Computer-aided optimum selection of roller bearings

Jaideep Ahluwalia, Sumit Kumar Gupta and V P Agrawal

The paper presents a methodology for evaluating roller bearings in terms of their suitability for a given application. The method is based on a multiple-attribute decision-making approach called TOPSIS (Technique for Order Preference by Similarity to the Ideal Solution). The method is suitable for computer processing. An interactive software package, BEARCAS, that selects an optimum roller bearing for a given set of conditions and attributes on the basis of this procedure has been developed. The package can be used by equipment manufacturers and designers. The proposed system is dynamic and easily updatable. The software’s facilities are exhaustive, and have hitherto not been available in this form so that they can become a stage in computer-aided mechanical engineering. The selection procedure is demonstrated by an example.

Keywords: evaluation, ranking, optimum selection, design attributes, TOPSIS, roller bearings

Roller bearings are designed/selected to support and locate rotating shafts or parts in machines, to transfer loads between the rotating and stationary members, and to permit free rotation with exceptionally low and almost uniform frictional resistance for both starting and running.

Selection problem

Spurred by technological success and growing demand from industry, there has been a large increase in the range of available bearings. Bearings with various capabilities and specifications are available for a wide range of applications.

The optimum selection of a bearing to suit a particular application from among the wide range of bearings available in the market today has become a difficult task. Various considerations, such as the load-bearing capacity, the life of the bearing, and the working rotational speed need to be considered before a suitable bearing can be selected.

Previous work

In recent years, a number of researchers have tried to develop expert systems/software which are useful in the design and selection of mechanical-engineering components. Computer-aided design evaluation and selection is still a partially solved problem. This is partly because of the large degree of subjectivity involved in the process, and the lack of suitable mathematical tools. The design and selection of an optimum bearing for a particular application requires consideration of a large number of design, manufacturing and economic factors (attributes), and their relative importance for the application under consideration. It is thus appropriate to use a multiple-attribute decision-making approach for the computer-aided evaluation and selection of roller bearings. The additive weight method has been used by designers and researchers in the past. A more powerful procedure, TOPSIS, has been selected and applied to the bearing-selection process. TOPSIS evaluates the bearing with respect to an ideal solution (i.e. the best bearing) and the negative ideal solution (i.e. the worst bearing), and ensures that the optimum bearing is the closest to an ideal solution, and the farthest from the worst solution.

Fagan has reported the development of an expert system for bearing selection. He used heuristics for the selection criteria. His grading scheme for selection is also very subjective, using grades such as very high, high, moderate and low. Also, the output from the expert system is just one bearing, rather than a couple of bearings so that the user can make a choice on the basis of cost, availability etc.

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Bearing design

Rolling-contact bearing design is limited to the selection of an optimum bearing from the manufacturer's catalog for the industry. The selection process starts with the identification of the design, manufacturing and other practical factors which it is necessary to consider. These are as follows:

- wear life,
- fatigue life,
- equivalent dynamic load,
- life and speed factors,
- temperature limitations,
- static loading,
- speed limit,
- clearance,
- tolerances,
- compensation for misalignments,
- fits,
- dimensions of surrounding parts,
- flexibility,
- mounting and dismounting,
- vibration and shock loads,
- permissible noise.

Conventionally, bearings are selected using the procedures given in the manufacturer's catalog and technical engineering-design books, on the basis of a few design parameters. Selected bearings are checked explicitly and/or implicitly for remaining design parameters (i.e. attributes).

PROPOSED APPROACH

The work described in this paper tries to overcome the drawbacks of Fagan's work by using a specific mathematical tool (TOPSIS) for the optimum selection of the bearing in place of heuristic procedures.

The objective of the project is to develop a 3-stage selection procedure to enable a user first to narrow down the list of the roller bearings available, to shortlist the acceptable alternatives, and second, to devise a method of tradeoff between alternatives to make it possible to rank the alternatives according to their suitability for the desired application. An interactive software package has been developed to assist an unassisted user to establish his/her priorities. Most of the design attributes mentioned above are considered in the proposed design procedure, either directly or indirectly. For load calculation, the shaft can have any number of the following elements of the drive mechanism:

- spur gear,
- helical gear,
- belt, pulley.

To evaluate the different design attributes, the procedure given in References 8 and 9 is used. The user has to specify the location of the drive mechanism and the loading conditions.

ELIMINATION SEARCH

On the basis of the threshold values of the pertinent attributes, a shortlist of bearings is obtained in the first stage of bearing selection. To achieve this, the database is scanned for the pertinent attributes, one at a time, to eliminate the bearing alternatives which have one or more pertinent attribute values that fall short of the minimum required values. A minidatabase is thus formed which comprises these satisfying solutions, i.e. alternatives all of whose attributes satisfy the acceptable levels of the aspiration. The problem is now reduced to that of finding the optimum, or best of these, satisfying solutions (in terms of roller bearings). This selection procedure therefore proceeds to rank these solutions in order of merit in its second stage.

TOPSIS METHOD

We now proceed to use an established MADM method, called TOPSIS (Technique for Order Preference by Similarity to the Ideal Solution), which has been found to be suitable for the problem.

The TOPSIS method is applied after the elimination search, after which the feasible set exceeds all the aspirations levels of each attribute. These are then ranked using the TOPSIS approach.

The first step is to present in matrix form all the information available from the database about these satisfying solutions. Such a matrix is called a decision matrix. Each row of this matrix is allocated to one alternative, and each column to one attribute. Therefore, an element $a[i, j]$ of the decision matrix $A$ gives the value of the $j$th attribute in raw (nonnormalized) form and units for the $i$th bearing. Thus, if the number of shortlisted bearings is $m$, and the number of pertinent attributes is $n$, the decision matrix is an $m \times n$ matrix.

The next step is to obtain information from the user on the relative importance of one attribute with respect to another, and this information is required in terms of a ratio. Information on all such pairwise comparisons is stored in a matrix called the $D$ matrix, which is an $n \times n$ matrix all of whose diagonal elements are unity.

The information stored in the $D$ matrix, being on a pairwise basis, cannot be used directly in established MADM methods. It must be modified into a representation that gives the relative weights of all the attributes taken together. The eigenvector method, a suitable technique, is used for this purpose. A particular advantage of this is that it allows for some inconsistencies in the judgment of the relative importance of attributes while pairwise comparisons are made. The inconsistencies arise because human judgments cannot be so accurate
as to satisfy the relationship \( d_{ij} = d_{ij}/d_{ij} \) completely, where

\[
d_{ij} = \frac{\text{importance of } i\text{th attribute}}{\text{importance of } j\text{th attribute}}
\]  
(1)

The eigenvector method seeks to find the weight-matrix vector \( W \), where

\[
DW = \alpha W
\]  
(2a)

\[
W = [w_1, w_2, w_3, \ldots, w_n]^T
\]  
(2b)

To avoid the trivial solution (when \( W = 0 \)) we have

\[
det(D - \alpha I) = 0
\]  
(3)

which gives us the eigenvector. The solution of the system of Equation 2b for the largest value of the eigenvector gives us the weight vector \( W \).

### Ranking of bearings using TOPSIS

The TOPSIS technique is based on the concept that the chosen alternative should be the shortest Euclidean distance from the ideal solution, and the longest from the negative ideal solution.

The ideal solution is a hypothetical solution for which all the attribute values correspond to the maximum attribute values in the database of the satisfying solutions; the negative ideal solution is a hypothetical solution for which all the attribute values correspond to the minimum attribute values in the database referred to above.

TOPSIS thus provides a solution that is not only closest to the hypothetically best solution, but also farthest from the hypothetically worst solution. The point is illustrated in Figure 1.

Note that \( A_i \) is a shorter distance from the ideal solution \( A^* \) and from the negative ideal solution \( A^- \) than

is the other alternative \( A_2 \). It is thus not easy to justify the selection of \( A_1 \). TOPSIS considers the distances to both the ideal and the negative ideal solutions simultaneously by defining the 'relative closeness to the ideal solution' \( C_i^* \) according to the relationship

\[
C_i^* = S_i^*/(S_i^* + S_i^-)
\]  
(4)

where \( S_i^* \) is the separation from the negative ideal solution measured by the \( n \)-dimensional Euclidean distance between the \( i \)th alternative and the negative ideal solution, and \( S_i^* \) is the separation from the ideal solution measured by the \( n \)-dimensional Euclidean distance between the \( i \)th alternative and the ideal solution.

It is clear that, if \( A_i = A^* \), then \( S_i^* = 0 \) and \( C_i^* = 1 \), and if \( A_i = A^- \), then \( S_i^- = 0 \) and \( C_i^* = 0 \). The solution with the highest \( C_i^* \) value is given the highest rank, and so on.

The first step in TOPSIS that is applied here is the construction of a 'normalized decision matrix' from the decision matrix \( A \) created earlier. An element \( r[i, j] \) of the normalized matrix \( R \) can be calculated as

\[
r[i, j] = \frac{a[i, j]}{\left( \sum_{i=1}^{m} (a[i, j])^2 \right)^{1/2}}
\]  
(5)

where \( a[i, j] \) is an element of the decision matrix \( A \). The construction of the normalized matrix is necessary to allow comparison across attributes, since all the attribute values are now in nondimensional form.

Next, the information stored in the weight-vector matrix \( W \) is incorporated into the normalized decision matrix by the formation of the 'weighted normalized matrix' \( V \) so that the true comparable value of each attribute may be written down.

The matrix \( V \) is given by

\[
V = \begin{bmatrix}
v(1, 1) & v(1, 2) & \ldots & v(1, n) \\
v(2, 1) & v(2, 2) & \ldots & v(2, n) \\
\vdots & \vdots & \ddots & \vdots \\
v(m, 1) & v(m, 2) & \ldots & v(m, n)
\end{bmatrix}
\]  
(6)

\[
V = \begin{bmatrix}
w_1r(1, 1) & w_2r(1, 2) & \ldots & w_nr(1, n) \\
\vdots & \vdots & \ddots & \vdots \\
w_1r(m, 1) & w_2r(m, 2) & \ldots & w_nr(m, n)
\end{bmatrix}
\]  
(7)

Next, we determine the ideal solution \( A^* \) and the negative ideal solution \( A^- \) by choosing from the \( V \) matrix the maximum and minimum values of the attributes. Thus,

\[
A^* = \begin{bmatrix}
\max_{i=1:m, j=1:n} v(i, j) \\
\max_{j=1:m, i=1:n} v(i, j) \\
\vdots \\
\max_{j=1:m, i=1:n} v(i, j)
\end{bmatrix}
\]  
(8a)

\[
A^- = [V_{1}^*, V_{2}^*, \ldots, V_{n}^*]
\]  
(8b)
Computer-aided optimum selection of roller bearings: J Ahluwalia et al.

\[ A^+ = \left( \min_{j=1;i=1} v(i,j) \right) \left( \min_{j=2;i=1} v(i,j) \right) \ldots \]

\[ = \left[ V_1^+, V_2^-, \ldots, V_n^- \right] \quad (9a) \]

Next, we calculate the separation measures of each alternative from \( A^+ \) and \( A^- \). This separation is measured by the \( n \)-dimensional Euclidean distance expressible as

\[ S_i^+ = \left[ \sum_{j=1}^{n} (v(i,j) - V_j^+)^2 \right]^{1/2} \quad (10) \]

\[ S_i^- = \left[ \sum_{j=1}^{n} (v(i,j) - V_j^-)^2 \right]^{1/2} \quad (11) \]

These are used to find the relative closeness to the ideal solution.

**ALGORITHM**

**Stage 1: Elimination search**

Scan the database, and obtain a list of bearings which satisfy the minimum requirements of all the pertinent attributes. Store these bearings in a minidatabase.

**Stage 2: Ranking procedure**

The steps of the ranking procedure are as follows:

- **Step 1:** Write down the decision matrix \( A \).
- **Step 2:** Obtain information from the user on the relative importance of the attributes via pairwise comparison. Write down this information in the \( D \) matrix (using Equation 1).
- **Step 3:** Obtain \( w_{max} \) (this equals the maximum eigenvalue) using Equation 3. Use this value to find the vector \( W \) using Equation 2b.
- **Step 4:** Construct the normalized decision matrix \( R \) (using Equation 5).
- **Step 5:** Determine the weighted normalized matrix \( V \) (using Equations 6 and 7).
- **Step 6:** Determine the ideal solution (using Equation 8a) and negative ideal solution (using Equation 9a).
- **Step 7:** Calculate the separation measures \( S_i^+ \) (using Equation 10) and \( S_i^- \) (using Equation 11).
- **Step 8:** Calculate the relative closeness to the ideal solution (using Equation 4).
- **Step 9:** Rank the alternatives according to descending order of \( C_i^+ \). The highest-ranked bearing is the preferable one on the basis of the consideration of a large number of attributes, their pairwise comparison for a particular application, and other logical considerations. Other bearings are arranged in order of preference.

**Figure 2 BEARCAS flowchart**
Stage 3: Role of user

The final decision on bearing selection after ranking may be made on the basis of other factors which have not yet been taken into account, such as
- economic considerations,
- availability,
- management constraints.

This is necessary because the computer cannot completely replace the historical practice of bearing selection on the basis of experience, availability etc.

BEARCAS SOFTWARE PACKAGE

A flowchart for the BEARCAS software package is shown in Figure 2.

This interactive package has been developed for the optimum selection of roller contact bearings. It has been written in TURBO PASCAL 5.5. This software can be used by equipment manufacturers, as well as designers.

Salient features

The salient features of the package are as follows:
- It is menu-driven.
- Any number of elements can be present on the shaft.
- The load on the bearing is automatically calculated.
- It is dynamic, and has an easily updatable database.
- It considers tapered, as well as cylindrical, roller contact bearings.
- The factors in relation to which the bearing selection is to be optimized can be chosen.
- It assigns a merit value to each selected bearing.
- The values of the various design parameters of the bearing for the selected bearings can be seen on the screen.

Output

The detailed output is stored in another file. The output includes the bearing number, dimensions, accuracy, weight, shaft and housing fits, shaft and housing shoulders, retention devices, lubrication, and other suggestions.

Data

Data has been taken from the FAG bearing manufacturer’s catalog. The data comprises the data for 300 cylindrical roller contact bearings, and 100 tapered roller contact bearings.

EXAMPLE

Example 1

Suppose that the user wants to select the optimum bearing for the following conditions:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>expected life, h</td>
<td>2000</td>
</tr>
<tr>
<td>reliability, %</td>
<td>99</td>
</tr>
<tr>
<td>bearing outer diameter, mm</td>
<td>40</td>
</tr>
<tr>
<td>bearing width, mm</td>
<td>12</td>
</tr>
<tr>
<td>operating smoothness</td>
<td>1</td>
</tr>
<tr>
<td>shaft length, m</td>
<td>0.5</td>
</tr>
<tr>
<td>shaft speed, rev/min</td>
<td>1800</td>
</tr>
<tr>
<td>location of bearing 1 from left end of shaft, m</td>
<td>0.1</td>
</tr>
<tr>
<td>location of bearing 2 from left end of shaft, m</td>
<td>0.3</td>
</tr>
<tr>
<td>number of elements on shaft</td>
<td>3</td>
</tr>
</tbody>
</table>

**element type code**

- spur gear = S
- helical gear = H
- belt = B

**type of element 1 = S**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>location of gear from left end of shaft, m</td>
<td>0.15</td>
</tr>
<tr>
<td>angle of point of contact with respect to xz plane, deg</td>
<td>90</td>
</tr>
<tr>
<td>power transmitted, W</td>
<td>100</td>
</tr>
<tr>
<td>pressure angle, deg</td>
<td>20</td>
</tr>
<tr>
<td>module</td>
<td>2</td>
</tr>
<tr>
<td>number of teeth</td>
<td>18</td>
</tr>
</tbody>
</table>

**type of element 2 = H**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>location of gear from left end of shaft, m</td>
<td>0.2</td>
</tr>
<tr>
<td>angle of point of contact with respect to xz plane, deg</td>
<td>180</td>
</tr>
<tr>
<td>power transmitted, W</td>
<td>75</td>
</tr>
<tr>
<td>normal pressure angle, deg</td>
<td>20</td>
</tr>
<tr>
<td>helix angle, deg</td>
<td>30</td>
</tr>
<tr>
<td>normal module</td>
<td>2</td>
</tr>
<tr>
<td>number of teeth</td>
<td>20</td>
</tr>
</tbody>
</table>

**type of element 3 = B**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>location of belt from left end of shaft, m</td>
<td>0.4</td>
</tr>
<tr>
<td>angle of point of contact with respect to xz plane, deg</td>
<td>270</td>
</tr>
<tr>
<td>power transmitted, W</td>
<td>50</td>
</tr>
<tr>
<td>coefficient of friction of belt with pulley</td>
<td>0.25</td>
</tr>
<tr>
<td>diameter of pulley, mm</td>
<td>50</td>
</tr>
<tr>
<td>angle of contact of belt with pulley, deg</td>
<td>135</td>
</tr>
</tbody>
</table>

The attributes to be optimized are the shaft diameter (SHAFT), the weight (WEIGHT), the bearing outer diameter (BEAR), and the bearing width (WIDTH). The 'relative-importance matrix' chart for bearing location 1 shown in Table 1 was used.

The results for bearing location 1 are shown in Table 2.
Table 1  Relative-importance matrix chart for bearing location 1 for Example 1

<table>
<thead>
<tr>
<th>SHAFT</th>
<th>WEGH</th>
<th>BEAR</th>
<th>WIDTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>2.0</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>2.0</td>
<td>2.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 2  Results for bearing location 1 for Example 1

<table>
<thead>
<tr>
<th>Selection number</th>
<th>Merit value</th>
<th>Bearing number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.6264</td>
<td>NU 252</td>
</tr>
<tr>
<td>2</td>
<td>0.4688</td>
<td>NU 248</td>
</tr>
<tr>
<td>3</td>
<td>0.3716</td>
<td>NU 203</td>
</tr>
<tr>
<td>4</td>
<td>0.3716</td>
<td>NU 203</td>
</tr>
<tr>
<td>5</td>
<td>0.3710</td>
<td>NU 204</td>
</tr>
</tbody>
</table>

Table 3  Relative-importance matrix chart for bearing location 2 for Example 1

<table>
<thead>
<tr>
<th>SHAFT</th>
<th>WEGH</th>
<th>BEAR</th>
<th>WIDTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.333</td>
<td>0.333</td>
<td>0.333</td>
</tr>
<tr>
<td>3</td>
<td>1.000</td>
<td>0.333</td>
<td>0.333</td>
</tr>
<tr>
<td>3</td>
<td>3.000</td>
<td>1.000</td>
<td>0.333</td>
</tr>
<tr>
<td>3</td>
<td>3.000</td>
<td>3.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Table 4  Results for bearing location 2 for Example 1

<table>
<thead>
<tr>
<th>Selection number</th>
<th>Merit value</th>
<th>Bearing number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.6814</td>
<td>NU 250</td>
</tr>
<tr>
<td>2</td>
<td>0.4928</td>
<td>NU 238</td>
</tr>
<tr>
<td>3</td>
<td>0.3186</td>
<td>NU 224</td>
</tr>
<tr>
<td>4</td>
<td>0.3186</td>
<td>NU 224</td>
</tr>
<tr>
<td>5</td>
<td>0.3181</td>
<td>NU 216</td>
</tr>
</tbody>
</table>

The relative-importance matrix chart for bearing location 2 shown in Table 3 was used.

The results for bearing location 2 are shown in Table 4.

Example 2

Using the data of Example 1, but optimizing with respect to the bearing outer diameter and the bearing width, the relative-importance matrix chart for bearing location 1 shown in Table 5 was used.

Table 5  Relative-importance matrix chart for bearing location 1 for Example 2

<table>
<thead>
<tr>
<th>SHAFT</th>
<th>WIDTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 6  Results for bearing location 1 for Example 2

<table>
<thead>
<tr>
<th>Selection number</th>
<th>Merit value</th>
<th>Bearing number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.6421</td>
<td>NU 252</td>
</tr>
<tr>
<td>2</td>
<td>0.6295</td>
<td>NU 248</td>
</tr>
<tr>
<td>3</td>
<td>0.6081</td>
<td>NU 234</td>
</tr>
<tr>
<td>4</td>
<td>0.5540</td>
<td>NU 238</td>
</tr>
<tr>
<td>5</td>
<td>0.5962</td>
<td>NU 222</td>
</tr>
</tbody>
</table>

Table 7  Relative-importance matrix chart for bearing location 2 for Example 2

<table>
<thead>
<tr>
<th>SHAFT</th>
<th>WIDTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 8  Results for bearing location 2 for Example 2

<table>
<thead>
<tr>
<th>Selection number</th>
<th>Merit value</th>
<th>Bearing number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.5737</td>
<td>NU 250</td>
</tr>
<tr>
<td>2</td>
<td>0.5634</td>
<td>NU 248</td>
</tr>
<tr>
<td>3</td>
<td>0.5502</td>
<td>NU 238</td>
</tr>
<tr>
<td>4</td>
<td>0.5189</td>
<td>NU 238</td>
</tr>
<tr>
<td>5</td>
<td>0.4047</td>
<td>NU 232</td>
</tr>
</tbody>
</table>

The results for bearing location 1 are shown in Table 6. The relative-importance matrix chart for bearing location 2 shown in Table 7 was used.

The results for bearing location 2 are shown in Table 8.

CONCLUSIONS

A computer program for the optimum selection of roller contact bearings on the basis of the TOPSIS ranking technique has been developed. The software is exhaustive; it uses the data in the FAG manufacturer's catalog for its tapered and cylindrical contact roller bearings data. The program allows optimization parameters to be specified. The database can also be updated to include different types of bearing from various manufacturers; it can easily cope with the development of new bearings. The program is available on a single floppy disk. It is easy to use, and should find extensive application in automobile engineering, machine-tool engineering, aircraft engineering, and other mechanical-engineering industries. It is hoped that BEARCAST will find acceptability among the practising engineers of these industries, and will be a useful module in the development of a general computer-aided design program.

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