Incorporating Negative Values in AHP Using Rule-Based Scoring Methodology for Ranking of Sustainable Chemical Process Design Options

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Abstract

Adopting Analytical Hierarchy Process (AHP) for selection and ranking of sustainable chemical process design that considers the trade-off between economic feasibility, environmental friendliness and social advantages offers good decision methodology for multi criteria problem. Typical AHP problem however are limited to handle only positive preferences. The introduction of negative preferences into AHP often creates various contradicting scenarios that result in spurious and inconsistent decision. To overcome such contradiction a rule-based scoring methodology is proposed. The system works by initially define each indicator according to its value-desirability behaviour. Next, using specific conversion factors that act accordingly to that behaviour the indicators value is converted into a credit-penalize scoring concept. Positive preference is credited with positive value while negative preference is penalized with negative value that shows its undesirability. Using a rule-based approach the score which span over positive and negative value are treated to elicit the final selection and ranking solution. The functionality of the proposed methodology will be demonstrated to selection and ranking of several biodiesel case scenarios in presence of positive and negative preferences.

Keywords: Analytic hierarchy process (AHP), process design, multicriteria decision making.

1. Motivation

Feasibility of process design alternatives is usually influence by techno-economic criteria. With the increasing awareness of sustainability development (SD) it is important to take into account the triple bottom line of sustainability namely environment friendliness and social advantages along side with economic feasibility. These conflicting objectives pose a multi criteria problem in decision making. Some of the commonly used techniques for multi criteria decision making (MCDM) are the analytic hierarchy process (AHP), distance function method and the multi attribute utility theory (MAUT). Among the three techniques, AHP is the most suitable for MCDM problems (Narayanan et al., 2007). In order to evaluate sustainable design option, the three criteria have to be quantified using appropriate indicators. Various indicators have been proposed in the past by various researchers and organizations. A few examples are profitability and rate of return (ROR) to measure economic feasibility, waste reduction (WAR) algorithm and gas emission to measure environmental impacts and safety and hazard analysis for social related criteria. Normally, decision making
using AHP involve indicators with positive value without realizing few indicators are constrained to be non-positive such as debts, assets, loss and expression of undesirability (Millet & Schoner, 2005). Some of the indicators mentioned above despite having positive value may span over negative value. Calculating profitability for instance could result in negative value which indicates losses. Other than that, social indicators could also have negative preferences to express undesirability. In addition, the decision indicators may also have different or contradicable value-desirability behaviour. Arguably it can be categorized to either higher-value-higher-desirability (HVHD) or lower-value-higher-desirability (LVHD). While HVHD behaviour is obvious for example in measuring profitability, LVHD refers to decision indicators which prefers lower value for example environmental indicators i.e. potential environment indicator (PEI) value, CO₂ emission etc. Applying conventional AHP in presence of the above mention conditions will become challenging and could elicit spurious and inconsistent results unless some modifications are made to the AHP process. Millet & Schoner (2005) mentioned two typical approaches have to handle positive and negative values in the AHP. The first is to handle positive and negative value separately and to calculate a benefit to cost ratio. The second approach, which is a standard method, involves inverting negative values into positive preferences. These two approaches however, cause computational complexity and elicit inconsistent results. They then proposed a new approach called Bipolar AHP (BAHP) that introduces modifications to AHP software user interface and also its computational process. It provides a simple solution to accommodating negative preferences while maintaining a true zero reference point. The approach however is highly software dependable and it does not consider the value-desirability behaviour of the indicators. In this work a new approach is proposed using a rule-based scoring methodology. This approach requires several simple modifications to the ranking and evaluation step of AHP. The former step involves defining each indicator according to its value-desirability behaviour. Using specific conversion factor the indicators value is converted into a credit-penalize score reflecting desirability-undesirability. In the evaluation step, treating both positive and negative value simultaneously however may create scenarios which can pose numerical inconsistencies. Therefore, a rule-based approach is proposed to accordingly treat each scenario to elicit the final solution.

2. Overview of the methodology

Figure 1 shows the overall AHP process incorporating the proposed methodology. The modifications introduced are shown in the ranking and evaluation step (step 3 and 4 of the figure). As previously mention decision indicators may span to positive-negative
values and in addition may also have contradictable value-desirability behaviour. The solution idea is to convert the initial indicators value to a scoring system with credit-penalize concept reflecting the accommodation of both HVHD and LVHD behaviour. In this concept any desirable value is credited with positive score while undesirability is penalized with negative score. Such concept will ensure that negative preferences are taken into consideration in the overall score instead of positively making it to lower preferable value. The conversion of the indicator value $v_{ij}$ into its corresponding score $S_{ij}$ depends on its behaviour which can be categorized as follows,

- **Category 1:** Credit score with HVHD behaviour for $v_{0a} \rightarrow v_{0b} > 0$

  \[ S_{ij} = \frac{v_{ij}}{T_{ij}^a} \left( S_{ij}^a \right), S_{ij}^a > S_{ij}^b, T_{ij}^a > T_{ij}^b \]  

- **Category 2:** Penalize score with HVHD behaviour for $v_{0a} \rightarrow v_{0b} < 0$

  \[ S_{ij} = \frac{v_{ij}}{T_{ij}^b} \left( S_{ij}^b \right), S_{ij}^a < S_{ij}^b, T_{ij}^a > T_{ij}^b \]  

- **Category 3:** Credit score with LVHD behaviour for $v_{0a} \rightarrow v_{0b} > 0$

  \[ S_{ij} = S_{ij}^a - \frac{v_{ij}}{T_{ij}^a} \left( S_{ij}^a \right), S_{ij}^a < S_{ij}^b, T_{ij}^a > T_{ij}^b \]  

- **Category 4:** Penalize score with LVHD behaviour for $v_{0a} \rightarrow v_{0b} > 0$

  \[ S_{ij} = \frac{v_{ij}}{T_{ij}^a} \left( S_{ij}^a \right), -S_{ij}^a < -S_{ij}^b, T_{ij}^a > T_{ij}^b \]  

- **Category 5:** Credit score with LVHD behaviour for $v_{0a} \rightarrow v_{0b} < 0$

  \[ S_{ij} = \frac{v_{ij}}{T_{ij}^b} \left( S_{ij}^b \right), S_{ij}^a < S_{ij}^b, T_{ij}^a < T_{ij}^b \]  

where $v_{ij}^a$ is the original value of $i$-th indicator for $j$-th criteria. The indicators value margin, $T_{a \rightarrow b}$ is set from the highest to the lowest value that corresponds to score margin of $S_{a \rightarrow b}$. In the ranking stage (step 3.1) requires the assessor to define each indicator to either one or two of the Category 1 to 5 reflecting the indicator’s value-desirability behaviour. This is important so that the indicators are evaluated accordingly that reflects its true behaviour. In the evaluation step (step 4) involves firstly determining the range of $T_{a \rightarrow b}$ and its corresponding score margin of $S_{a \rightarrow b}$. Note that setting the score margin $S_{a \rightarrow b}$ however depends on its value-desirability behaviour. For HVHD high value has been assign with high score while LVHD assign low score to high value. It is also important to note that a negative score is given to negative preferences as penalization for its undesirability. After the indicators value has been defined (step 4) step 4.2 involve converting this value into its corresponding score using equation (1) to (5). The next step involves calculation of normalized score using the weighting vectors determined in the weights set-up step and the score determined previously. The calculation is however not straightforward since the score span over negative and positive value and this
creates contradicting scenarios that could affect the overall result. In order to correctly response to each scenario a rule-based approach is proposed. It consist sets of rules to handle specific scenario as follows,

- **RULE 1: IF** $S_{ij} > 0$ **THEN**
  \[
  S'_{ij} = \frac{S_{ij}}{\sum_i S_{ij}^{ij}} (n') \quad (6)
  \]

- **RULE 2: IF** $S_{ij} < 0$ **THEN**
  \[
  S'_{ij} = \frac{S_{ij}}{\sum_i S_{ij}^{ij}} (-n') \quad (7)
  \]

- **RULE 3: IF** $S_{ij} < 0$ **AND** $S_{ij} > 0$ **THEN**
  \[
  S'_{ij} = \frac{S_{ij}}{\sum_i S_{ij}^{ij} - \sum_i S_{ij}^{neg}} \quad (8)
  \]

where $S_{ij}$ is the normalized score for the $i$-th alternative in the $j$-th criteria, $n'$ is the normalized value for criteria $j$, and $S_{pos}$ and $S_{neg}$ are the positive and negative score, respectively. Applying these rules helps to properly handles various situation of mix positive and negative scores for correct and consistent solution rankings. Adopting the rule-based scoring methodology offers the opportunity for automated decision support using computer programs i.e. spreadsheet, Visual Basic etc.

### 3. Application of the methodology

In 2003 Zhang et al. conducted a good techno-economic assessment on four simulated biodiesel processes namely alkali-catalyzed system using virgin oil (Case 1), alkali-catalyzed system using waste cooking oil (Case 2), acid-catalyzed process using waste cooking oil (Case 3) and acid-catalyzed system using hexane extraction (Case 4). Their simulation results concluded that all of these processes are proved to be technically and economically feasible but each had its limitations. Their conclusions however are limited to only techno-economic criteria and furthermore, no selection and ranking of alternatives methodology were applied. To test the functionality of the proposed methodology the four biodiesel processes will be used as case study in this work. As the work focuses only towards techno-economic assessment additional work on environment and social assessment have been performed utilizing the data and reviews included in their work. Note however, for the environmental assessment the effect of energy usage was not considered. The lists of indicators and its categorical behavior are shown in Table 1. This table also includes the range of indicators value and its corresponding score used in this work. A spreadsheet program has been developed embedding all the equations mention earlier to assist decision making. The user only needs to provide the data or parameters as in Table 1 into the spreadsheet. The results are shown in Figure 2. The proposed rule-based scoring methodology was able to recognize the positive-negative values and perform overall ranking of alternatives
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according to the normalized score priorities. Figure 1a shows the segregation of the results according to the three sustainability criteria. In economic evaluation Case 3 and 4 are the most promising. Although all options have negative net annual profit but based on after-tax rate of return and break-even price of biodiesel, the acid-catalyzed processes (Case 3 and 4) were economically competitive alternatives compared to the alkali process systems. These results are consistent with the work from Zhang. Environment assessment shows a significant difference of environmental performance between different design systems whereby the alkali-catalyzed processes is environmentally friendlier than the acid-catalyzed systems. This result is contributed mostly by the large amount of methanol used by the acid-catalyzed system for transesterification reaction. High amount of calcium sulphate deposited also contribute to the high impact to the environment. Among cases in each system however the difference is small.

Table 1. Summary of the indicators’ values and the score conversion specification

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Cat.</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
<th>Score Conversion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Value, $T_{a\rightarrow b}$</td>
</tr>
<tr>
<td><strong>Econ.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$T_a$</td>
</tr>
<tr>
<td>Net annual profit, ($x10^{-6}$)</td>
<td>1.2</td>
<td>-2.06</td>
<td>-2.28</td>
<td>-0.35</td>
<td>-0.82</td>
<td>10</td>
</tr>
<tr>
<td>After-tax rate of return, %</td>
<td>1</td>
<td>-85.27</td>
<td>-51.18</td>
<td>-15.63</td>
<td>-21.48</td>
<td>100</td>
</tr>
<tr>
<td>Break-even price, $</td>
<td>3</td>
<td>857</td>
<td>884</td>
<td>644</td>
<td>702</td>
<td>885</td>
</tr>
<tr>
<td><strong>Env. friendliness</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total rate of PEI output</td>
<td>3</td>
<td>26.48</td>
<td>16.47</td>
<td>131.66</td>
<td>125.24</td>
<td>132</td>
</tr>
<tr>
<td>Total PEI output/product</td>
<td>3</td>
<td>0.02</td>
<td>0.01</td>
<td>0.12</td>
<td>0.11</td>
<td>0.13</td>
</tr>
<tr>
<td>Total rate PEI gen.</td>
<td>5</td>
<td>-550.1</td>
<td>-464.8</td>
<td>-663.7</td>
<td>-608.4</td>
<td>0</td>
</tr>
<tr>
<td>Total PEI gen./product</td>
<td>5</td>
<td>-0.49</td>
<td>-0.42</td>
<td>-0.59</td>
<td>-0.54</td>
<td>0</td>
</tr>
<tr>
<td><strong>Societal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safety during operation</td>
<td>1.2</td>
<td>3</td>
<td>3</td>
<td>-1</td>
<td>-1</td>
<td>10</td>
</tr>
<tr>
<td>Operability of the plant</td>
<td>1.2</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Safe start-up and shutdown</td>
<td>1.2</td>
<td>5</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Fit for purpose</td>
<td>1.2</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Design should meet</td>
<td>1.2</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>location specific demands</td>
<td>1.2</td>
<td>-1</td>
<td>-1</td>
<td>3</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Control of product quality and quantity</td>
<td>1.2</td>
<td>-1</td>
<td>-1</td>
<td>3</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Maintenance</td>
<td>1.2</td>
<td>5</td>
<td>5</td>
<td>4.5</td>
<td>4.5</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 2. AHP results (a) normalized individual score (b) overall normalized ranking result
Social criteria show almost similar score for Case 1, 3 and 4. The fact that Case 2 was the most complex process with the greatest number of equipment because of the addition of a pretreatment unit for free fatty acid removal (Zhang et al., 2003) make it the least preferable. The overall ranking of the four biodiesel processes is shown in Figure 1b. Introduction of penalization concept makes alkali-catalyzed processes are less preferable than the acid-catalyzed systems mainly because of its huge economic disadvantages. The most sustainably feasible design option is Case 3. Although environmentally unattractive but taking into consideration the trade-off between the two other criteria it perform better the others. However, it is important to note that the decision results using AHP is very sensitive. Any modifications made either to the process models or weights in the AHP weights set-up step could significantly affect the decision outcome. Overall, from the results obtained it shows the proposed methodology is able to successfully consider both desirability-undesirability in design assessment, which cannot be done in the conventional AHP.

4. Conclusions & future work

A rule-based scoring methodology has been proposed to handle positive and negative preferences in process design selection and ranking. The functionality of the approach has been successfully demonstrated through the use of four biodiesel design options. It able to correctly evaluate the credit-penalize score and provide consistent result despite presence of various contradicting scenarios. The useful feature of this methodology is that the modification took place at the numerical calculation step of AHP specifically at the ranking and evaluation step thus enable decision makers to focus more on the real issues in process design development. Potentially, such approach offers the opportunity for automated decision support e.g. using spreadsheet.

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References