{5\}\end{cases}$	$u(x_{20})=\begin{cases}0.03\ldots x_{20}\in\{1\}\\0.17\ldots x_{20}\in\{2\}\\0.27\ldots x_{20}\in\{3\}\\0.43\ldots x_{20}\in\{4\}\\0.10\ldots x_{20}\in\{5\}\end{cases}$	$u(x_{21})=\begin{cases}0.33\ldots x_{21}\in\{3\}\\0.40\ldots x_{21}\in\{4\}\\0.27\ldots x_{21}\in\{5\}\end{cases}$
$u(x_{22})=\begin{cases}0.03\ldots x_{22}\in\{1\}\\0.27\ldots x_{22}\in\{2\}\\0.17\ldots x_{22}\in\{3\}\\0.33\ldots x_{22}\in\{4\}\\0.20\ldots x_{22}\in\{5\}\end{cases}$	$u(x_{23})=\begin{cases}0.03\ldots x_{23}\in\{1,2\}\\0.23\ldots x_{23}\in\{3\}\\0.33\ldots x_{23}\in\{4\}\\0.37\ldots x_{23}\in\{5\}\end{cases}$	$u(x_{24})=\begin{cases}0.13\ldots x_{24}\in\{1,3\}\\0.47\ldots x_{24}\in\{2\}\\0.17\ldots x_{24}\in\{4\}\\0.10\ldots x_{24}\in\{5\}\end{cases}$	$u(x_{25})=\begin{cases}0.07\ldots x_{25}\in\{1\}\\0.17\ldots x_{25}\in\{2\}\\0.40\ldots x_{25}\in\{3\}\\0.23\ldots x_{25}\in\{4\}\\0.13\ldots x_{25}\in\{5\}\end{cases}$
$u(x_{26})=\begin{cases}0.03\ldots x_{26}\in\{2\}\\0.17\ldots x_{26}\in\{3\}\\0.50\ldots x_{26}\in\{4\}\\0.30\ldots x_{26}\in\{5\}\end{cases}$	$u(x_{27})=\begin{cases}0.23\ldots x_{27}\in\{3\}\\0.53\ldots x_{27}\in\{4\}\\0.24\ldots x_{27}\in\{5\}\end{cases}$	$u(x_{28})=\begin{cases}0.10\ldots x_{28}\in\{1\}\\0.17\ldots x_{28}\in\{2\}\\0.40\ldots x_{28}\in\{3\}\\0.30\ldots x_{28}\in\{4\}\\0.03\ldots x_{28}\in\{5\}\end{cases}$	$u(x_{29})=\begin{cases}0.20\ldots x_{29}\in\{2\}\\0.33\ldots x_{29}\in\{3,4\}\\0.14\ldots x_{29}\in\{5\}\end{cases}$

Table 4 Initialized data

Index	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8	R_9	R_{10}	R_{11}	R_{12}	R_{13}	R_{14}	R_{15}	R_{16}	R_{17}	R_{18}	R_{19}	R_{20}	R_{21}	R_{22}	R_{23}	R_{24}	R_{25}	R_{26}	R_{27}	R_{28}	R_{29}	R_{30}
X_1	0.37	0.37	0.40	0.37	0.37	0.40	0.23	0.40	0.40	0.37	0.23	0.40	0.23	0.40	0.37	0.40	0.40	0.40	0.23	0.37	0.37	0.40	0.40	0.40	0.37	0.23	0.37	0.23	0.23	0.37
X_2	0.17	0.40	0.40	0.27	0.27	0.40	0.27	0.40	0.27	0.27	0.40	0.17	0.17	0.40	0.40	0.07	0.07	0.10	0.17	0.40	0.27	0.27	0.10	0.10	0.40	0.40	0.17	0.40	0.27	0.40
X_3	0.23	0.23	0.23	0.40	0.37	0.37	0.37	0.23	0.37	0.37	0.40	0.40	0.23	0.37	0.40	0.40	0.23	0.40	0.37	0.40	0.40	0.37	0.37	0.37	0.40	0.40	0.23	0.40	0.40	0.37
X_4	0.27	0.37	0.37	0.27	0.37	0.37	0.23	0.37	0.23	0.37	0.27	0.27	0.37	0.27	0.27	0.27	0.37	0.37	0.37	0.23	0.37	0.13	0.13	0.13	0.23	0.23	0.23	0.27	0.13	0.23
X_5	0.47	0.10	0.10	0.43	0.47	0.10	0.43	0.47	0.43	0.43	0.43	0.47	0.47	0.47	0.43	0.43	0.47	0.47	0.47	0.47	0.43	0.47	0.47	0.47	0.43	0.43	0.43	0.43	0.43	0.47
X_6	0.37	0.27	0.27	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.27	0.37	0.27	0.27	0.37	0.37	0.37	0.37	0.27	0.37	0.37	0.27	0.37	0.37	0.27	0.37
X_7	0.23	0.20	0.23	0.53	0.53	0.23	0.53	0.23	0.20	0.53	0.23	0.53	0.20	0.53	0.23	0.53	0.23	0.20	0.53	0.53	0.20	0.03	0.53	0.20	0.53	0.53	0.53	0.53	0.53	0.53
X_8	0.20	0.23	0.17	0.33	0.23	0.33	0.23	0.33	0.33	0.17	0.20	0.33	0.07	0.33	0.33	0.20	0.07	0.23	0.17	0.23	0.33	0.17	0.23	0.23	0.20	0.33	0.20	0.20	0.17	0.33
X_9	0.50	0.13	0.50	0.50	0.20	0.17	0.17	0.20	0.50	0.50	0.17	0.17	0.50	0.13	0.50	0.50	0.50	0.20	0.13	0.20	0.50	0.50	0.20	0.50	0.20	0.50	0.50	0.13	0.17	0.50
X_{10}	0.37	0.37	0.37	0.10	0.37	0.27	0.20	0.37	0.27	0.07	0.20	0.37	0.37	0.07	0.27	0.27	0.20	0.27	0.20	0.37	0.37	0.37	0.10	0.10	0.27	0.27	0.20	0.20	0.27	0.37
X_{11}	0.57	0.57	0.17	0.27	0.57	0.57	0.57	0.27	0.57	0.57	0.57	0.27	0.57	0.17	0.27	0.27	0.27	0.27	0.57	0.17	0.17	0.27	0.17	0.57	0.57	0.57	0.57	0.57	0.57	0.57
X_{12}	0.43	0.23	0.23	0.33	0.43	0.33	0.43	0.43	0.43	0.33	0.43	0.23	0.23	0.33	0.43	0.33	0.43	0.43	0.43	0.43	0.33	0.23	0.23	0.23	0.43	0.33	0.33	0.33	0.43	0.33
X_{13}	0.20	0.20	0.20	0.47	0.07	0.47	0.07	0.47	0.07	0.47	0.47	0.20	0.20	0.20	0.47	0.47	0.20	0.47	0.47	0.20	0.47	0.20	0.07	0.47	0.20	0.20	0.20	0.47	0.47	0.47
X_{14}	0.17	0.20	0.37	0.20	0.20	0.07	0.20	0.17	0.37	0.20	0.37	0.20	0.37	0.20	0.20	0.20	0.20	0.17	0.20	0.17	0.07	0.37	0.17	0.20	0.37	0.37	0.37	0.37	0.37	0.37
X_{15}	0.13	0.27	0.37	0.37	0.27	0.03	0.27	0.27	0.37	0.27	0.27	0.27	0.37	0.37	0.37	0.20	0.20	0.37	0.37	0.37	0.13	0.20	0.13	0.13	0.27	0.37	0.20	0.20	0.37	0.20
X_{16}	0.27	0.27	0.27	0.07	0.27	0.13	0.13	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.07	0.27	0.27	0.27	0.27	0.13	0.13	0.27	0.27	0.27	0.27	0.27	0.27
X_{17}	0.23	0.23	0.23	0.23	0.37	0.23	0.23	0.23	0.10	0.37	0.23	0.23	0.37	0.37	0.37	0.07	0.23	0.23	0.37	0.23	0.37	0.23	0.23	0.37	0.37	0.37	0.10	0.37	0.07	0.10
X_{18}	0.30	0.43	0.43	0.30	0.30	0.30	0.30	0.43	0.43	0.30	0.27	0.43	0.30	0.27	0.30	0.43	0.43	0.27	0.27	0.30	0.27	0.27	0.43	0.43	0.27	0.43	0.43	0.43	0.43	0.27
X_{19}	0.37	0.43	0.43	0.20	0.37	0.37	0.43	0.43	0.37	0.37	0.43	0.37	0.43	0.20	0.43	0.37	0.20	0.37	0.37	0.37	0.20	0.20	0.43	0.43	0.20	0.43	0.43	0.43	0.37	0.43
X_{20}	0.10	0.43	0.43	0.43	0.27	0.27	0.10	0.03	0.17	0.27	0.43	0.43	0.27	0.43	0.27	0.43	0.17	0.43	0.43	0.10	0.17	0.27	0.43	0.43	0.27	0.27	0.17	0.17	0.43	0.43
X_{21}	0.27	0.33	0.27	0.27	0.40	0.33	0.40	0.33	0.40	0.27	0.40	0.33	0.27	0.27	0.40	0.33	0.33	0.40	0.33	0.27	0.33	0.33	0.40	0.40	0.40	0.33	0.40	0.40	0.27	0.40
X_{22}	0.27	0.33	0.33	0.33	0.33	0.33	0.20	0.33	0.17	0.17	0.33	0.17	0.27	0.20	0.17	0.20	0.20	0.27	0.33	0.20	0.03	0.17	0.20	0.33	0.27	0.27	0.27	0.27	0.33	0.27
X_{23}	0.33	0.37	0.37	0.37	0.37	0.37	0.37	0.23	0.23	0.33	0.37	0.23	0.37	0.33	0.33	0.23	0.37	0.33	0.33	0.23	0.03	0.03	0.37	0.33	0.33	0.33	0.33	0.23	0.37	0.23
X_{24}	0.47	0.47	0.47	0.47	0.17	0.47	0.17	0.13	0.47	0.13	0.47	0.13	0.10	0.13	0.47	0.13	0.47	0.13	0.17	0.17	0.13	0.47	0.10	0.10	0.13	0.47	0.47	0.47	0.17	0.47
X_{25}	0.40	0.17	0.23	0.23	0.23	0.23	0.13	0.40	0.07	0.40	0.07	0.23	0.23	0.40	0.40	0.40	0.17	0.13	0.17	0.23	0.40	0.17	0.13	0.13	0.40	0.40	0.40	0.40	0.40	0.17
X_{26}	0.50	0.30	0.30	0.50	0.30	0.17	0.50	0.30	0.50	0.30	0.17	0.50	0.50	0.50	0.50	0.30	0.17	0.30	0.30	0.30	0.03	0.17	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.17
X_{27}	0.23	0.53	0.53	0.53	0.53	0.23	0.23	0.53	0.23	0.23	0.23	0.53	0.53	0.53	0.23	0.53	0.23	0.23	0.23	0.53	0.23	0.23	0.53	0.23	0.53	0.53	0.53	0.23	0.53	0.53
X_{28}	0.30	0.17	0.30	0.10	0.40	0.17	0.40	0.17	0.10	0.03	0.30	0.30	0.10	0.30	0.30	0.40	0.40	0.17	0.30	0.30	0.40	0.40	0.40	0.30	0.40	0.40	0.17	0.40	0.40	0.40
X_{29}	0.13	0.20	0.33	0.33	0.33	0.20	0.33	0.33	0.33	0.20	0.33	0.13	0.33	0.20	0.13	0.33	0.33	0.33	0.20	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.20	0.13	0.33

$$\begin{vmatrix} 1.0000 & 0.8198 & 0.7030 & 0.8040 & 0.6876 \\ 0.8198 & 1.0000 & 0.6828 & 0.8082 & 0.6637 \\ 0.7030 & 0.6828 & 1.0000 & 0.6760 & 0.6553 \\ 0.8040 & 0.8082 & 0.6760 & 1.0000 & 0.7050 \\ 0.6876 & 0.6637 & 0.6553 & 0.7050 & 1.0000 \end{vmatrix} \tag{9}$$

$$\begin{vmatrix} 1.0000 & 0.5541 & 0.6030 \\ 0.5541 & 1.0000 & 0.5131 \\ 0.6030 & 0.5131 & 1.0000 \end{vmatrix} \tag{10}$$

$$\begin{vmatrix} 1.0000 & 0.6837 & 0.5846 & 0.5863 \\ 0.6837 & 1.0000 & 0.5798 & 0.6016 \\ 0.5846 & 0.5798 & 1.0000 & 0.6667 \\ 0.5863 & 0.6016 & 0.6667 & 1.0000 \end{vmatrix} \tag{11}$$

As shown in the above matrices 6–10, reflexivity and symmetry are satisfied due to $R(y_i, y_i)=1$; $R(y_i, y_j)=R(y_j, y_i)$, but do not meet the transitivity. Therefore, values cannot be classified directly. So, fuzzy equivalent matrices were established according to the eq. (3). Six fuzzy equivalent matrices of cutting area design (12), logging technology (13), impacts on ecological environment (14), resources and energy use (15), sustainable development and safety production (16), and labor protection (17) should be calculated by the squares method, as shown in eq. (12)–(17).

Matrices (12)–(17), reflexivity, symmetry and transitivity are all satisfied, so classification will be done directly. Each value in the matrices means the λ value.

$$\begin{vmatrix} 1.0000 & 0.6904 & 0.8085 & 0.7380 \\ 0.6904 & 1.0000 & 0.6904 & 0.6904 \\ 0.8085 & 0.6904 & 1.0000 & 0.7380 \\ 0.7380 & 0.6904 & 0.7380 & 1.0000 \end{vmatrix} \tag{12}$$

$$\begin{vmatrix} 1.0000 & 0.7408 & 0.6813 & 0.6699 & 0.6441 \\ 0.7408 & 1.0000 & 0.6813 & 0.6699 & 0.6441 \\ 0.6813 & 0.6813 & 1.0000 & 0.6699 & 0.6441 \\ 0.6699 & 0.6699 & 0.6699 & 1.0000 & 0.6441 \\ 0.6441 & 0.6441 & 0.6441 & 0.6441 & 1.0000 \end{vmatrix} \tag{13}$$

$$\begin{vmatrix} 1.0000 & 0.6384 & 0.6831 & 0.6522 & 0.7061 & 0.7221 & 0.7293 & 0.6731 \\ 0.6384 & 1.0000 & 0.6384 & 0.6384 & 0.6384 & 0.6384 & 0.6384 & 0.6384 \\ 0.6831 & 0.6384 & 1.0000 & 0.6522 & 0.6831 & 0.6831 & 0.6831 & 0.6731 \\ 0.6522 & 0.6384 & 0.6522 & 1.0000 & 0.6522 & 0.6522 & 0.6522 & 0.6522 \\ 0.7061 & 0.6384 & 0.6831 & 0.6522 & 1.0000 & 0.7061 & 0.7061 & 0.6731 \\ 0.7221 & 0.6384 & 0.6831 & 0.6522 & 0.7061 & 1.0000 & 0.7221 & 0.6731 \\ 0.7293 & 0.6384 & 0.6831 & 0.6522 & 0.7061 & 0.7221 & 1.0000 & 0.6731 \\ 0.6731 & 0.6384 & 0.6731 & 0.6522 & 0.6731 & 0.6731 & 0.6731 & 1.0000 \end{vmatrix} \tag{14}$$

$$\begin{vmatrix} 1.0000 & 0.8198 & 0.7030 & 0.8082 & 0.7050 \\ 0.8198 & 1.0000 & 0.7030 & 0.8082 & 0.7050 \\ 0.7030 & 0.7030 & 1.0000 & 0.7030 & 0.7030 \\ 0.8082 & 0.8082 & 0.7030 & 1.0000 & 0.7050 \\ 0.7050 & 0.7050 & 0.7030 & 0.7050 & 1.0000 \end{vmatrix} \tag{15}$$

$$\begin{vmatrix} 1.0000 & 0.5541 & 0.6030 \\ 0.5541 & 1.0000 & 0.5541 \\ 0.6030 & 0.5541 & 1.0000 \end{vmatrix} \tag{16}$$

$$\begin{vmatrix} 1.0000 & 0.6837 & 0.6016 & 0.6016 \\ 0.6837 & 1.0000 & 0.6016 & 0.6016 \\ 0.6016 & 0.6016 & 1.0000 & 0.6667 \\ 0.6016 & 0.6016 & 0.6667 & 1.0000 \end{vmatrix} \tag{17}$$

According to the eq. (4) and (5), λ cut matrices were calculated and different classifications were gained. Six classified results of cutting area design (Table 5), logging technology (Table 6), impacts on ecological environment (Table 7), resources and energy use (Table 8), sustainable development and safety production (Table 9), and labor protection indices (Table 10) can be calculated by assigning to λ from large to small and classification, as shown in Tables 5–10.

A total of twelve indices were chosen for evaluation. Two indices were selected from each of the following conditions: cutting area design, logging tech-

Table 5 The cluster result of cutting area design

λ value	Classification number	Specific category
1	4	$\{X_1\},\{X_2\},\{X_3\},\{X_4\}$
0.81	3	$\{X_1X_3\},\{X_2\},\{X_4\}$
0.74	2	$\{X_1X_3X_4\},\{X_2\}$
0.69	1	$\{X_1X_2X_3X_4\}$

Table 6 The cluster result of logging technology

λ value	Classification number	Specific category
1	5	$\{X_5\},\{X_6],\{X_7\},\{X_8\},\{X_9\}$
0.74	4	$\{X_5X_6\},\{X_7\},\{X_8\},\{X_9\}$
0.68	3	$\{X_5X_6X_7\},\{X_8\},\{X_9\}$
0.67	2	$\{X_5X_6X_7X_8\},\{X_9\}$
0.64	1	$\{X_5X_6X_7X_8X_9\}$

Table 7 The cluster result of ecological environmental impact

λ value	Classification number	Specific category
1	8	$\{X_{10}\}$ $\{X_{11}\},\{X_{12}\}.\{X_{13}\},\{X_{14}\},\{X_{15}\},\{X_{16}\},\{X_{17}\}$
0.73	7	$\{X_{10},X_{16}\}$ $\{X_{11}\},\{X_{12}\}.\{X_{13}\},\{X_{14}\},\{X_{15}\},\{X_{17}\}$
0.72	6	$\{X_{10},X_{15},X_{16}\},\{X_{11}\},\{X_{12}\}.\{X_{13}\},\{X_{14}\},\{X_{17}\}$
0.71	5	$\{X_{10},X_{14},X_{15},X_{16}\},\{X_{11}\},\{X_{12}\}.\{X_{13}\},\{X_{17}\}$
0.68	4	$\{X_{10},X_{12},X_{14},X_{15},X_{16}\},\{X_{11}\},\{X_{13}\},\{X_{17}\}$
0.67	3	$\{X_{10},X_{12},X_{14},X_{15},X_{16},X_{17}\},\{X_{11}\},\{X_{13}\}$
0.65	2	$\{X_{10},X_{12},X_{13},X_{14},X_{15},X_{16},X_{17}\},\{X_{11}\},$
0.64	1	$\{X_{10},X_{12},X_{13},X_{14},X_{15},X_{16},X_{17},X_{11}\},$

Table 8 The cluster result of utilization of resources and energy

λ value	Classification number	Specific category
1	5	$\{X_{18}\},\{X_{19}\},\{X_{20}\},\{X_{21}\},\{X_{22}\}$
0.82	4	$\{X_{18},X_{19}\},\{X_{20}\},\{X_{21}\},\{X_{22}\}$
0.81	3	$\{X_{18},X_{19},X_{21}\},\{X_{20}\},\{X_{22}\}$
0.71	2	$\{X_{18},X_{19},X_{21},X_{22}\},\{X_{20}\}$
0.7	1	$\{X_{18},X_{19},X_{21},X_{20},X_{22}\}$

Table 9 The cluster result of sustainable development

λ value	Classification number	Specific category
1	3	$\{X_{23}\},\{X_{24}\},\{X_{25}\}$
0.6	2	$\{X_{23},X_{25}\},\{X_{24}\}$
0.5	1	$\{X_{23},X_{25},X_{24}\}$

Table 10 The cluster result of safety production management and protection

λ value	Classification number	Specific category
1	4	$\{X_{26}\},\{X_{27}\},\{X_{28}\},\{X_{29}\}$
0.68	3	$\{X_{26},X_{27}\},\{X_{28}\},\{X_{29}\}$
0.67	2	$\{X_{26},X_{27}\},\{X_{28},X_{29}\}$
0.6	1	$\{X_{26},X_{27},X_{28},X_{29}\}$

nology, impacts on ecological environment, resources and energy use, sustainable development and safety production, and labor protection. For the cutting area, specific categories of $\{X_1,\ X_{3,}\ X_4\}$ and $\{X_2\}$ yielded a value of λ=0.74, where $\{X_2\}$ was a part directly put in the index set, but one typical index should be selected from $\{X_1,\ X_{3,}\ X_4\}$. For logging technology, specific categories of $\{X_5,\ X_6,\ X_7,\ X_8\}$ and $\{X_9\}$ yielded a value of λ=0.67, where $\{X_9\}$ was a part directly put in the index set, but one typical index should be selected from $\{X_5,\ X_6,\ X_7,\ X_8\}$, similar to the others. Similar indices have to selected by the correlation index method. Here, the logging technology is taken as an example.

The correlation indices r of $X_5,\ X_6,\ X_7,\ X_8$ should be calculated first, as shown in Table 11.

Table 11 Correlation coefficients of X_5,X_6,X_7,X_8

r_{ij}	X_5	X_5	X_5	X_5
X_5	1.0000	0.2999	0.2723	0.0539
X_6	0.2999	1.0000	0.1531	0.1322
X_7	0.2723	0.1531	1.0000	0.1087
X_8	0.0539	0.1322	0.1087	1.0000

The correlation indices R are calculated as follows.

$$R_5 = \frac{r_{56}^2 + r_{57}^2 + r_{58}^2}{3} = 0.0557 \tag{18}$$

$$R_6 = \frac{r_{65}^2 + r_{67}^2 + r_{86}^2}{3} = 0.0436 \tag{19}$$

$$R_7 = \frac{r_{75}^2 + r_{76}^2 + r_{78}^2}{3} = 0.0684 \tag{20}$$

$$R_8 = \frac{r_{85}^2 + r_{86}^2 + r_{87}^2}{3} = 0.0107 \tag{21}$$

In this instance, the results indicate that R_5>R_6>R_7>R_8. Therefore, R_5 was put into the category because it was the maximum.

The results of the above calculations showed that the indices of logging technology were the rational processes and economics and safe ways to work. So, the indices of cutting area design, impacts on ecological environment, environmental benefits, as well as sustainable development and labor protection could be calculated by the above methods, and the results are shown in Table 12.

The indices shown in Table 12 yielded the following results: first, the relative fuzzy similarity matrix was set up by the maximum and minimum method; then, the fuzzy equivalence matrix was calculated from squares and transitive closure; finally, the indices were selected by the correlation coefficient method.

Table 12 *CP* assessment indicators of plantation logging – six first grade indices and twelve second grade indices (max and min matrix method)

Cutting area design	Logging technology	Impacts on ecological environment	Resources and energy use	Sustainable development	Safety production management and protection
Cutting area survey	Rational processes	Soil physical properties	Utilization ratio of wood	Survive ratio of renew	Safety management
Engineering design	Economics and safety of ways to work	Biodiversity	Utilization ratio of slashes	Renew ratio of cutting area	Labor protection

(2) Relation coefficient method

A fuzzy similarity matrix was set up by the relation coefficient method, and then the indices of *CP* evaluation for plantation logging can be calculated by the steps that were similar to the maximum and minimum method.

After the raw data was initialized, the relation coefficients between each index were calculated, and the absolute value of the relation coefficients can be the elements for determining the fuzzy similarity matrix. Six fuzzy similarity matrices of cutting area design (22), logging technology (23), impacts on the ecological environment (24), resources and energy use (25), sustainable development and safety production management (26) and labor protection (27) were calculated by relation coefficient method, as shown in eq. (22)–(27).

$$\left|\begin{array}{cccc} 1.0000 & 0.1606 & 0.1473 & 0.0574 \\ 0.1606 & 1.0000 & 0.1168 & 0.0852 \\ 0.1473 & 0.1168 & 1.0000 & 0.3724 \\ 0.0574 & 0.0852 & 0.3724 & 1.0000 \end{array}\right| \tag{22}$$

$$\left|\begin{array}{ccccc} 1.0000 & 0.2999 & 0.2723 & 0.0539 & 0.1084 \\ 0.2999 & 1.0000 & 0.1531 & 0.1322 & 0.0067 \\ 0.2723 & 0.1531 & 1.0000 & 0.1087 & 0.2941 \\ 0.0539 & 0.1322 & 0.1087 & 1.0000 & 0.0745 \\ 0.1084 & 0.0067 & 0.2941 & 0.0745 & 1.0000 \end{array}\right| \tag{23}$$

$$\left|\begin{array}{cccccccc} 1.0000 & 0.0460 & 0.0025 & 0.1657 & 0.0903 & 0.0186 & 0.4263 & 0.1835 \\ 0.0460 & 1.0000 & 0.1677 & 0.0214 & 0.3787 & 0.1073 & 0.1053 & 0.0310 \\ 0.0025 & 0.1677 & 1.0000 & 0.1179 & 0.0916 & 0.2481 & 0.0852 & 0.0748 \\ 0.1657 & 0.0214 & 0.1179 & 1.0000 & 0.1741 & 0.0976 & 0.1401 & 0.0297 \\ 0.0903 & 0.3787 & 0.0916 & 0.1741 & 1.0000 & 0.3394 & 0.3937 & 0.1963 \\ 0.0186 & 0.1073 & 0.2481 & 0.0976 & 0.3394 & 1.0000 & 0.1546 & 0.0869 \\ 0.4263 & 0.1053 & 0.0852 & 0.1401 & 0.3937 & 0.1546 & 1.0000 & 0.0359 \\ 0.1835 & 0.0310 & 0.0748 & 0.0297 & 0.1963 & 0.0869 & 0.0359 & 1.0000 \end{array}\right| \tag{24}$$

$$\left|\begin{array}{ccccc} 1.0000 & 0.3713 & 0.0046 & 0.0516 & 0.1345 \\ 0.3713 & 1.0000 & 0.0218 & 0.2802 & 0.3744 \\ 0.0046 & 0.0218 & 1.0000 & 0.0237 & 0.2917 \\ 0.0516 & 0.2802 & 0.0237 & 1.0000 & 0.0076 \\ 0.1345 & 0.3744 & 0.2917 & 0.0076 & 1.0000 \end{array}\right| \tag{25}$$

$$\left|\begin{array}{ccc} 1.0000 & 0.0346 & 0.1412 \\ 0.0346 & 1.0000 & 0.1019 \\ 0.1412 & 0.1019 & 1.0000 \end{array}\right| \tag{26}$$

$$\left|\begin{array}{cccc} 1.0000 & 0.2620 & 0.1077 & 0.2588 \\ 0.2620 & 1.0000 & 0.0470 & 0.1584 \end{array}\right| \tag{27}$$

Six fuzzy equivalence matrices of cutting area design (28), logging technology (29), impacts on the ecological environment (30), resources and energy use (31), sustainable development and safety production management (32) and labor protection (33) were calculated by the squares method, as shown in eq. (28)–(33).

$$\left|\begin{array}{cccc} 1.0000 & 0.1606 & 0.1473 & 0.1473 \\ 0.1606 & 1.0000 & 0473 & 0.1473 \\ 0.1473 & 0.1473 & 1.0000 & 0.3724 \\ 0.1473 & 0.1473 & 0.3724 & 1.0000 \end{array}\right| \tag{28}$$

$$\left|\begin{array}{ccccc} 1.0000 & 0.2999 & 0.2723 & 0.0539 & 0.1084 \\ 0.2999 & 1.0000 & 0.1531 & 0.1322 & 0.0067 \\ 0.2723 & 0.1531 & 1.0000 & 0.1087 & 0.2941 \\ 0.0539 & 0.1322 & 0.1087 & 1.0000 & 0.0745 \\ 0.1084 & 0.0067 & 0.2941 & 0.0745 & 1.0000 \end{array}\right| \tag{29}$$

$$\begin{vmatrix} 1.0000 & 0.3787 & 0.2481 & 0.1741 & 0.3937 & 0.3394 & 0.4263 & 0.1963 \\ 0.3787 & 1.0000 & 0.2481 & 0.1741 & 0.3787 & 0.3394 & 0.3787 & 0.1963 \\ 0.2481 & 0.2481 & 1.0000 & 0.1741 & 0.2481 & 0.2481 & 0.2481 & 0.1963 \\ 0.1741 & 0.1741 & 0.1741 & 1.0000 & 0.1741 & 0.1741 & 0.1741 & 0.1741 \\ 0.3937 & 0.3787 & 0.2481 & 0.1741 & 1.0000 & 0.3394 & 0.3937 & 0.1963 \\ 0.3394 & 0.3394 & 0.2481 & 0.1741 & 0.3394 & 1.0000 & 0.3394 & 0.1963 \\ 0.4263 & 0.3787 & 0.2481 & 0.1741 & 0.3937 & 0.3394 & 1.0000 & 0.1963 \\ 0.1963 & 0.1963 & 0.1963 & 0.1741 & 0.1963 & 0.1963 & 0.1963 & 1.0000 \end{vmatrix} \tag{30}$$

$$\begin{vmatrix} 1.0000 & 0.3713 & 0.2917 & 0.2802 & 0.3713 \\ 0.3713 & 1.0000 & 0.2917 & 0.2802 & 0.3744 \\ 0.2917 & 0.2917 & 1.0000 & 0.2802 & 0.2917 \\ 0.2802 & 0.2802 & 0.2802 & 1.0000 & 0.2802 \\ 0.3713 & 0.3744 & 0.2917 & 0.2802 & 1.0000 \end{vmatrix} . \tag{31}$$

$$\begin{vmatrix} 1.0000 & 0.1019 & 0.1412 \\ 0.1019 & 1.0000 & 0.1019 \\ 0.1412 & 0.1019 & 1.0000 \end{vmatrix} \tag{32}$$

$$\begin{vmatrix} 1.0000 & 0.2620 & 0.1077 & 0.2588 \\ 0.2620 & 1.0000 & 0.1077 & 0.2588 \\ 0.1077 & 0.1077 & 1.0000 & 0.1077 \\ 0.2588 & 0.2588 & 0.1077 & 1.0000 \end{vmatrix} \tag{33}$$

Later steps were quite the same using the maximum and minimum method, and the indices are shown in Table 13.

Results from Table 12 and Table 13 were quite similar. Only two indices were different, which indicates that both of the methods were reliable for calculating the index. Using both methods strengthens the analysis.

4. Discussion

In this study, we have selected some evaluation indices of *CP* on the basis of plantation logging and set principles. *CP* has been widely applied in all kinds of industry, but seldom used in forestry. In recent years, the theories and concepts of *CP* have been considered for the harvesting area in China, but they only discussed the concept, role of target, and no real analysis of the products. While the production process was generally found to be environmentally acceptable during timber harvesting, a more formal process is needed for an accurate evaluation (Qiang 2000, Zhao 2000, Zhao 2008, Yu 2009). There was a lack of specifics and targeted results in practice, and guidance was not strong in the forest enterprise. The findings of this study indicate implementation of cleaner production in China could have a guiding role in forest engineering companies.

To evaluate the contents of cleaner production in plantation harvesting operations, we distributed 100 questionnaires to professors in university, researchers in forestry research institute and loggers or workers in forestry enterprises and recovered thirty valid questionnaires. The low participation may indicate that most of them put less emphasis on cleaner production, especially the forest engineering enterprises in China. It has been proposed that the Chinese government should increase publicity and education in this area. Like other industries, implementation could include the introduction of incentives or relevant laws and regulations to ensure that more attention is paid on the cleaner production in the forestry enterprises.

According to the investigation results based on the thirty submitted responses, the fuzzy clustering method was used to initially screen twenty-nine second-grade indices. Six first-grade indices and twelve second-grade indices were selected as formal evaluation indices. As we all know, the other second-grade indices not selected are also important, but too many indices will be difficult to analyze in practice in forest companies. According to the principles for determining evaluation indices, the index system for *CP* could not cover all the processes in the plantation logging. Generally the most simple and focused indices are implemented effectively. The purpose of the questionnaire was issued for the forestry enterprises, with the more important indices related to the implementation of cleaner production in plantation logging. According to the 30 valid questionnaires, the fuzzy cluster methods were used to select the more important indices. This indicates that the selected second-grade indices are more important than other second-grade indices not selected according to the results of questionnaires and fuzzy cluster methods.

At the same time, several methods were used to screen evaluation indices, such as the gray correlation method, analytic hierarchy process, etc., (Shen 2002, Xu 2007) but the fuzzy clustering analysis was widely used for objectivity and accuracy (Yang 2011). The results showed that the fuzzy clustering method is reliable for screening indices. *CP* of plantation logging had its own advantages compared with other *CP* objectives that were combined, such as saving resources, reasonable use of renewable energy in forests, protecting the environment in forests and educating personal protection for workers. The basic principle with *CP* is »prevention must come first, treatment should only

Table 13 *CP* assessment indicators of plantation logging – six first grade indices and twelve second grade indices (correlation coefficient matrix method)

Cutting area design	Logging technology	Impacts on the ecological environment	Resources and energy use	Sustainable development	Safety production management and labor protection
Cutting area survey	Rational processes	Soil physical properties	Utilization ratio of wood	Survive ratio of renew	Safety management
Production process design	Economics and safety of ways to work	Biodiversity	Logging equipment fuel consumption	Renew ratio of cutting area	Labor protection

be needed in special circumstances« in all the stages of the logging process.

Our initial findings indicate the methods of using advanced technology and improving process and equipment. Different logging methods (included cutting, bucking, skidding and transportation) were used in cutting areas due to different terrain conditions, and even the working efficiencies differed when using the same logging methods in the same cutting area. For example, skidding with cableway was suitable for hills or mountain communities, but skidding with tractors was suitable for flat communities. The harvesting machine has been used due to its high work efficiency; however, it is not suitable for all cutting areas because of working conditions. Therefore, it is better to use advanced technology and improve processing and equipment based on local conditions.

Secondly, in the ways of saving and rationally using resources and energy, the tree was the raw material for *CP* of logging. The best time to log was when the tree biomass has been at its maximum. On the other hand, the special characteristics of *CP* for logging were the complex working conditions, fertility of the slash, overlapping of the working system and ecological system, complexity and fuzziness of multiple factors.

In recent years, two areas have been studied on plantation logging. One area was the impacts of logging on the ecological environment, whic included the soils, vegetation, tree survival, wild animals, biological diversity, landscapes, and use of slash (Wang 2005, Rab 1994a and 1996b, Li 1994, Qiu 1998, Chen 1999, Croke et al. 2001a and 2006b, Blumfield et al. 2003, Hartanto et al. 2003, Bird et al. 2004, Pennington et al. 2004, Radel et al. 2006, Demir et al. 2007, Langer et al. 2008, Frey et al. 2009, Walmsley et al. 2009, Stoffel et al. 2010) The other study was done on the ecological logging processes and technology, which included the evaluation of ecological, economic and combined benefits (Huang 1995, Deng 2005, Zhang 2005, Spinelli et al. 2012, Berhongaray et al. 2013). Many evaluation systems for *CP* have been widely used in chemical engineering, services, and agricultures all over the world. Studies on *CP* for forests pointed out the conception, overall goals, guidelines, and the implementation of the measures without further investigations. In China, some rules and regulations of *CP* have been accomplished in a few large logging enterprises, as indicated in the article »The Measures for *CP* by Genhe Forestry Bureau«. Unfortunately, there was not any further analysis involving contents, index system for evaluation, and methods for evaluation. Therefore, more studies will be needed on *CP* for plantation logging.

5. Conclusions

In this paper, an index system of *CP* evaluation for plantation logging was set up on the basis of *CP*, according to the characteristics of plantation logging. The contents of such an index system included the following six first-grade criteria: cutting area design, logging technology, impacts on the ecological environment, resources and energy use, sustainable development and safety production management, and labor protection. The fuzzy cluster method was used to select the indices. Finally, twelve second-grade indices were selected as the evaluation indices. A comparison using both maximum and minimum analysis and correlation analysis showed that 10 of the 12 indices were acceptable. The twelve second-grade indices selected are just the first step for *CP* of logging. According to the results of selecting, these made the standard for *CP* evaluation of plantation logging. Then, according to the standards, cleaner production audit will be implemented to check the forest companies, expecting forest companies to meet the standards. The implemented guidelines of *CP* in plantation logging will give them the right directions. So, the results of selecting indices will be beneficial for sustainable production and management of plantation forests in China.

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Authors' address:

Assoc. prof., Aihua Yu, PhD.
e-mail: azy0008@auburn.edu
Prof., Chen Zhao, PhD.
e-mail: czh@njfu.edu.cn
Lecturer, Yao Zhao, PhD.
e-mail:zhaoyaonfu@163.com
Department of Forest Engineering
Nanjing Forestry University
159 RongPan Road
210037 Nanjing, Jiangsu province
P.R. CHINA

Assoc. prof., Tom Gallagher, PhD.*
e-mail: tgallagher@auburn.edu
School of Forestry and Wildlife Sciences
Auburn University
3425 Forestry and Wildlife Sciences Building
36830 Auburn, Alabama
USA

* Corresponding author

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