Performance measurement of manufacturing plants: An integrated model

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Abstract:
This paper proposes an integrated multiple criteria decision making (MCDM) model that combines the voting method and the VIKOR method to evaluate the performance of manufacturing plants. The VIKOR method helps decision-makers (DMs) carry out analysis and comparisons in ranking their performance of the alternatives. Since the evaluation result is often greatly effected by the weights used in the evaluation process, the voting method is used in this study to determine the appropriate criteria weights. A case study is then given to show applicability of the proposed model.

Keywords: Performance measurement; MCDM; voting; VIKOR

1. Introduction
In recent years, with the rapid development of IT industry, the aggravation of severe competition, the ceaseless changes of market demand, manufactures face severe challenges of reducing the cost, decreasing the storage, improving the quality and service, raising efficiency and heightening competitive awareness. For the manufacturing industry, production performance is very important in the highly competitive environment. Superior production performance often leads to competitiveness. Hence, an appropriate performance measurement is critical to a manufacturing firm revenue, market share and return on investment are widely accepted as representative measures of firm performance. Doyle,(1994). Veriouse performance indicators were adopted in the oretical and empirical studies for the evaluation of manufacturing capability Ferdows and Demeyer , (1990); Gupta and Somers , (1996); New and Szweczewski, (1995); White, (1996)

The performance measurement is regarded as a MCDM problem, which selects an alternative from a set of alternatives characterized in the terms of their criteria. The DM
may express or define a ranking for the criteria as a weighting. Criteria weighting plays an important role in most MCDM models because the evaluation result is often greatly affected by the criteria weights used in the evaluation process. Hence, many methods have been proposed for setting criteria weights in the MCDM problems. For example, see Hand field et al., (2002); Diakoulaki and Mavrotas, (1995).

VIKOR is a classical MCDM technique. It helps DM carry out analysis and comparisons in ranking their performance for the alternatives. This study adopts the VIKOR method to evaluate the performance of manufacturing plants. In this paper a new voting method is proposed to determine the appropriate weights of criteria in the proposed approach. This paper is organized as follows. Aiming at the performance measurement in manufacturing plants, the methodology is introduced briefly in section 2, including introducing the basic principle of VIKOR algorithm, and the proposed voting method. In fact, this section describes the framework of the proposed integrated performance measurement approach. A case study is presented in section 3, in which the proposed approach is applied to five manufacturing plants. Concluding remarks and discussion on the limitations and possible extensions in further research are finally presented in section 4.

2. Methodology

2.1 The basic principle of VIKOR algorithm

The VIKOR algorithm was proposed by Opricovic (1998), which is a MCDM method for complex system based on ideal point method. The basic view of VIKOR is determining positive ideal solution and negative ideal solution in the first place. The positive ideal solution is the best value of alternatives under assessment criteria, and the negative ideal solution is the worst value of alternatives under assessment criteria. Finally, arrange the priority of the schemes according to the proximity of the alternatives’ assessed value to the ideal schemes. In comprehensive evaluation, VIKOR adopted metric aggregate function:

\[ L_{pj} = \left\{ \sum_{i=1}^{n} \left[ w_i \left( f_i^* - f_{ij} \right) / \left( f_i^* - f_i^- \right) \right] \right\}^{1/p} \]  

(1)

Where \( 1 \leq p \leq \infty \) and \( j = 1,2,...J \). \( J \) respects the number of alternatives. Each alternative is indicated as \( a_j \), \( f_{ij} \) is the evaluation value of the \( i \)th criterion for alternative \( a_j \); the measure \( L_{pj} \) means the distance between alternative \( a_j \) and positive ideal solution. Ranking by VIKOR may produce different values of criteria weights. Criteria weights impact compromise solution. The VIKOR method determines the weights the weights stability intervals, using the methodology proposed by Opricovic (1998). The compromise solution obtained with initial weights \( w_i, i = 1,2,...n \) will be replaced if the value of a weight isn’t within the stability interval.

2.2 The steps of VIKOR algorithm

Step1: Calculate each criterion’s value \( f_i^* \) and negative ideal solution’s value \( f_i^- \) for \( i = 1,2,...n \).

\[ f_i^* = \left\{ \left( \max_j f_{ij} \mid i \in I_1 \right), \left( \min_j f_{ij} \mid i \in I_2 \right) \right\} \]  

(2)
\[ f_i^+ = \{ ( \min_j f_{ij} \mid i \in I_1 ), ( \max_j f_{ij} \mid i \in I_2 ) \} \]  

(3)

Where \( I_1 \) and \( I_2 \) show benefit and cost criteria, respectively.

Step2: Calculate the value of \( S_i \) and \( R_i \), \( j = 1, 2, ... J \); \( S_i \) is the optimal solution of alternative’s comprehensive evaluation, \( R_i \) is most inferior solution of alternative’s comprehensive evaluation:

\[ S_i = \sum_{i=1}^{n} w_i ( f_i^+ - f_{ij} ) / ( f_i^+ - f_i^- ) \]  

(4)

\[ R_i = \max \left[ w_i ( f_i^+ - f_{ij} ) / ( f_i^+ - f_i^- ) \right] \]  

(5)

Where \( w_i \) are weights of each criterion, meaning the relative importance among the criteria. The weights of each criterion is determined by voting method in this paper, see subsection 2.3.

Step3: Calculate \( Q_j \), the value of interests ratio brought by scheme \( j = 1, 2, ... J \)

\[ Q_j = v ( S_i - S^+ ) / ( S^- - S^+ ) + (1 - v) ( R_i - R^+ ) / ( R^- - R^+ ) \]  

(6)

Where

\[ S^+ = \min_j S_j \quad , \quad S^- = \max_j S_j \quad , \quad R^+ = \min_j R_j \quad , \quad R^- = \max_j R_j \]

\( v \) represents the weights of "the majority of criteria" strategy or the largest group's utility value, here we consider the value \( v=0.5 \).

Step4: According to \( S \), \( R \) and \( Q \) separately to rank the alternatives, we get 3 rank tables.

Step5: If the following two conditions are met simultaneously, then the alternative the optimal compromise alternative \( A_1 \) is the best alternative

\[ Q(A_2) - Q(A_1) \geq 1 / (m - 1) \]  

(7)

\( A_2 \) is the suboptimal alternative in the rank tables according to \( Q \). \( A_1 \) is the optimal solution in \( S \) or \( R \) rank tables with \( Q \) ranking has been simultaneously. This compromise solution is stable in decision making process, it may differ as \( v \) varies when \( v>0.5 \), decision making will be according to majority criteria; when \( v \approx 0.5 \). The selection will consider to overall and individual’s evaluation; when \( v < 0.5 \), veto the alternatives set. Here, \( v \) is the weight of the decision making strategy. In one of the above two condition isn't satisfied, we will get a compromise solution set. Including

(1) If the second condition isn't satisfied, then \( A_1 \) and \( A_2 \) are both compromise solution.
(2) If the first condition isn't satisfied, we will get alternative \( \{ A_1, A_2, ..., A_r \} \) and \( A_r \) is determined by the relation

\[ Q(A_r) - Q(A_1) \geq 1 / (m - 1) \]

for maximum (the position of these alternative are "in closeness").

2.3 The proposed voting method for determining the weights
In preferential voting systems, each voter selects \( m \) candidates from among \( n \) candidates (\( n \geq m \)) and ranks them from the most to the least preferred. Each candidate may receive some votes in different ranking places. The total score of each candidate is the weighted sum of the votes he/she receives in different places. So, the key issue of the preference aggregation in a preferential voting system is how to determine the weights associated with different ranking places.

Let \( w_j \) be the relative importance weight attached to the \( j \)th ranking place \( (j = 1, 2, \ldots, m) \) and \( v_{ij} \) be the vote of candidate \( i \) being ranked in the \( j \)th place. The total score of each candidate is defined as

\[
z_i = \sum_{j=1}^{n} v_{ij} w_j \quad i = 1, 2, \ldots, n
\]

Once the weights are given or determined, candidates can be ranked in terms of their total score.

To determine the relative importance weight, Cook and Kress (1990) suggest the following data envelopment analysis (DEA) model:

\[
\begin{align*}
\text{max} & \quad z_i = \sum_{j=1}^{m} v_{ij} w_j \\
\text{s.t} & \quad \sum_{j=1}^{m} v_{ij} w_j \leq 1 \quad j = 1, 2, \ldots, n \\
& \quad w_j - w_{j+1} \geq d(j, \varepsilon) \quad j = 1, 2, \ldots, m-1 \\
& \quad w_m \geq d(m, \varepsilon)
\end{align*}
\]

Where \( d(\cdot, \varepsilon) \) is referred to as a discrimination intensity in a nonnegative discriminating intensity factor \( \varepsilon \) and satisfies \( d(0) = 0 \). It has been found that the choice of \( d(\cdot, \varepsilon) \) and the discriminating intensity factor \( \varepsilon \) has significant impacts as the winner.

For example, Cook and Kress (1990) investigate three special cases of the discrimination intensity function \( d(\cdot, \varepsilon) \): \( d(j, \varepsilon) = \varepsilon \), \( d(j, \varepsilon) = \varepsilon/j \) and \( d(j, \varepsilon) = \varepsilon/j! \). Each of them leads to a different winner.

To avoid the difficulties mentioned above, Noguchi et al. (2002) suggest a strong ordering DEA model which is as follows

\[
\begin{align*}
\text{max} & \quad z_i = \sum_{j=1}^{m} v_{ij} w_j \\
\text{s.t} & \quad \sum_{j=1}^{m} v_{ij} w_j \leq 1 \quad j = 1, 2, \ldots, n \\
& \quad w_1 \geq 2w_2 \geq \cdots \geq mw_m \\
& \quad w_m \geq 2/Nm(m+1)
\end{align*}
\]

Where \( N \) is the number of voters. In our view, the strong ordering constraint \( w_1 > w_2 > \cdots > w_m \) and \( w_1 - w_2 > w_2 - w_3 > \cdots > w_{m-1} - w_m > 0 \). It also makes the choice of the \( d(\cdot, \varepsilon) \) unnecessary. So, this strong ordering constraint will be adopted in the new model to be developed.
However, it is found that the choice of $\varepsilon$ is somewhat arbitrary and there is no evidence to support $\varepsilon$ to take the value of $2/Nm(m+1)$. Besides, to determine the value of $\varepsilon$ in model (10), the number of voters is required to be known, but this not always the case. In what follows, we present the proposed model, which don’t require predetermining any parameters because the new model usually product only one best candidate. The model is as follows:

$$\max \quad z_i = \sum_{j=1}^{m} v_{ij} w_j$$

$$s.t \quad w_1 \geq 2w_2 \geq \cdots \geq mw_m$$

$$1 \quad \sum_{j=1}^{m} w_j^2 = 1$$

This model is a nonlinear programming problem, which determines the most favorable weights for each candidate, and the analytical solution to above model is found be

$$w_j^* = \frac{z_i}{\sqrt{\sum_{i=1}^{n} z_i}}$$

3. Case study
In this section we illustrate the application of the proposed approach to real-world performance evaluation problem. The case company is manufacturer of sport balls. The company has sales offices worldwide and manufacturing plants in Pakistan, India, Iran, and Europe. There are five manufacturing plants ($A_1, A_2, \ldots, A_5$) in Iran. These plants produce volleyball ball ($A_1$), basketball ball ($A_2$), football ball ($A_3$), tennis ball ($A_4$) and baseball ball ($A_5$).

The top level management was seeking a good assessment method to evaluate and compare the performance of five manufacturing plants. In order to evaluate and rank the performance of the five manufacturing plants, we first synthesize key performance measures of manufacturing capabilities commonly associated with manufacturing plants into five criteria and nine sub-criteria, as shown in Table 1.
Table 1:
Performance rating of the five plants in the case study

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Sub-criteria</th>
<th>A₁</th>
<th>A₂</th>
<th>A₃</th>
<th>A₄</th>
<th>A₅</th>
</tr>
</thead>
<tbody>
<tr>
<td>C₁ Productivity</td>
<td>C₁₁ average monthly ratio</td>
<td>0.74</td>
<td>0.73</td>
<td>0.72</td>
<td>0.64</td>
<td>0.63</td>
</tr>
<tr>
<td>C₂ Production Amount</td>
<td>C₂₁ production amount</td>
<td>69.3</td>
<td>63.41</td>
<td>65.8</td>
<td>58.69</td>
<td>67.58</td>
</tr>
<tr>
<td>C₃ Production Cost</td>
<td>C₃₁ raw material cost</td>
<td>63916.66</td>
<td>57886.14</td>
<td>48183.4</td>
<td>46023.33</td>
<td>52134.22</td>
</tr>
<tr>
<td></td>
<td>C₃₂ direct labor cost</td>
<td>926.08</td>
<td>774.22</td>
<td>452.44</td>
<td>884.23</td>
<td>634.78</td>
</tr>
<tr>
<td></td>
<td>C₃₃ factory overhead</td>
<td>3811.22</td>
<td>3201.74</td>
<td>2533.16</td>
<td>3012.2</td>
<td>2877.88</td>
</tr>
<tr>
<td>C₄ Sale Amount</td>
<td>C₄₁ internal detail Sale</td>
<td>3741.96</td>
<td>2658.67</td>
<td>2295.61</td>
<td>2845.9</td>
<td>2526.43</td>
</tr>
<tr>
<td></td>
<td>C₄₂ internal general Sale</td>
<td>644.59</td>
<td>532.86</td>
<td>723.66</td>
<td>444.41</td>
<td>462.45</td>
</tr>
<tr>
<td></td>
<td>C₄₃ external sale</td>
<td>862.71</td>
<td>556.54</td>
<td>444.86</td>
<td>364.68</td>
<td>612.1</td>
</tr>
<tr>
<td>C₅ Quality Cost</td>
<td>C₅₁ internal failure cost</td>
<td>172.36</td>
<td>172.36</td>
<td>198.95</td>
<td>530.96</td>
<td>478.23</td>
</tr>
<tr>
<td></td>
<td>C₅₂ external failure cost</td>
<td>200.35</td>
<td>200.35</td>
<td>234.14</td>
<td>348.74</td>
<td>366.2</td>
</tr>
<tr>
<td></td>
<td>C₅₃ prevention cost</td>
<td>245.25</td>
<td>245.25</td>
<td>290.65</td>
<td>114.37</td>
<td>145.63</td>
</tr>
</tbody>
</table>

3.1 Determining the weight using proposed voting model
In this sub-section, we express the use of proposed voting model for determining the weight of sub-criteria and criteria. Forty managers participated in this study. The management were asked to weight the criteria. The voter for \( C_1 \) (productivity), \( C_2 \) (production amount), \( C_3 \) (production cost), \( C_4 \) (Sale Amount) and \( C_5 \) (quality cost) and the related sub criteria are shown in Table 2 and 3.

Table 2:
Voting result for criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
<th>5th</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity</td>
<td>4</td>
<td>3</td>
<td>5</td>
<td>13</td>
<td>15</td>
</tr>
<tr>
<td>Production Amount</td>
<td>8</td>
<td>9</td>
<td>7</td>
<td>10</td>
<td>6</td>
</tr>
<tr>
<td>Production Cost</td>
<td>12</td>
<td>10</td>
<td>12</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Sale Amount</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>22</td>
<td>11</td>
</tr>
<tr>
<td>Quality Cost</td>
<td>5</td>
<td>3</td>
<td>5</td>
<td>12</td>
<td>15</td>
</tr>
</tbody>
</table>
Table 3: Voting result for Sub-criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
</tr>
</thead>
<tbody>
<tr>
<td>C31</td>
<td>10</td>
<td>17</td>
<td>13</td>
</tr>
<tr>
<td>C32</td>
<td>15</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>C33</td>
<td>14</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>C41</td>
<td>12</td>
<td>15</td>
<td>16</td>
</tr>
<tr>
<td>C42</td>
<td>13</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>C43</td>
<td>16</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>C51</td>
<td>18</td>
<td>14</td>
<td>8</td>
</tr>
<tr>
<td>C52</td>
<td>15</td>
<td>12</td>
<td>11</td>
</tr>
<tr>
<td>C53</td>
<td>10</td>
<td>12</td>
<td>20</td>
</tr>
</tbody>
</table>

Employing the proposed voting method the weight of $C_1$, $C_2$, $C_3$, $C_4$ and $C_5$ are 0.3563, 0.4922, 0.5940, 0.3882 and 0.3550, respectively.

Beside, Table 4 shows the weight of each sub-criteria using the proposed voting method.

Table 4: Sub-criteria weight

<table>
<thead>
<tr>
<th>sub-criteria</th>
<th>weight</th>
<th>sub-criteria</th>
<th>weight</th>
<th>sub-criteria</th>
<th>weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>C31</td>
<td>0.5501</td>
<td>C41</td>
<td>0.5796</td>
<td>C51</td>
<td>0.6326</td>
</tr>
<tr>
<td>C32</td>
<td>0.6023</td>
<td>C42</td>
<td>0.5523</td>
<td>C52</td>
<td>0.5754</td>
</tr>
<tr>
<td>C33</td>
<td>0.0782</td>
<td>C43</td>
<td>0.5990</td>
<td>C53</td>
<td>0.5182</td>
</tr>
</tbody>
</table>

3.2 Aggregate assessment

In this sub-section we proposed a method to aggregate assessments with respective to sub criteria for each criteria to transform the performance rating in Table 4 into the aggregate assessment. The proposed method is as follows. Consider a problem which includes a set of $m$ alternatives $A_i$ ($i = 1, 2, ..., n$) which is evaluated based on a set of $n$ criteria $C_j$ ($j = 1, 2, ..., n$).

Under each criterion $C_j$ a second level consists of $P_j$ sub-criteria $C_{jk}$ ($k = 1, 2, ..., P_j$). Thus the problem include two data sets

(1) The weight vector

$W = (w_1, w_2, ..., w_n)$ for the first level criteria and $W_j = (w_{j1}, w_{jk}, ..., w_{jp_j})$ for the second level sub-criteria

(2) The decision matrices

$X = [x_{ij}]_{m \times n}$ and $Y_{cj} = [y_{ki}]_{p_j \times m}$, ($j = 1, 2, ..., n$)

The decision matrix $X$ and $Y_{cj}$ represent the performance ratings of alternative $A_i$ with respect to criteria $C_j$ ($j = 1, 2, ..., n$) and sub-criteria $C_{jk}$ ($k = 1, 2, ..., P_j$) respectively. While $Y_{cj}$ ($j = 1, 2, ..., n$) are given based on actual performance of the alternatives, the
decision matrix $X$ is constructed by aggregating the weight ratings of Kaufman and Gupta, (1985) from sub-criteria for each criteria by

$$
(x_{1j}, x_{2j}, \ldots, x_{mj}) = \frac{w_j Y_{cj}}{\sum_{k=1}^{p_j} w_{jk}} \quad (j = 1, 2, \ldots, n)
$$

Where the decision matrix $Y_{cj} = [y_{kl}]$ have to be normalized by

$$
y_{kl} = \frac{y_{kl}}{\sqrt{\sum_{l=1}^{n} y_{kl}^2}}
$$

Now using the weight in Table 4 and Eqs.(13) and (14), we aggregate assessments with respect to sub-criteria for each criteria. Table 5 shows the obtained result.

**Table 5:** Aggregate the assessments from sub-criteria for each criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>$A_1$</th>
<th>$A_2$</th>
<th>$A_3$</th>
<th>$A_4$</th>
<th>$A_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>0.4770</td>
<td>0.4710</td>
<td>0.4640</td>
<td>0.4126</td>
<td>0.4062</td>
</tr>
<tr>
<td>$C_2$</td>
<td>0.4756</td>
<td>0.4360</td>
<td>0.4524</td>
<td>0.4028</td>
<td>0.4647</td>
</tr>
<tr>
<td>$C_3$</td>
<td>0.9303</td>
<td>0.7993</td>
<td>0.5874</td>
<td>0.7679</td>
<td>0.6976</td>
</tr>
<tr>
<td>$C_4$</td>
<td>0.9907</td>
<td>0.7277</td>
<td>0.7275</td>
<td>0.6204</td>
<td>0.7102</td>
</tr>
<tr>
<td>$C_5$</td>
<td>0.4284</td>
<td>0.4708</td>
<td>0.5506</td>
<td>0.8217</td>
<td>0.8881</td>
</tr>
</tbody>
</table>

3.3 Ranking performance using VIKOR

The final result obtained by the proposed method are shown in Table 6. According to our findings, the best performance among the five plants is plant $A_3$. The overall performance ranking is $A_3 > A_2 > A_5 > A_1 > A_4$.

**Table 6:** Analysis result

<table>
<thead>
<tr>
<th>Criteria</th>
<th>$A_1$</th>
<th>$A_2$</th>
<th>$A_3$</th>
<th>$A_4$</th>
<th>$A_5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>0.5940</td>
<td>0.9967</td>
<td>0.6642</td>
<td>2.4610</td>
<td>1.3296</td>
</tr>
<tr>
<td>$Q$</td>
<td>0.5940</td>
<td>0.3670</td>
<td>0.2778</td>
<td>0.3882</td>
<td>0.4149</td>
</tr>
<tr>
<td>$R$</td>
<td>0.5000</td>
<td>0.2494</td>
<td>0.5189</td>
<td>0.6745</td>
<td>0.4137</td>
</tr>
<tr>
<td>Rank</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td>3</td>
</tr>
</tbody>
</table>

4. Conclusions

In this paper we proposed an integrated approach for the manufacturing performance measurement in a multiple plants setting. Here a voting method was integrated into the VIKOR method to obtain the rank of each manufacturing plant. The proposed approach is easier to implement than the other method such as AHP.
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