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Research article

Multi-criteria decision making for sustainability assessment of boxboard production: A life cycle perspective considering water consumption, energy consumption, GHG emissions, and internal costs

Yi Man [a], Yulin Han [a], Yue Liu [b], Ruojue Lin [b], Jingzheng Ren [b,*]

[a] *State Key Laboratory of Pulp and Paper Engineering, South China University of Technology, Guangzhou, 510640, China*
[b] *Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, HongKong, China*

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ABSTRACT

Papermaking is a capital-intensive industry that requires a high consumption of plant fibers, energy, and water. Previous sustainability assessments of papermaking industry primarily focused on separate evaluations for multiple criteria without the integration for criteria and could not compare the overall priority of the production alternatives. The life cycle sustainability for the most representative boxboard production is analyzed as a case study in this work. Life cycle water consumption, energy consumption, greenhouse gas emissions, and internal costs are selected as the assessment criteria. The two multi-criteria decision-making methods are applied to integrate the above criteria to obtain the sustainability sequence under different production pathways. When the papermaking enterprises are regarded as decision-makers, the alternative using waste paper as raw material to manufacture boxboard is the most sustainable, following by mixed fiber. The sustainability sequence of the alternatives using wood and straw as raw materials is controversial due to the different calculation models. Changing the proportion of raw materials and the criteria weights might adjust sustainability sequence of the alternatives.

1. Introduction

Papermaking is a capital-intensive industry with a long industrial chain, it contributes to about 3% of global end uses of energy (Ma et al., 2018), 2% of global industrial carbon emissions (Bajpai, 2016), and 40% of global industrial wastewater (Ashrafi et al., 2015). In China, the rapid development of papermaking industry brings extensive energy demand and high emission generation, the sustainable development of papermaking industry has received widespread attention (Ingwersen et al., 2016; Wang et al., 2016; Corcelli et al., 2018). As the largest paper producer around the world, the papermaking industry in China is surrounded by several challenges: the energy structure dominated by coal leads to significant emissions of greenhouse gases (GHG) (Wang et al., 2016); the technology level varies greatly and too much capital is invested for unit product in some enterprises; low forest cover (Zhu et al., 2017) and policies on restricting deforestation prompt that papermaking industry has to import large quantities of wood and pulp board, resulting in increased cost and material replacement. Therefore, in order to achieve sustainable development of the papermaking industry, it needs to overcome environmental, economic and social obstacles.

Since 2007, the production of boxboard has headed the list in China's papermaking industry for 11 years and it accounted for 21.4% of the total paper production in 2017. Boxboard papermaking industry is still in a rising state with the development of packaging and logistics industries (CPA, 2017). The boxboard papermaking enterprises are widely distributed in every province in China, most of them use recycled waste paper to produce non-deinked pulp to manufacture boxboard, some sorts of high-grade boxboard are manufactured by using natural wood pulp cooked from wood chips or using natural straw pulp, the latter is mostly distributed in the major straw-producing area in north China. Besides, mixing virgin pulp and waste paper pulp as a raw material is also a common solution for the production of boxboard.

Variety of production pathways have a different effect on the sustainability criteria for papermaking industry. The industrial process assessment (Wen et al., 2016; Li et al., 2015) and life cycle analysis (Man et al., 2018a; Ewijk et al., 2018) of papermaking industry analyzed environmental and economic criteria from different boundaries. The

* Corresponding author..
E-mail address: jzhren@polyu.edu.hk (J. Ren).

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previous sustainability research for the papermaking industry aimed to obtain a relative prioritized pathway by quantifying and comparing the single or multiple criteria, ignoring the overall optimal pathway identified by integrating multiple criteria. As a result, it is necessary to adopt the multi-criteria decision making (MCDM) method to papermaking industry for supporting decision-makers in selecting the most sustainable pathway.

MCDM method is introduced and regarded as the best solution for dealing with sustainability conflicts at both micro and macro levels of analysis (Antunes et al., 2005). The use of MCDM methods to assess sustainability has been extended to diverse fields in recent years (Diaz-Balteiro et al., 2016). Kumar et al. (2013) considered the quantitative properties obtained from chemical experiments and morphological analysis, and demonstrated the applicability of pulp raw material selection problems using TOPSIS (a technique for order preference by similarity to an ideal solution) method. Goh et al. (2013) combined AHP (analytical hierarchical process) and TOPSIS methods for large pulp mill electrical system, the objective is to determine the ranking of the load according to their importance level. However, in addition to the above researches, no other MCDM studies on the papermaking industry have been found, the application of MCDM in papermaking industry to assess its sustainability is rare.

There is an increasing trend to assess the sustainability of industrial systems with life cycle perspective (Heijungs et al., 2010). Life cycle analysis is able to collect the data of the assessment criteria from "cradle" to "grave" instead of mere industrial process. For example, in papermaking industry, the growth of raw materials such as forest and agricultural straw require a large amount of water for irrigation, their impacts on water resources might be underestimated if only the industrial process is considered; additionally, transportation accounts for more than 10% of the total operating costs of pulp and paper companies (Sanitation, 2004). In recent years, the research focused on life cycle analysis for papermaking industry provided enough data basis for sustainability assessment (Gemechu et al., 2013; Sun et al., 2018; Man et al., 2018b; Xu and Becker, 2012).

Balancing environmental sustainability and profitability is a challenge for the papermaking industry (Sanitation, 2004). In order to consider multiple criteria simultaneously to find the most sustainable production pathway, the production of boxboard is analyzed as a case study with four alternative production pathways, in which the raw materials they used are wood (A_1), straw (A_2), waste paper (A_3) and mixed fiber (A_4), respectively. A total of four criteria including water consumption, energy consumption, GHG emissions, and internal costs are employed for life cycle analysis. Two MCDM methods are used for integrating the above criteria to rank the sustainability of various pathways for verifying the effectiveness of the MCDM methods. This work can achieve the selection of the most sustainable raw material and pathway and promote the sustainable development of the boxboard papermaking industry.

2. Literature review

In the past few decades, the new MCDM method has been continuously proposed and improved. Best-worst method (BWM) was proposed by Rezaei (2015) and attracted many scholars' attention in recent years. Ren et al. (2018) extended the method to solve the problem of uncertainties using interval numbers. With the same objective to address the uncertainties of information, Aboutorab et al. (2018) provide an integration of BWM and Z-numbers, namely ZBWM, the authors emphasized the capabilities of the proposed method to process big data information and achieve the higher consistency. The BWM finds the optimal weights of multiple criteria based on the preference of only one decision maker (DM), Mohammadi and Rezaei (2019) introduced Bayesian BWM to find the aggregated final weight for a groups of DMs at once. Mi et al. (2019) reviewed 124 publications on BWM, exploring the applicable areas and extensions. Both AHP and BWM can calculate the weight of the criteria, and the BWM requires fewer comparison data and complexity and can achieve more reliable results (Rezaei, 2015; Ren et al., 2018; Mi et al., 2019).

Other MCDM methods, such as TOPSIS, ELECTRE, VIKOR, and PROMETHEE, can utilize the calculated weights to obtain the alternative rankings. The TOPSIS method was proposed by Hwang and Yoon (1981). Olson (2004) reviewed several applications of the TOPSIS method using different weighting schemes and compared them with other methods. The results showed that the TOPSIS method is quite good at low-order application. Jahanshahloo and Lotfi (2006) extended the TOPSIS method to solve the ambiguity of decision-making problems with interval numbers. Kacprzak (2019) extended the TOPSIS method to group decision making using ordered fuzzy numbers. The TOPSIS method can make full use of allocated information which need not be independent (Kumar et al., 2017), so it is suitable for this paper because of the existence of water-energy nexus and energy-related GHG emissions. ISWM (interval sum weighted method) is often used to compare with other MCDM to verify rationality (Kumar et al., 2017; Ren et al., 2018; Chung and Kim, 2014). Therefore, the integration of BWM and TOPSIS is applied to the life cycle sustainability assessment of the paper industry, and the result of the ISWM is used as a reference.

The aforementioned methods have been applied to various fields. Biomass conversion technology is mainly divided into three types: combustion, pyrolysis and gasification, Kaa et al. (2017) selected 12 relevant factors for standard dominance, BWM is utilized to calculate the weights of these factors and rank the three technologies, gasification has the greatest chance of achieving the standard advantage. According to the assessment of Iranian provincial performance data based on BWM, Kheybari et al. (2019) selected the best location for bioethanol production based on three dimensions of sustainability. Chung and Kim (2014) sorted the priorities of treated wastewater use locations based on dozens of criteria affecting water quantity and water quality using fuzzy TOPSIS. Mir et al. (2016) defined 11 domestic waste treatment methods and introduced an improved version of TOPSIS to select the best treatment method according to the environment (LCA) and economic criteria according to the waste management regulations. Gupta and Barua (2018) and Gupta (2018) used the BWM and TOPSIS methods to explore green management, both studies were divided into three phases: 1. Identify barriers or criteria in green practice; 2. Use BWM to treat the weight of the barriers or practices; 3. The Fuzzy TOPSIS method is used to rank the barriers of the solutions or manufacturing organizations on the basis of the new practices.

In summary, this study takes the production path of boxboard as the research object, selects interval BWM to evaluate the weights of decision maker on each life cycle assessment criteria, ISWM and interval TOPSIS methods are applied to rank the alternatives and sensitivity analysis is conducted.

3. Methodology

3.1. Criteria for life cycle analysis in boxboard production

The life cycle boundary of the boxboard production is shown in Fig. 1. For large and medium papermaking industries, pulp production, papermaking production, waste treatment, and utilities for heat, electricity, and circulating water are usually integrated. Some enterprises also integrate the raw material plantation and collection process. Therefore, the system boundary for holistic boxboard papermaking starts with the cultivation and collection of raw materials, through pulp making and paper forming, to the finished products being used. Part of the waste paper is recycled to the next production cycle. The utilities provide the energy for the industrial chain, the GHG emissions from the combustion of fossil fuels contribute the largest share of total emissions (Wang et al., 2016).

The water consumption in the life cycle of boxboard includes direct and indirect water consumption (Man et al., 2018a). The direct water

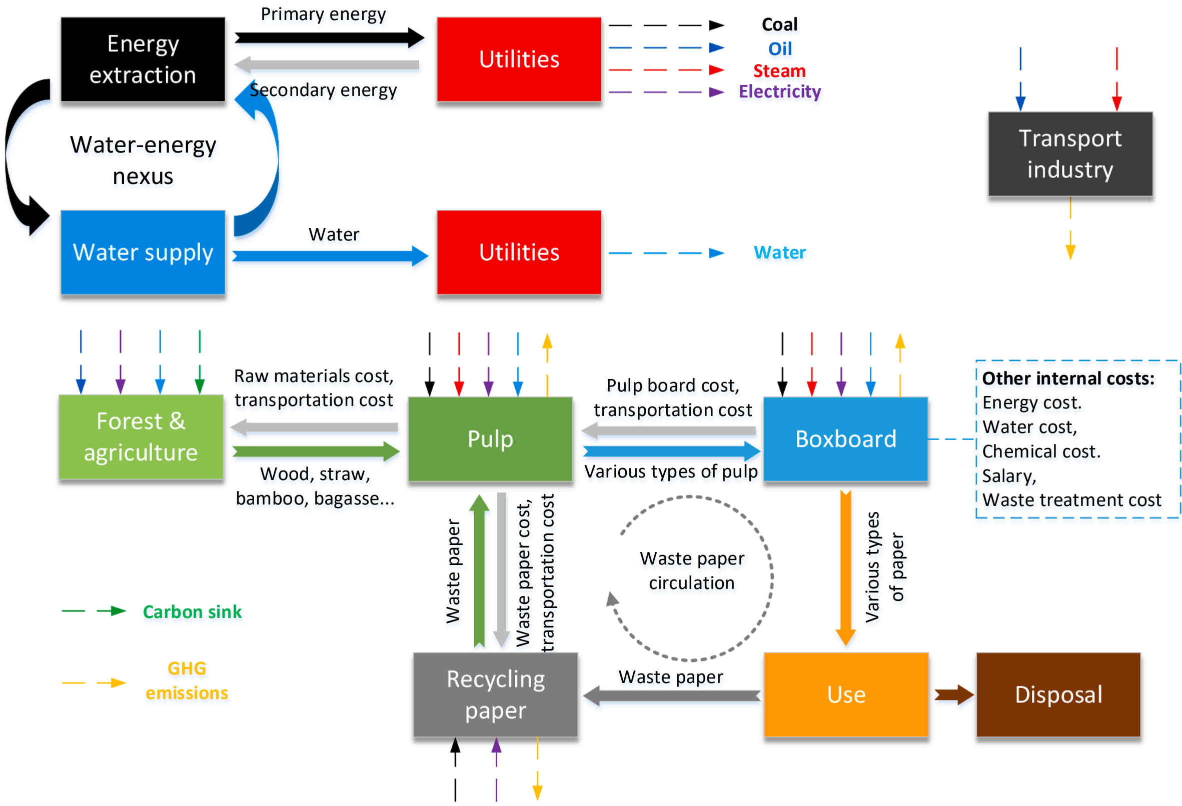

Fig. 1. Life cycle boundary of the boxboard production.

consumption refers to the water intake for crops irrigation and pulp and papermaking production processes, the indirect water consumption is involved in energy supply. In the life cycle stages of boxboard, water is required for mineral extraction in mining operations, drilling and resource recovery in petroleum production, and cooling and processing in thermoelectric power generation.

Energy is required for collecting raw materials by forestry and agricultural machinery, coal-based cogeneration in pulp and paper-making industrial parks, transportation sector and energy supply sector itself.

In addition to the GHG emissions from the combustion of fossil fuels in the industrial chain, it also occurs in the pulp and papermaking production processes, including the combustion of the lost biomass and black liquor, limestone calcination and wastewater treatment (Wang et al., 2016).

The life cycle internal costs of boxboard refer to the direct costs associated with the production, including the costs of raw materials, process operation, transportation, energy, waste disposal, and salary.

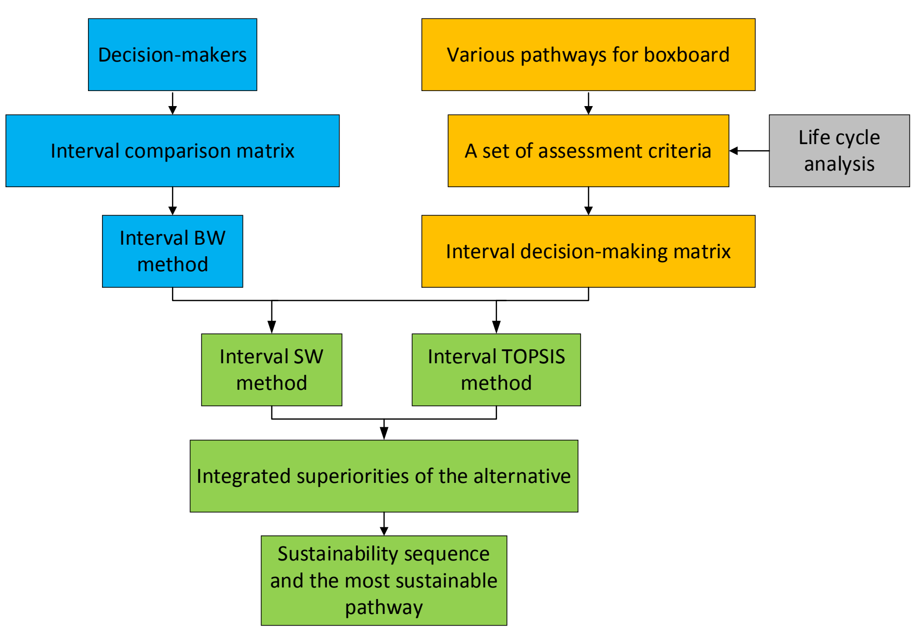

Fig. 2. The framework of the proposed sustainability assessment methodology.

In many cases, it is difficult to quantify the various assessment criteria using definite numbers, where only uncertain and ambiguous attributes are available (Ren, 2018), therefore, the performance of each life cycle assessment criterion is a scope described by an interval number.

3.2. MCDM model

The sustainability assessment framework of this work is presented in Fig. 2. The assessment criteria in all production pathways are obtained by life cycle analysis, and the weights of assessment criteria are determined by the role of decision-makers.

3.2.1. Best-worst method

The developed interval BW method contains the following steps (Ren et al., 2018):

(1) Determining the best and worst criterion , denotes by C_B and C_W
(2) The preference of the best criterion over all the other criteria and that of all the other criteria over the worst criterion are determined by using interval numbers according to the nine-scale system in Saaty method (Saaty, 1978). The definition and arithmetic operations of interval number are presented in Ren et al. (2018).

$$BO = [\tilde{a}_{B1}\tilde{a}_{B2}\cdots\tilde{a}_{Bn}] \tag{1}$$

$$OW = [\tilde{a}_{1W}\tilde{a}_{2W}\cdots\tilde{a}_{nW}] \tag{2}$$

$$\tilde{a}_{Bj} = \left[a_{Bj}^{L} \quad a_{Bj}^{U}\right] \ (j = 1, 2, \ldots, n) \tag{3}$$

$$\tilde{a}_{jW} = \left[a_{jW}^{L} \quad a_{jW}^{U}\right] \ (j = 1, 2, \ldots n) \tag{4}$$

where $\tilde{a}_{Bj}$ and $\tilde{a}_{jW}$ are interval numbers which refer to the relative preference of the best criterion and the worst criterion over the j-th criteria. The superscripts L and U represent lower and upper limits of the interval numbers, respectively. When $j = B$, then $\tilde{a}_{Bj} = 1 = [1 \quad 1]$.

(3) Calculate the optimal weights of criteria, denotes by $(\tilde{\omega}_1\tilde{\omega}_2\cdots\tilde{\omega}_n)$

$$\frac{\tilde{\omega}_B}{\tilde{\omega}_j} = \tilde{a}_{Bj} \ (j = 1, 2, \cdots n) \tag{5}$$

$$\frac{\tilde{\omega}_j}{\tilde{\omega}_w} = \tilde{a}_{jw} \ (j = 1, 2, \cdots n) \tag{6}$$

$$\tilde{\omega}_j = \left[\omega_j^{L} \quad \omega_j^{U}\right] \tag{7}$$

where $\tilde{\omega}_j$ represents the interval weight of the j-th criterion, $\tilde{\omega}_B$ and $\tilde{\omega}_W$ represent the interval weights of the best and the worst criteria. The above equations can be further rewritten as equations (8)–(12) (Ren et al., 2018).

$$\frac{\omega_B^{L}}{\omega_j^{U}} = a_{Bj}^{L} \ (j = 1, 2, \cdots n) \tag{8}$$

$$\frac{\omega_B^{U}}{\omega_j^{L}} = a_{Bj}^{U} \ (j = 1, 2, \cdots n) \tag{9}$$

$$\frac{\omega_j^{L}}{\omega_W^{U}} = a_{jW}^{L} \ (j = 1, 2, \cdots n) \tag{10}$$

$$\frac{\omega_j^{U}}{\omega_W^{L}} = a_{jW}^{U} \ (j = 1, 2, \cdots n) \tag{11}$$

$$\xi = \text{minmax}_j \left\{ \left|\frac{\omega_B^{L}}{\omega_j^{U}} - a_{Bj}^{L}\right|, \left|\frac{\omega_B^{U}}{\omega_j^{L}} - a_{Bj}^{U}\right|, \left|\frac{\omega_j^{L}}{\omega_W^{U}} - a_{jW}^{L}\right|, \left|\frac{\omega_j^{U}}{\omega_W^{L}} - a_{jW}^{U}\right| \right\} \tag{12}$$

The vectors of interval weights are constrained by the following inequalities (Sugihara et al., 2004):

$$\omega_i^{L} + \sum_{j=1, j\neq i}^{n} \omega_j^{U} \geq 1 \tag{13}$$

$$\omega_i^{U} + \sum_{j=1, j\neq i}^{n} \omega_j^{L} \leq 1 \tag{14}$$

$$\omega_j^{U} \geq \omega_j^{L} \tag{15}$$

$$\omega_j^{L} \geq 0 \tag{16}$$

This is a non-linear programming and the optimal weights$(\tilde{\omega}_1\tilde{\omega}_2\cdots\tilde{\omega}_n)$ can be obtained by solving programming. ξ^* is the value of the objective function under the optimal conditions.

(4) Consistency check

The interval comparison vectorsBO andOW are consistent only if $[a_{Bj}^{L} \quad a_{Bj}^{U}] \times [a_{jW}^{L} \quad a_{jW}^{U}] = [a_{BW}^{L} \quad a_{BW}^{U}]$ holds. This step provides a method for checking and measuring the consistency degree of the interval comparison vectors (Ren et al., 2018).

The calculation of consistency index$(C\tilde{I})$ is presented as follow , where δ^{*L} andδ^{*U} represent lower and upper bounds.

$$\delta^{*L} = a_{BW}^{U} - \sqrt{2 \times a_{BW}^{U} + \frac{1}{4}} + \frac{1}{2} \tag{17}$$

$$\delta^{*U} = a_{BW}^{U} - \sqrt{a_{BW}^{U} + a_{BW}^{L} + \frac{1}{4}} + \frac{1}{2} \tag{18}$$

The consistency ratio$(C\tilde{R})$ can be calculated for measuring the consistency degree of the interval comparison vectors, as shown in equation (19).

$$C\tilde{R} = \frac{\xi^*}{C\tilde{I}} = \frac{\xi^*}{[\delta^{*L} \quad \delta^{*U}]} = \left[\frac{\xi^*}{\delta^{*U}} \quad \frac{\xi^*}{\delta^{*L}}\right] \tag{19}$$

$$m(C\tilde{R}) = \frac{C\tilde{R}^{L} + C\tilde{R}^{U}}{2} \tag{20}$$

where $m(C\tilde{R})$ is the midpoint of $C\tilde{R}$, 0.15 was set as the threshold of $m(C\tilde{R})$by Ren et al. (2018).

3.2.2. ISWM model

In order to increase the reliability of the application, this work applies two MCDM models which are ISWM and TOPSIS to analyze the sustainability of the alternatives and compare their results. The calculation steps of the ISWM model are illustrated in many researches (Kumar et al., 2017; Ren et al., 2018; Chung and Kim, 2014):

(1) Determining the decision-making matrix

The elements of the decision-making matrix include all the performance data of the assessment criteria with respect to different alternatives, as shown in equation (21).

$$\tilde{D} = \begin{matrix} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} \begin{matrix} C_1 C_2 \cdots C_n \\ \begin{pmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{pmatrix} \end{matrix} \tag{21}$$

where $\tilde{D}$ represents the decision-making matrix, A_i is the i-th alternative, $C_j$is the j-th criterion, $\tilde{x}_{ij} = [\tilde{x}_{ij}^L \quad \tilde{x}_{ij}^U]$ represents the interval value of the j-th criterion with respect to the i-th alternative.

(2) Normalizing the decision-making matrix (ISWM)

The meanings and dimensions of the criteria are different, in order to compare the criteria in a dimensionless form, the decision-making matrix needs to be normalized, as presented in equation (22). The normalizations of benefit-type-criteria and cost-type-criteria are given in equations (23) and (24), respectively (Ren et al., 2018).

$$\tilde{R} = \begin{matrix} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} \begin{matrix} C_1 C_2 \cdots C_n \\ \begin{pmatrix} \tilde{r}_{11} & \tilde{r}_{12} & \cdots & \tilde{r}_{1n} \\ \tilde{r}_{21} & \tilde{r}_{22} & \cdots & \tilde{r}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{r}_{m1} & \tilde{r}_{m2} & \cdots & \tilde{r}_{mn} \end{pmatrix} \end{matrix} \tag{22}$$

$$\tilde{r}_{ij} = \left[x_{ij}^L \Big/ \max_{i=1,2,\cdots m}\left\{x_{ij}^U\right\}, \ x_{ij}^U \Big/ \max_{i=1,2,\cdots m}\left\{x_{ij}^L\right\} \right] \tag{23}$$

$$\tilde{r}_{ij} = \left[\min_{i=1,2,\cdots m}\left\{x_{ij}^L\right\} \Big/ x_{ij}^U, \ \min_{i=1,2,\cdots m}\left\{x_{ij}^L\right\} \Big/ x_{ij}^L \right] \tag{24}$$

where $\tilde{R}$ represents the normalized interval decision-making matrix, all the normalized data are interval numbers between 0 and 1.

(3) Determining the weighted decision-making matrix

$$\tilde{V} = \begin{matrix} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} \begin{matrix} C_1 C_2 \cdots C_n \\ \begin{pmatrix} \tilde{\omega}_1 \times \tilde{r}_{11} & \tilde{\omega}_2 \times \tilde{r}_{12} & \cdots & \tilde{\omega}_n \times \tilde{r}_{1n} \\ \tilde{\omega}_1 \times \tilde{r}_{21} & \tilde{\omega}_2 \times \tilde{r}_{22} & \cdots & \tilde{\omega}_n \times \tilde{r}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{\omega}_1 \times \tilde{r}_{m1} & \tilde{\omega}_2 \times \tilde{r}_{m2} & \cdots & \tilde{\omega}_n \times \tilde{r}_{mn} \end{pmatrix} \end{matrix} \tag{25}$$

where $\tilde{V}$ represents the weighted decision-making matrix, $\tilde{\omega}_j$ represents the optimal weight of the j-th criterion, $\tilde{r}_{ij}$ represents the normalized performance data of the i-th alternative with respect to the j-th criterion (Ren et al., 2018).

(4) Determining the integrated superiorities of the alternatives (ISWM)

The integrated superiorities of the alternatives are determined by equation (26).

$$IS_i = \sum_{j=1}^{n} (\tilde{\omega}_i \times \tilde{r}_{ij}) = \sum_{j=1}^{n} \tilde{v}_{ij} \tag{26}$$

where $\tilde{v}_{ij}$ represents the weighted value of the i-th alternative with respect to the j-th criterion. IS_i represents the integrated superiorities of the i-th alternative (Ren et al., 2018).

3.2.3. TOPSIS model

The principle of TOPSIS is to find the positive ideal solution and negative ideal solution of the assessment criteria, the overall priority is determined according to the Euclidean distance among the ideal solutions and other alternatives (Jahanshahloo and Lotfi, 2006). The alternative that is closest to the positive ideal solution and far away from the negative solution is the most sustainable. The calculation steps of the TOPSIS model differs from the ISWM (Jahanshahloo and Lotfi, 2006):

(1) Determining the decision-making matrix, this step is the same as the ISWM

(2) Normalizing the decision-making matrix (TOPSIS)

$$\tilde{R} = \begin{matrix} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{matrix} \begin{matrix} C_1 C_2 \cdots C_n \\ \begin{pmatrix} \tilde{n}_{11} & \tilde{n}_{12} & \cdots & \tilde{n}_{1n} \\ \tilde{n}_{21} & \tilde{n}_{22} & \cdots & \tilde{n}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{n}_{m1} & \tilde{n}_{m2} & \cdots & \tilde{n}_{mn} \end{pmatrix} \end{matrix} \tag{27}$$

$$\tilde{n}^L{}_{ij} = x_{ij}^L \Big/ \sqrt{\sum_{j=1}^{m} \left(x_{ij}^L\right)^2 + \left(x_{ij}^U\right)^2} \tag{28}$$

$$\tilde{n}^U{}_{ij} = x_{ij}^U \Big/ \sqrt{\sum_{j=1}^{m} \left(x_{ij}^L\right)^2 + \left(x_{ij}^U\right)^2} \tag{29}$$

The normalized of decision-making matrix in TOPSIS model does not distinguish the types of the assessment criteria, the range of normalized interval numbers belong to [0 1] (Jahanshahloo and Lotfi, 2006).

(3) The way to determine the interval weighted decision-making matrix in TOPSIS model is the same as ISWM.

(4) Determining the positive ideal solution ($\tilde{A}^+$) and negative ideal solution ($\tilde{A}^-$)

$$\tilde{A}^+ = \{\tilde{v}_1^+, \ \cdots \ , \ \tilde{v}_n^+\} = \left\{ \left(\max_j \tilde{v}_{ij}^U \middle| \ i \in I \right), \ \left(\min_j \tilde{v}_{ij}^L \middle| \ i \in J \right) \right\} \tag{27}$$

$$\tilde{A}^- = \{\tilde{v}_1^-, \ \cdots \ , \ \tilde{v}_n^-\} = \left\{ \left(\min_j \tilde{v}_{ij}^L \middle| \ i \in I \right), \ \left(\max_j \tilde{v}_{ij}^U \middle| \ i \in J \right) \right\} \tag{28}$$

where I and J represent the benefit-type-criteria and cost-type-criteria, respectively (Jahanshahloo and Lotfi, 2006).

(5) Determining the Euclidean distance of each alternative from the ideal solutions

$$\tilde{d}_j^+ = \left\{ \sum_{i \in I} \left(\tilde{v}_{ij}^L - \tilde{v}_i^+ \right)^2 + \sum_{i \in J} \left(\tilde{v}_{ij}^U - \tilde{v}_i^+ \right)^2 \right\}^{\frac{1}{2}}, \ j = 1, \ \cdots, \ n. \tag{29}$$

$$\tilde{d}_j^- = \left\{ \sum_{i \in I} \left(\tilde{v}_{ij}^U - \tilde{v}_i^- \right)^2 + \sum_{i \in J} \left(\tilde{v}_{ij}^L - \tilde{v}_i^- \right)^2 \right\}^{\frac{1}{2}}, \ j = 1, \ \cdots, \ n. \tag{30}$$

where $\tilde{d}_j^+$ and $\tilde{d}_j^-$ represent the separations of each alternative from the positive ideal solution and negative ideal solution, respectively (Jahanshahloo and Lotfi, 2006).

(6) Defining the closeness coefficient

The closeness coefficient ($\tilde{R}_j$) of the alternative is defined as equation (31) to determine the sustainability sequence of all alternative, $\tilde{R}_j$ is closer to 1 , the alternative A_j is closer to the positive ideal solution (Jahanshahloo and Lotfi, 2006).

$$\tilde{R}_j = \tilde{d}_j^- \Big/ \left(\tilde{d}_j^+ + \tilde{d}_j^- \right), \ j = 1, \ \cdots, \ n. \tag{31}$$

4. MCDM for boxboard production

The production of boxboard in China mainly have four production pathways which use wood, straw, waste paper, and mixed fiber as raw materials. Man et al. (2018a) provided and quantified a set of sustainability criteria for boxboard papermaking, including life cycle water consumption, energy consumption, GHG emissions, and internal costs under the aforementioned pathways and these criteria are regarded as the data basis in this work. After determining the optimal weights of various assessment criteria, both the ISWM and TOPSIS models are adapted to find the most sustainable production pathways from the life cycle perspective.

4.1. Criteria weights and consistent check

This work considers paper producers as decision-makers and determines the interval comparison vectors according to the preference of papermaking enterprises. The results of optimal weights and consistent check are shown in Table 1. The paper producers fill the interval numbers which reflect the importance of the criteria to determine the *BO* and *OW* vectors, and then the weights of the criteria are obtained using interval BW method, the optimal weights can be obtained by solving programming for Eqs. (5)–(16), the calculation methods of these parameters for consistent check are presented from Eqs. (17)–(20).

Papermaking enterprises often view the production cost as the most important assessment criterion, ignoring the GHG emissions and low-cost water consumption. So this work determines that the *BO* vector is $BO = \begin{bmatrix} C_4/C_1 & C_4/C_2 & C_4/C_3 & C_4/C_4 \\ [3\ \ 4] & [1\ \ 2] & [5\ \ 7] & [1\ \ 1] \end{bmatrix}$ and the *OW* vector is $OW = \begin{bmatrix} C_1/C_3 & C_2/C_3 & C_3/C_3 & C_4/C_3 \\ [2\ \ 3] & [3\ \ 5] & [1\ \ 1] & [5\ \ 7] \end{bmatrix}$. The optimal weights of criteria can be obtained by solving the non-linear programming, as presented in Table 1. It is consistent with the preference of decision-makers that the weights of life cycle internal costs are much higher than that of life cycle GHG emissions.

The midpoint of consistency ratio can be determined by equation (20), it is $m(C\tilde{R}) = 0.0938 < 0.15$, which means that the interval comparison vectors are consistent and do not require to be modified.

4.2. Results under ISWM model

The decision-making matrix in ISWM and TOPSIS models are same, as shown in Table 2, the data source is the reference of Man et al. (2018a)., and the contributions of criteria at each life cycle stage are presented in Table A1 - A4.

Since the four assessment criteria belong to the cost-type-criteria, the normalization of the decision-making matrix is calculated according to Eq. (24), as shown in Table 3. Subsequently, the weighted decision-making matrix can be obtained directly according to Eq. (25).

For the ISWM model, the integrated superiorities and sustainability sequence of the alternatives can be determined and ranked, as shown in Fig. 3, the values represent the sum of the superiority contributions of each criterion in various alternatives. The integrated superiorities of the four alternatives for the production of boxboard are as follows: A_3 (papermaking with waste paper)>A_4 (papermaking with mixed fiber)> A_2 (papermaking with straw)>A_1 (papermaking with wood). Although the pathway using straw as the raw material has the lowest internal cost and the decision-makers view the cost as the most important assessment criterion, the performances of other criteria in this pathway are poor, so the sustainability sequence is in the third place. The four criteria in the pathway using waste paper as raw material are relatively lower among all the alternatives, so the pathway using waste paper as raw material for the production of boxboard is the most sustainable in this work.

4.3. Results under TOPSIS model

For the TOPSIS model, after determining the interval weighted decision-making matrix, the positive ideal solution and negative ideal solution are $\tilde{A}^+ = \begin{Bmatrix} C_1 & C_2 & C_3 & C_4 \\ 0.0146 & 0.0594 & 0.0113 & 0.1280 \end{Bmatrix}$ and $\tilde{A}^- = \begin{Bmatrix} C_1 & C_2 & C_3 & C_4 \\ 0.1218 & 0.1621 & 0.0402 & 0.2245 \end{Bmatrix}$, and then the Euclidean distance and closeness coefficient is determined according to equation (29)–(31), as shown in Fig. 4. The blue and green dots represent the Euclidean distance of each alternative from the positive ideal solution and negative ideal solution and the red dots are obtained according to Eq. (31). The smaller the value of the blue dots, the closer the alternative is to the positive ideal solution. The bigger the value of the green and red dots, the farther the alternative is to the negative ideal solution and the alternative is more sustainable.

The sustainability sequence can be obtained according to the value of the closeness coefficient, the sustainability sequence under this model is $A_3 > A_4 > A_1 > A_2$, which is different from the result under ISWM model. The alternative using straw as the raw material is the least sustainable one and it has the farthest separation of this alternative from the positive ideal solution while the closest separation from the negative ideal solution.

The reason of different results between the two MCDM models may be that the ISWM model calculates the integrated superiorities of the pathways based on simple sum but cannot fully consider the difference of each pair of two pathways with respect to various criteria compare with the TOPSIS model. Besides, the life cycle water consumption of alternative using straw as the raw material is much higher than that of other alternatives, the inferiority of this alternative is expanded when calculating the Euclidean distance of this criterion in this alternative from the ideal criteria in an ideal solution. Therefore, reducing water consumption and increasing water recycling rate are beneficial to the sustainability of the alternative using straw as raw material.

Table 1
Interval BW method for determining the weights of the four criteria by paper producers.

DM	The most important: C_4		The least important: C_3	
Criteria	C_1	C_2	C_3	C_4
BO	[3 4]	[1 2]	[5 7]	[1 1]
OW	[2 3]	[3 5]	[1 1]	[5 7]
Weights	[0.1361 0.1739]	[0.2578 0.3360]	[0.0666 0.0844]	[0.4545 0.4917]

$\xi^* = 0.3870$, $\tilde{a}_{BW} = [5\ \ 7]$, $C\tilde{I} = [3.7251\ \ 4.6277]$, $C\tilde{R} = [0.0836\ \ 0.1039]$, $m(C\tilde{R}) = 0.0938$

Table 2
The life cycle sustainability decision-making matrix.

	C_1 (L water/t paper)	C_2 (GJ/t paper)	C_3 (CO_2 eq/t paper)	C_4 (CNY/t paper)
A_1	[36.14 39.94]	[22.44 24.80]	[4.89 5.40]	[4527 4907]
A_2	[156.06 172.48]	[27.11 29.96]	[4.70 5.20]	[3027 3345]
A_3	[26.33 29.11]	[14.31 15.81]	[1.92 2.13]	[3206 3544]
A_4	[30.54 33.76]	[17.09 18.89]	[2.87 3.18]	[3506 3933]

Table 3
Normalized interval decision-making matrix.

	C_1	C_2	C_3	C_4
A_1	[0.0897 0.1267]	[0.1488 0.2143]	[0.0237 0.0331]	[0.2804 0.3288]
A_2	[0.0208 0.0293]	[0.1231 0.1774]	[0.0246 0.0345]	[0.4113 0.4917]
A_3	[0.1231 0.1739]	[0.2333 0.3360]	[0.0600 0.0844]	[0.3882 0.4642]
A_4	[0.1061 0.1499]	[0.1953 0.2813]	[0.0402 0.0565]	[0.3498 0.4245]

5. Sensitivity analysis

In order to explore the influence of the mixed ratio of raw materials on the sustainability and avoid subjective interference in the process of preference allocation, sensitivity analysis of the aforementioned MCDM models is introduced in this section.

Sensitivity analysis in MCDM is typically divided into two categories (Marco et al., 2014): (1) varying criteria performance; (2) altering criteria weights. Sensitivity analysis is implemented in this section by changing the proportion of mixed fiber and the weights of the criteria.

A variety of pulps need to be mixed in a certain proportion before papermaking, for example, long-fiber and short-fiber pulps are mixed to improve paper properties, wood pulp, and waste paper pulp are mixed to reduce production cost. This work varies the criteria performance by changing the proportion of mixed pulp, the proportion of raw materials can be obtained by dividing by the pulp yield. It is assumed that the proportion of mixed pulp (A_4) is changed as follows: (1) The proportion of wood pulp and waste paper pulp increases from 1:9 to 9:1, i.e. the

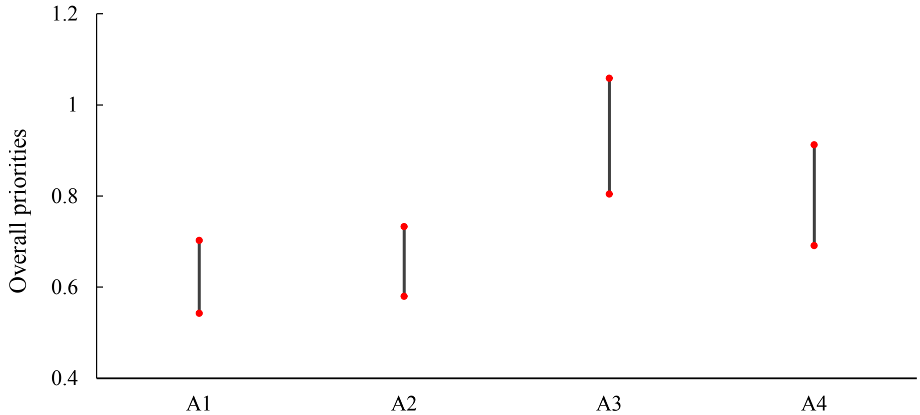

Fig. 3. The integrated superiorities of the four alternatives.

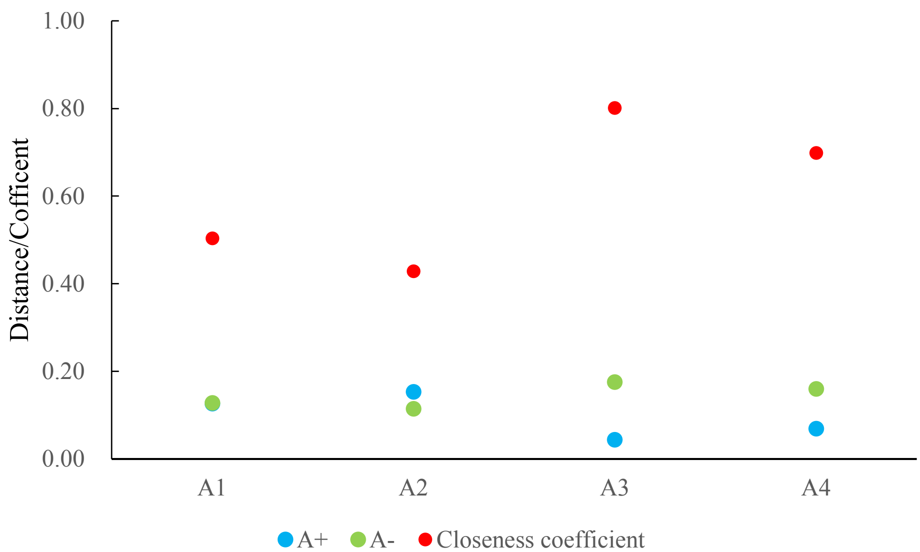

Fig. 4. The Euclidean distance of each alternative from the ideal solutions and closeness coefficient of each alternative.

proportion begins from 10% wood pulp +90% waste paper pulp, and then the proportion of wood pulp increases by 10% each time with a decreased proportion of waste paper pulp, until the proportion becomes 90% wood pulp +10% waste paper pulp. (2) Replacing the wood pulp in case 1 with straw pulp and the other conditions remain unchanged.

5.1. Sensitivity analysis by changing the proportion of mixed fiber

The sensitivity analysis results of the ISWM model by changing the proportion of mixed fiber are presented in Fig. 5. The midpoint of interval number is used to indicate the integrated priorities of alternatives in Fig. 5. The integrated priorities of the three alternatives (A_1, A_2, A_3) using single pulp are stable and that of the two alternatives using mixed pulp are decreased with the increasing proportion of virgin pulp. When the proportion of wood pulp exceeds 70%, the sustainability of the corresponding alternative begins lagging behind the alternative that has the same proportion of straw pulp. When the proportion of wood pulp reaches 83%, the sustainability sequence of the corresponding alternative falls below the alternative using straw pulp (A_2).

The sensitivity analysis results of the TOPSIS model by changing the proportion of mixed fiber are presented in Fig. 6. The closeness coefficient of the alternative using mixed fiber as the raw material is approximately linearly reduced with the increase of the proportion of virgin pulp and the alternative using the mixed straw pulp and waste paper pulp has a larger decline than the alternative using mixed wood

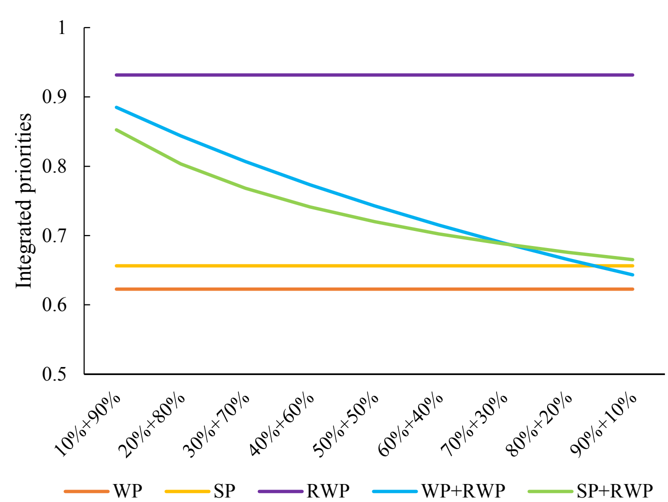

Fig. 5. The sensitivity analysis by changing the proportion of mixed fiber (ISWM).

pulp and waste paper pulp. The closeness coefficients of alternatives which use the single type fiber as the raw material have a little change. When the proportion of straw pulp and waste paper pulp reaches to 9:1,

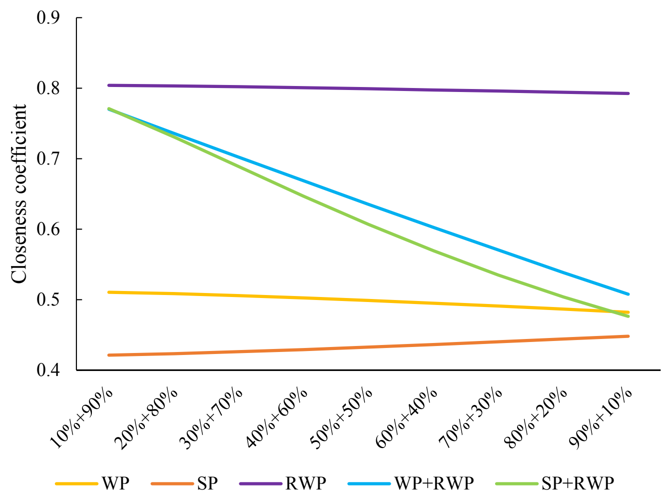

Fig. 6. The sensitivity analysis by changing the proportion of mixed fiber (TOPSIS).

the sustainability of the corresponding alternative is less than that of the alternative using wood as raw material.

5.2. Sensitivity analysis by changing criteria weights

The following cases are investigated for sensitivity analysis by altering criteria weights.

Case 0: $\tilde{\omega}_j = \frac{1}{4}$ $(j = 1,2,3,4)$, the relative importance of the four criteria is assumed to be equal.

Case 1–4: $\tilde{\omega}_j = 0.9$ $(j = 1,2,3,4)$, $\tilde{\omega}_k = \frac{1}{30}$ $(k = 1,2,3,4, k \neq j)$, a dominant weight is assigned to a criterion with a weight of 0.9, and the residual weights are distributed equally to the other criteria.

The sensitivity analysis results of the ISWM model by changing the weights of assessment criteria are presented in Fig. 7. The production of boxboard using waste paper (A_3) is recognized as the most sustainable in all alternatives. The increasing preference for life cycle GHG emissions and internal costs lead to a higher sustainability sequence for the alternative using straw (A_2). The alternative using straw (A_2) has the lowest life cycle internal cost but its sequence cannot exceed the alternative using waste paper (A_3) even the dominated weight of life cycle internal cost. Therefore, this work continues to increase the weight of life cycle internal cost to get case 5, the sustainability of the alternative using straw (A_2) begins to be superior to the alternative using waste paper (A_3) when the weight of life cycle internal cost reaches 92%.

The sensitivity analysis results of the TOPSIS model by changing the weights of assessment criteria are presented in Fig. 8. The sustainability sequence trend under TOPSIS model is similar to the ISWM model. It is calculated that the sustainability sequence of the alternative using straw as raw material begins to the first place when the weight of life cycle internal cost reaches to 85%.

In addition to the boxboard, most paper types also have various production pathways and their sustainability can be evaluated in a similar way. The assessment criteria can be extended, such as water pollution, profit margin and human toxicity potential. The selection of decision-makers affects the interval comparison vectors, thus change the criteria weights. The actual data of assessment criteria should be brought into the models for the specific scenarios.

Applying the MCDM method to the papermaking industry can determine the most sustainable production pathway. By comparing the relative sustainability of different pathways, this work can find the optimal proportion of raw materials to help the users guide production and provide scientific production basis for the structure of raw materials and pulp in the whole papermaking industry.

6. Conclusion

This work applies the MCDM methods to find the most sustainable pathway for the production of boxboard from a life cycle perspective. The life cycle water consumption, energy consumption, GHG emissions, and internal costs are identified to be assessment criteria and the four production pathways which use wood (A_1), straw (A_2), waste paper (A_3) and mixed fiber (A_4) as raw material are selected to be the four alternatives.

The sustainability sequence of the alternatives under the ISWM and TOPSIS models are $A_3 > A_4 > A_2 > A_1$ and $A_3 > A_4 > A_1 > A_2$, respectively. The alternative using waste paper as the raw material is the most sustainable pathway in the two models, however, the sequence of the alternatives using straw and wood is controversial. For the ISWM model, when the proportion of wood pulp reaches 83% in mixed pulp, sustainability sequence of the corresponding alternative falls below the alternative using the straw pulp. For the TOPSIS model, when the proportion of straw pulp to waste paper pulp reaches 9:1 in mixed pulp, the sustainability of the corresponding alternative is less than that of the

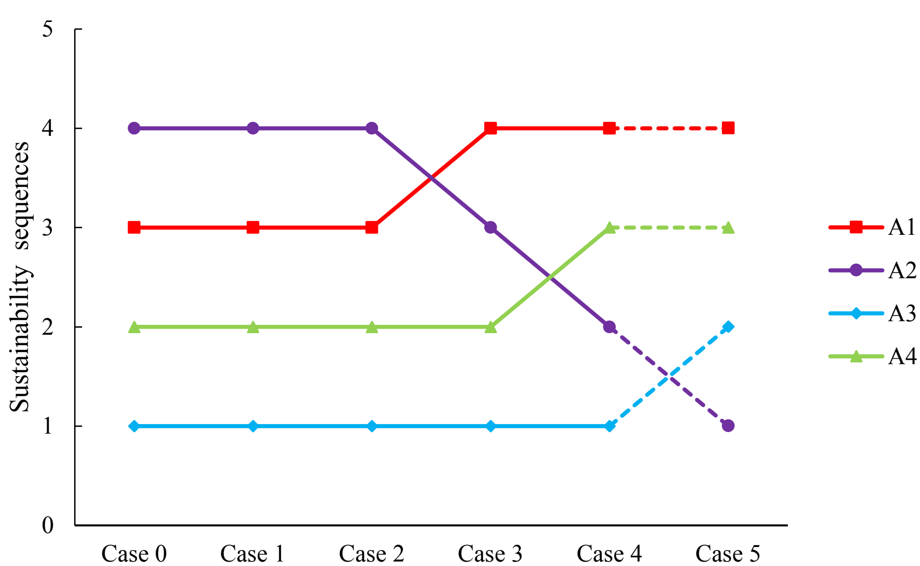

Fig. 7. The sensitivity analysis by changing criteria weights (ISWM) (Case 5: the weight of life cycle internal cost reaches 92% and the residual weights are distributed equally to the other criteria).

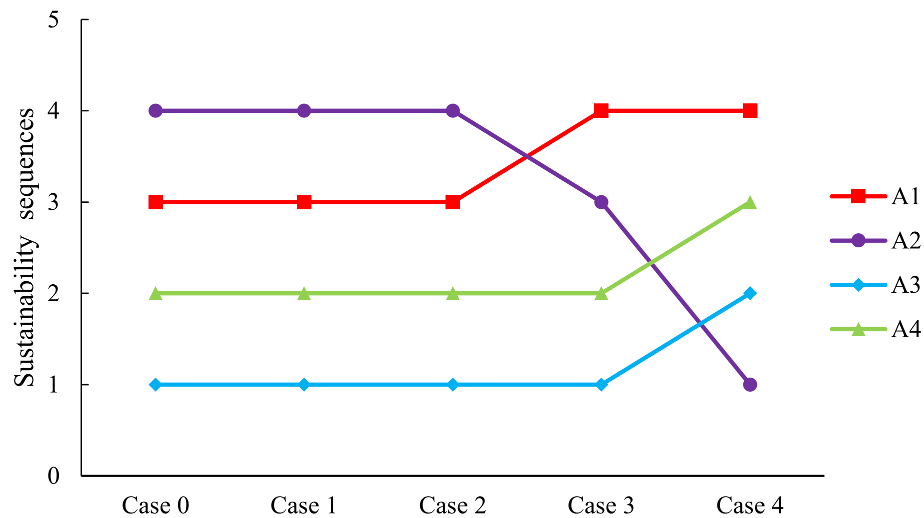

Fig. 8. The sensitivity analysis by changing criteria weights (TOPSIS).

alternative using wood as raw material. The sustainability sequence of the alternative using straw as raw material begins to the first place when the weight of life cycle internal cost reaches 85% and this value is 92% under ISWM model.

The number of sustainable criteria for a product or process is far beyond the four types in this study, future research should depend on the specific production situation. For example, in water-scarce areas, the selections of papermaking wastewater discharge and water eutrophication are realistic. Most of the existing MCDM methods have universal applicability, the development of targeted MCDM methods can achieve a more scientific sustainability assessment of the papermaking industry.

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Appendix

The contributions of criteria at each life cycle stage.

Table A1
Life cycle assessment criteria of an alternative using wood as raw material

Wood	C_1 (L water/t paper)	C_2 (GJ/t paper)	C_3 (CO_2 eq/t paper)	C_4 (CNY/t paper)
Raw material growth and collection	[0.08 0.09]	[0.73 0.81]	[0.04 0.05]	[2080 2397]
Transportation	[0.21 0.23]	[1.82 2.02]	[0.20 0.22]	[295 339]
Chemicals	NA	[0.88 0.98]	[0.07 0.08]	[178 205]
Pulping	[22.32 24.67]	[9.31 10.29]	[3.23 3.57]	[831 958]
Papermaking	[13.53 14.95]	[9.69 10.71]	[1.35 1.49]	[874 1007]

Table A2
Life cycle assessment criteria of an alternative using straw as raw material

Straw	C_1 (L water/t paper)	C_2 (GJ/t paper)	C_3 (CO_2 eq/t paper)	C_4 (CNY/t paper)
Raw material growth and collection	[54.21 59.91]	[0.61 0.68]	[0.12 0.14]	[234 258]
Transportation	[0.24 0.27]	[1.92 2.12]	[0.20 0.22]	[324 358]
Chemicals	NA	[1.23 1.36]	[0.10 0.11]	[213 235]
Pulping	[88.10 97.38]	[13.66 15.09]	[2.94 3.25]	[1283 1418]
Papermaking	[13.51 14.93]	[9.69 10.71]	[1.35 1.49]	[973 1076]

Table A3
Life cycle assessment criteria of an alternative using waste paper as raw material

Waste paper	C_1 (L water/t paper)	C_2 (GJ/t paper)	C_3 (CO_2 eq/t paper)	C_4 (CNY/t paper)
Raw material growth and collection	[2.71 2.99]	[0.30 0.33]	[0.03 0.03]	[1517 1676]
Transportation	[0.17 0.19]	[1.44 1.59]	[0.14 0.16]	[171 189]
Chemicals	NA	[0.24 0.27]	[0.02 0.02]	[86 96]
Pulping	[10.06 11.12]	[2.64 2.91]	[0.39 0.43]	[584 645]
Papermaking	[13.39 14.79]	[9.69 10.71]	[1.35 1.49]	[848 938]

Table A4
Life cycle assessment criteria of an alternative using mixed fiber as raw material

Mix fiber	C_1 (L water/t paper)	C_2 (GJ/t paper)	C_3 (CO_2 eq/t paper)	C_4 (CNY/t paper)
Raw material growth and collection	[4.11 4.54]	[0.44 0.48]	[0.03 0.04]	[1639 1839]
Transportation	[0.18 2.00]	[1.57 1.73]	[0.16 0.18]	[212 238]
Chemicals	NA	[0.46 0.51]	[0.04 0.04]	[117 131]
Pulping	[12.85 14.20]	[4.96 5.45]	[1.30 1.43]	[678 761]
Papermaking	[13.40 14.81]	[9.69 10.71]	[1.35 1.49]	[860 964]

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