CHAPTER 7

CASE STUDIES

7.1 CASE STUDY ON OPTIMUM DESIGN SELECTION THROUGH EVALUATION OF JIGS/FIXTURES USING DIGRAPH AND MATRIX APPROACH

7.1.1 Introduction

Jig/fixture is an important element in any manufacturing process that determines greater accuracy, efficiency and cost of machining, assembling and inspection of products. Seldom a (it is hard to find) product is produced in an industry that does not contain one or more holes. The location, finish and size of these holes may be critical as in the case of a component for a missile. In this way, the jigs/fixtures play an important role.

There are many jigs/fixtures for a component, which may vary in their features based on the experience of the designer and there is no specific methodology for the selection. So, selection (design) of an appropriate jig/fixture for a component is not an easy task. Many authors suggested various methods and techniques for the selection of jig/fixture, which are detailed here. Kang et al. (2003) presented computer-aided fixture design verification technique for verifying and improving the existing fixture designs. Hurtado and Melkote (2002) presented a model for analysis of the effect of fixture-workpiece conformability on static stability. Carlson (2001) used kinematics analysis and derived a quadratic sensitivity equation that relates position error in locators with the resulting displacement of the part held by
the locating scheme. Nee et al. (1987) reported the development of fixture design procedure using artificial intelligence. In their research work, a knowledge-based program structure was used to decide on an appropriate fixture with respect to a particular workpiece specification. Qin et al. (2006) presented a general analysis methodology that was able to characterise the effects of localisation source errors based on the position and orientation of the work piece. Wang et al. (2005) presented a method of fixturing error measurement including component movement and component deflection. In their research work, the error measurements in machined surfaces were used for analysis and evaluation of fixture. Zheng (2005) in his PhD dissertation established the finite element model of fixture for analyzing stiffness and developed the experimental approaches to identify contact stiffness. Lin et al. (2004) computed and analyzed the natural compliance of fixturing and grasping arrangements. They derived a closed-form formula for the stiffness matrix of multiple contact arrangements and used the same for investigating the impact of different choices of contact model on the assessment of the stability of multiple contact arrangements. Thus, many authors considered various methods for the analysis and evaluation of jigs/fixtures, but no author has reported the relative important between the attributes. Hence, a unique selection method/procedure is much helpful in design stage.

Matrix and digraph approach is a logical approach and is applied by various researchers (Venkata Rao R. and Gandhi O.P. 2002a, 2002b; Ventaka Rao R, 2006a, 2006b; Sandeep Grover et al., 2004, 2005; Wani M.F and Gandhi O.P 1999; Gandhi O.P. and Agrawal V.P. 1992; Sushma Kulkarni 2005; Garg et al., 2006). Specifically, the research works of Dr. Venkata Rao motivated the author to use graph theory and matrix method for this problem. In this section, matrix and digraph approach is used for the selection of jig/fixture. The selection procedure includes the following phases:
1. Identification of design selection attributes
2. Construction of digraph model
3. Development of design selection permanent matrix from digraph model
4. Development of design selection permanent function
5. Development of design selection index using design selection permanent function.
6. Comparing the values of design selection index and identification of optimum design.

7.1.2 Selection of attributes

Selection of jigs/fixtures is dependent on various features and factors discussed by Donaldson, (2001) and Korsakov (1983), which are termed as selection attributes. These attributes influence the design process and they have relationship among/between them and these inter-relationships also influence the design process. They are:

1. Location
2. Clamping
3. Loading and unloading
4. Stability and rigidity
5. Fool proof
6. Provision for indexing
7. Provision for tool guidance
8. Safety
9. Weight
10. Coolant supply
11. Economy
The importance of the factors is summarized in table 7.1.

**Table 7.1 Importance of the factors**

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Description</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Relative positioning of work with respect to tool</td>
<td>By arresting degrees of freedom and by accurate positioning</td>
</tr>
<tr>
<td>Clamping</td>
<td>Keeping work stable during machining</td>
<td>Stability</td>
</tr>
<tr>
<td>Loading and unloading</td>
<td>Placing/replacing the work on/from the jig/fixture</td>
<td>How easier for loading and unloading</td>
</tr>
<tr>
<td>Stability and rigidity</td>
<td>Stiffness of the jig/fixture against the cutting force</td>
<td>How stiff against the cutting force</td>
</tr>
<tr>
<td>Fool proof</td>
<td>Provision for correct positioning of work on the jig/fixture</td>
<td>Proper location is possible</td>
</tr>
<tr>
<td>Provision for indexing</td>
<td>Different orientation of work against tool without removing the work from the jig/fixture</td>
<td>Saves time</td>
</tr>
<tr>
<td>Provision for tool guidance</td>
<td>Provision for guiding the tool</td>
<td>Helps to measure the dimensions of surface being machined</td>
</tr>
<tr>
<td>Weight</td>
<td>Weight of the jig/fixture</td>
<td>Easy to handle</td>
</tr>
<tr>
<td>Safety</td>
<td>Safe to the operator</td>
<td>Level of safety to the worker</td>
</tr>
<tr>
<td>Coolant supply</td>
<td>Lubricate and reduce the heat from the work as well as jig / fixture</td>
<td>Prevention from over heating and wear</td>
</tr>
<tr>
<td>Economy (cost)</td>
<td>Cost of the jig/fixture</td>
<td>How much cheaper</td>
</tr>
</tbody>
</table>

7.1.3 **Construction of digraph model**

Construction of digraph helps to know the complexity of the problem at a glance. Also it shows the relation between attributes of the problem objective. Selection attributes are identified in Section 7.1.2 on the basis of features, which play an important role for jig/fixture. These characteristics of features help to develop the relationship among the attributes. The relationship between the attributes is called inter-relationship (relative importance) or degree of facilitation. The inter-relationships between attributes are given in table 7.2. The relative importance of one attribute is in stronger relation on another attribute(s) from design point of view. The relative importance is
considered as strong, medium, weak and none and also represented by numerical values 4, 3, 2, and 0 respectively. For example, location has strong relationship with clamping, stability and rigidity and fool proof, medium relationship with loading and unloading, weight and cost and has weak relationship with provision for indexing, etc. Here, the importance of location on design is compared with the relative importance of other attributes on design selection. In the same way, the degree of relationship between other attributes is obtained and is presented in table 7.2. A team of design, production and maintenance engineers derives these degrees of inter-relationship.

**Table 7.2 Design selection attributes and influence among attributes**

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Design selection Attributes</th>
<th>Strong = 4</th>
<th>Medium = 3</th>
<th>Weak = 2</th>
<th>None = 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Location</td>
<td>2,4,5</td>
<td>3,8,11</td>
<td>6,9</td>
<td>7,10</td>
</tr>
<tr>
<td>2.</td>
<td>Clamping</td>
<td>1,3,4,8,9,11</td>
<td>---</td>
<td>5,6,7,10</td>
<td>---</td>
</tr>
<tr>
<td>3.</td>
<td>Loading &amp; Unloading</td>
<td>2,5,4</td>
<td>1,6,7,8,9,11</td>
<td>10</td>
<td>---</td>
</tr>
<tr>
<td>4.</td>
<td>Stability &amp; Rigidity</td>
<td>1,2,3,8,9</td>
<td>6,11</td>
<td>5,7,10</td>
<td>---</td>
</tr>
<tr>
<td>5.</td>
<td>Fool Proof</td>
<td>1,2</td>
<td>3,4,9</td>
<td>8,11</td>
<td>6,7,10</td>
</tr>
<tr>
<td>6.</td>
<td>Provision for Indexing</td>
<td>---</td>
<td>3,4,11</td>
<td>1,2,8</td>
<td>5,7,9,10</td>
</tr>
<tr>
<td>7.</td>
<td>Provision for tool guidance</td>
<td>---</td>
<td>4,8,11</td>
<td>2,3</td>
<td>1,5,6,9,10</td>
</tr>
<tr>
<td>8.</td>
<td>Weight</td>
<td>4,6,11</td>
<td>1,2,3,7</td>
<td>5,9</td>
<td>10</td>
</tr>
<tr>
<td>9.</td>
<td>Safety</td>
<td>2</td>
<td>1,3,4,5,11</td>
<td>6,7,8</td>
<td>10</td>
</tr>
<tr>
<td>10.</td>
<td>Coolant Supply</td>
<td>---</td>
<td>11</td>
<td>2,3,4,6,8</td>
<td>1,5,7,9</td>
</tr>
<tr>
<td>11.</td>
<td>Economy (cost)</td>
<td>2,8</td>
<td>1,4,5,6,7</td>
<td>3,9,10</td>
<td>---</td>
</tr>
</tbody>
</table>

Table 7.2 is developed into digraph model by considering graph theory concept. Selection attribute digraph \( G = (S, R) \) for a system is defined, where \( S = \{s_1, s_2, s_3 \ldots\} \) is a set of nodes representing the attributes and \( R = \{r_{12}, r_{13} \ldots r_{ij} \ldots\} \) is a set of edges between the nodes, representing the degrees of relationship, e.g. edge \( r_{12} \) connects node \( s_1 \) to node \( s_2 \). The direction edge \( r_{12} \) from \( s_1 \) to \( s_2 \) indicates influence of \( s_2 \) on \( s_1 \). The influence of \( s_2 \) on \( s_1 \) is
also possible. This is represented by two directed edges in opposite directions forming closed loop. Design selection digraph model is shown in figure-7.1.

![Design Selection Attributes Digraph model](image)

**Figure 7.1 Design Selection Attributes Digraph model**

### 7.1.4 Development of Design Selection Permanent Matrix (DSPM)

With the reference to the section 6.3, a MXM square matrix developed and called universal selection attributes matrix, which is shown in equation 7.1. Here $s_1, s_2...s_n$ are the values of the $i^{th}$ attribute represented by node and $r_{ij}$ is the relative importance of the $i^{th}$ attribute over the $j^{th}$ attribute represented by the edge $r_{ij}$, i.e., degree of dependence of features. The design selection matrix gives a mathematical entity to the selection digraph. This matrix helps the designer for analyzing the jig/fixture.

### 7.1.5 Development of Design Selection Permanent Function (DSPF)

The permanent function is developed which interprets the design characteristics of the jig. DSPF is a function in which the influence of all attributes and their interdependence and structural complexity are accounted. Moreover, the function given in equation 7.2 does not contain any negative
sign and hence no information is lost. This is written in sigma form as determinant Per [S]. The DSPF ensures a realistic estimate for the design evaluation of jig/fixture.

\[
S = \begin{pmatrix}
S_1 & r_{12} & r_{13} & r_{14} & r_{15} & r_{16} & r_{17} & r_{18} & r_{19} & r_{110} & r_{111} \\
r_{21} & S_2 & r_{23} & r_{24} & r_{25} & r_{26} & r_{27} & r_{28} & r_{29} & r_{210} & r_{211} \\
r_{31} & r_{32} & S_3 & r_{34} & r_{35} & r_{36} & r_{37} & r_{38} & r_{39} & r_{310} & r_{311} \\
r_{41} & r_{42} & r_{43} & S_4 & r_{45} & r_{16} & r_{17} & r_{18} & r_{19} & r_{110} & r_{111} \\
r_{51} & r_{52} & r_{53} & r_{54} & S_5 & r_{56} & r_{57} & r_{58} & r_{59} & r_{510} & r_{511} \\
r_{61} & r_{62} & r_{63} & r_{64} & r_{65} & S_6 & r_{67} & r_{68} & r_{69} & r_{610} & r_{611} \\
r_{71} & r_{72} & r_{73} & r_{74} & r_{75} & r_{76} & S_7 & r_{78} & r_{79} & r_{710} & r_{711} \\
r_{81} & r_{82} & r_{83} & r_{84} & r_{85} & r_{86} & r_{87} & S_8 & r_{89} & r_{810} & r_{811} \\
r_{91} & r_{92} & r_{93} & r_{94} & r_{95} & r_{96} & r_{97} & r_{98} & S_9 & r_{910} & r_{911} \\
r_{101} & r_{102} & r_{103} & r_{104} & r_{105} & r_{106} & r_{107} & r_{108} & r_{109} & S_10 & r_{1011} \\
r_{111} & r_{112} & r_{113} & r_{114} & r_{115} & r_{116} & r_{117} & r_{118} & r_{119} & r_{1110} & S_{11}
\end{pmatrix}
\]

(7.1)

\[
\text{Per} (S) = \prod_{i=1}^{11} S_i + \sum_{i} \sum_{j} \sum_{k} \sum_{l} \ldots \ldots \sum_{11} (r_{ij} r_{jk} r_{ki} S_{kl} S_{lm} \ldots S_{11})
\]

(7.2)

The permanent function contains terms arranged in N+ 1 grouping. Here, N=11 and therefore the number of groupings is 12. The first grouping
consists of only one term and is a set of design measures of \( N \) (11) characteristics. In general, the second grouping is absent due to the absence of a self-loop in design selection digraph. The grouping represents a set of two characteristics of self-loops in the design selection loops (i.e. \( r_{ij} r_{ji} \)) and the dependence of characteristic i and j and the design measure of \( N-2 \) (i.e. 9 characteristics). Each term of the fourth grouping is a set of three characteristic design loops, i.e. \( r_{ij} r_{jk} r_{kl} \) or its pair \( r_{ik} r_{kj} r_{ji} \) and the design measure of \( N-3 \), i.e. 8 characteristics. The terms of the fifth grouping are arranged in two groupings. Each term of the first grouping is a set of two, two characteristic design loops (i.e. \( r_{ij} r_{ji} \) and \( r_{kl} r_{lk} \)) and the design measure of \( N-4 \), (i.e. 7 characteristics). Each term of the second grouping is a set of four characteristic design loops, (i.e. \( r_{ij} r_{jk} r_{kl} r_{li} \) or its pair \( r_{il} r_{lk} r_{kj} r_{ji} \)) and the design measure of \( N-4 \), (i.e. 7 characteristics). The sixth grouping also contains two sub groupings. The terms of the first sub grouping are a set of two characteristic design loops, i.e. \( r_{ij} r_{ji} \), a three characteristic design loop (i.e. \( r_{kl} r_{lm} r_{mk} \) or its pair \( r_{km} r_{ml} r_{lk} \)) and design measures of \( N-5 \) (6 characteristics). Each term of the second grouping is a five characteristic design loop (i.e. \( r_{ij} r_{jk} r_{kl} r_{lm} r_{ni} \) or its pair \( r_{im} r_{ml} r_{lk} r_{ji} \)) and the design measure of \( N-5 \) (i.e. 6 characteristics). Similarly, other terms of the function are defined. Each and every term of the groupings and sub groupings has its own independent identity.

### 7.1.6 Calculation of selection index using DSPF

Analysis for various designs for a jig is carried out in accordance with the terms of DSPF, as it is the representation of the design selection. For analysis purpose, its terms, which are considered as a set of distinct diagonal elements (\( s_1, s_2,... \)) and loops (\( r_{ij} r_{jk} ... r_{qi} \)) consist of off-diagonal matrix elements. Each function leads to a useful test for analysis if a term is interpreted as a set and not a dot product. There are \( N_1 \) distinct ways in which
it can be formed from the design selection features. Based on this, selection of design is carried out with respect to the terms appearing in its DSPF.

**Design Selection Index (DSI)**

DSPF becomes a useful tool to derive a quantitative measure/index for the selection of jig/fixture. This index is known as a design selection index (DSI). DSI is arrived from DSPF and it takes into account the values of attributes and values for interrelationship between attributes. The index can be evaluated if \( s_i \) and \( r_{ij} \) are assigned qualitative or quantitative values. These values are assigned on appropriate scale. The values of interdependence given in table 7.2 are arrived by a brainstorming session. The values of attributes are given in table 7.3. These values are assigned based on the understanding of the features which may be normalized from 0-4/0-10. For the beneficial attributes, the maximum values are given, if they are more desirable for the given application. For example, 4 is given for very high accuracy location and 1 is given for low accuracy location. Where non-beneficial attribute is one, the lower value is desirable. For non beneficial attributes, value 4 is given as the least desirable for the given application (for example- 4 is given for low weight fixture and 1 is given for heavy weight fixture).

### 7.1.7 Selection of optimum design by comparison of DSI

DSI is a means to evaluate the various designs of Jig/ Fixture through which an optimum design can be selected. This DSI is calculated for all design varieties by assigning values in the function. Based on this value, various designs of jig/fixture are arranged in ascending/descending order and a design can be selected as optimum, whose DSI is larger.
7.1.8 Numerical example

In order to select the optimum design, it is necessary to evaluate the jig/fixture and to obtain the DSI. Example of jig for flange coupling is considered for illustrating the procedure for evaluating DSI and is shown in figure 7.2. First, the jig is analyzed for its various features (attributes). The evaluation of jig/fixture is carried out by the following steps:

1. Selection of attributes

All 11 attributes shown in table 7.3 are not much significant for the given jig. And to simplify the illustration, only five significant (main) attributes are considered. They are 1. Location, 2. Clamping, 3. Loading & unloading, 4. Stability & rigidity, 5. Provision for tool guidance.

Figure 7.2 Jig for flange coupling
### Table 7.3 Scoring for design selection attributes

<table>
<thead>
<tr>
<th>SI. No</th>
<th>Design selection Attributes</th>
<th>Attributes (features) value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Location</td>
<td>1(low accuracy) 2(medium accuracy) 3(higher accuracy) 4(very high accuracy)</td>
</tr>
<tr>
<td>2.</td>
<td>Clamping</td>
<td>1(low rigidity) 2(medium rigidity) 3(higher rigidity) 4(very high rigidity)</td>
</tr>
<tr>
<td>3.</td>
<td>Loading &amp; Unloading</td>
<td>1(very difficulty) 2(medium difficulty) 3(easier) 4(much easier)</td>
</tr>
<tr>
<td>4.</td>
<td>Stability &amp; Rigidity</td>
<td>1(low) 2(medium) 3(higher) 4(very high)</td>
</tr>
<tr>
<td>5.</td>
<td>Fool Proof</td>
<td>0 (Not exist) --- --- 4(exist)</td>
</tr>
<tr>
<td>6.</td>
<td>Provision for Indexing</td>
<td>0 (Not exist) --- --- 4(exist)</td>
</tr>
<tr>
<td>7.</td>
<td>Provision for Tool Guidance</td>
<td>0 (Not exist) --- --- 4(exist)</td>
</tr>
<tr>
<td>8.</td>
<td>Weight</td>
<td>1(very heavy) 2 (medium heavy) 3 (light) 4 (very light)</td>
</tr>
<tr>
<td>9.</td>
<td>Safety</td>
<td>1(low) 2 (medium) 3 (safer) 4 (much safer)</td>
</tr>
<tr>
<td>10.</td>
<td>Coolant Supply</td>
<td>0 (Not exist) 1(exist)</td>
</tr>
<tr>
<td>11.</td>
<td>Economy ( cost)</td>
<td>1(low) 2 (medium) 3 (higher) 4 (very high)</td>
</tr>
</tbody>
</table>

### 2. Construction of digraph model

Digraph model as shown in figure 7.3 is constructed by considering the attributes as nodes and relationship between them as edges. The relationship between the attributes is given in table 7.2.
3. Development of design evaluation matrix

Then Design Selection/evaluation Matrix (DSM) is formed based on the digraph model. It is a one to one representation of the digraph model and is given in equation 7.3. In DSPM, \( s_1 \ldots s_5 \) are the attributes and \( r_{12}, r_{21}, \ldots r_{54} \) are the interrelationships between the attributes.

\[
S = \begin{pmatrix}
  s_1 & r_{12} & r_{13} & r_{14} & r_{15} \\
  r_{21} & s_2 & r_{23} & r_{24} & r_{25} \\
  r_{31} & r_{32} & s_3 & r_{34} & r_{35} \\
  r_{41} & r_{42} & r_{43} & s_4 & r_{45} \\
  r_{51} & r_{52} & r_{53} & r_{54} & s_5 \\
\end{pmatrix}
\]  

(7.3)

3. Development of design selection/evaluation function

A design selection permanent function (DSPF) given in equation 7.4 is derived. This function gives the meaningful interpretation to the DSPM. This completes phase 4. From DSPF, index for different design alternatives is calculated by substituting the values of \( s_i \) & \( r_{ij} \), which are called as Design Selection Index. The values for the attributes \( s_1 \ldots s_5 \) are taken from table 7.3 and the values for interrelationships \( r_{12}, r_{21} \ldots r_{54} \) are taken from table 7.2. The
following matrix equation 7.5 with numerical values is obtained by substituting the values for \( r_{ij} \) and \( s_i \).

\[
\text{Per}(S) = \sum_{i=1}^{5} S_i + \sum_{i,j} \sum_{k,l} \sum_{m} \sum_{l} (r_{ij} r_{kl}) S_j S_l \ldots S_m \\
+ \sum_{i,j} \sum_{k,l} \sum_{m} \sum_{l} (r_{ij} r_{kl} r_{ki} + r_{ik} r_{kj} r_{ji}) S_j \ldots S_m \\
+ \left( \sum_{i,j} \sum_{k,l} \sum_{m} \sum_{l} (r_{ij} r_{jk}) (r_{kl} r_{lk}) S_j S_l \ldots S_m \right) \\
+ \left( \sum_{i,j} \sum_{k,l} \sum_{m} \sum_{l} (r_{ij} r_{jk} r_{kl} r_{lk}) (r_{il} r_{ik} r_{ji}) S_j S_l \ldots S_m \right) \\
+ \left( \sum_{i,j} \sum_{k,l} \sum_{m} \sum_{l} (r_{ij} r_{jk} r_{kl} r_{lk}) (r_{ml} r_{ml} r_{lk} r_{lk} r_{ji}) S_j S_l \ldots S_m \right)
\]

(7.4)

\[
S = \begin{bmatrix}
3 & 4 & 3 & 4 & 4 \\
4 & 3 & 4 & 4 & 2 \\
3 & 4 & 2 & 4 & 4 \\
4 & 4 & 3 & 3 & 2 \\
0 & 2 & 2 & 3 & 4
\end{bmatrix}
\]

(7.5)

4. Design selection/evaluation index (DSI)

For the above derived matrix, a design selection index (DSI) is obtained by substituting the values of the attributes and interrelationships in the function, which is given as:

\[
\text{DSI} = 216 + 1644 + 3744 + 35952 + 9216 = 50772
\]

Such DSI (indices) can be evaluated for various design varieties. The design, which has the higher numerical value, is considered as the optimum one. This simple example has been elaborated for understanding the methodology. Although the procedure may appear troublesome, the calculations are performed manually. So, it is recommended to use computer programming.
7.2 ANALYSIS AND EVALUATION OF PRODUCT DESIGN THROUGH DESIGN ASPECTS USING DIGRAPh AND MATRIX APPROACH

7.2.1 Introduction

A successful product design fulfils the consumer’s needs. It is very important for the designers to recognize these needs that go beyond the utilitarian and functional to include the inspirational, emotional and cultural. New product development also is indeed very important for manufacturers. However, developing newer products is a risky and uncertain process. In order to reduce the risks and uncertainties, companies need to evaluate their new product initiatives carefully and make accurate decisions. This demonstrates the increasing importance of the role of design both for economic competitiveness and for improvement of the quality of life and work. One of the major directions during the design process is that the products should manifest end users point of view, from initial concept to their distribution to the market place. Thus, product design evaluation is a must at all phases of the product development process from concept phase to detailed design phase. Design evaluation is time consuming and laborious, since many factors have to be considered in relation to the development and design which vary in character and complexity. Design evaluation cannot be made without structured decision making tools (aids). Since the decision alternatives are too many and simultaneous, criteria impact on the decision are too vast to consider at once by human decision makers.

Maddulapalli A.K and Azarm S. (2006) addressed both kinds of variability, i.e., variability in the preferences of the decision maker and variability in the attribute levels of the design alternatives. They presented a method for product design selection with variability in preferences for an implicit value function and later extended it to account for variability in attribute levels of design alternatives. Besharati B. et al. (2006) presented an
integrated design and marketing approach to facilitate the generation of an optimal robust set of product design alternatives to carry forward to the prototyping stage. Their approach evaluates the performance and robustness of a design alternative due to variations in its uncontrolled parameters. Vanegas V.L and Labib A.W. (2005) presented several fuzzy approaches to design evaluation. Weight of criteria and performance levels are captured by fuzzy numbers, and the overall performance of an alternative is calculated through the new fuzzy weighted average.

Li H. and Azarm S. (2000) presented an approach wherein product design is viewed as a selection process with two main stages: design alternative generation and design alternative evaluation. The focus of their paper was mainly on a design alternative evaluation model in which designer’s preferences, customers’ preferences, and market competition are accounted for the selection of the best possible design. See et al. (2004) discussed the problem of selecting a design from a set of alternatives using multiple, potentially conflicting criteria. They also demonstrated the strengths and weaknesses of the various decision-making approaches using an aircraft selection problem and then presented a method based on the concept of hypothetical equivalents and expanded the method to include hypothetical in equivalents. Ibusuki U. and Kaminski P.C. (2007) suggested a methodology for the product development process in an automotive company, aiming at the correct systematic approach of Value Engineering (VE) and target-costing in cost management. Their proposed approach was validated in a case study focused on the engine-starter system of a vehicle, aiming at improved product cost, functionality and quality accomplishment, in accordance with customer needs and the company strategy. Albritton M.P. and McMullen P.R. (2007) suggested optimal product problem, where the “best” mix of product features was formulated into an ideal offering and was optimized using Ant Colony Optimization (ACO). Here, algorithm based on the behavior of social insects
was applied to a consumer decision model designed to guide new product decisions and to allow planning and evaluation of product offering scenarios.

Chen L.H. and Weng M.L. (2006) suggested Quality Function Deployment (QFD) to a product development process to achieve higher customer satisfaction. The engineering characteristics affecting the product performance are designed to match the customer requirements. Kim H.M. et al. (2003) analyzed Automotive Vehicle Design by using Target Cascading, a systematic effort to propagate the desired top-level system design targets to appropriate specifications for subsystems and components in a consistent and efficient manner. Many methodologies had been developed during the past two decades by the academia and industry such as concurrent engineering, robust design, design for manufacture and assembly, total quality development, etc. Some other methods and techniques, which are used, are given in the table 7.4.

Digraph and matrix approach has been used extensively by a number of researchers in various engineering applications such as failure cause analysis by Roa R.V et al. (2002), reliability evaluation by Sehgal R. et al. (2000), proactive fault identification by Yu, Y et al. (2005), TQM evaluation by Grover S. et al and Kulkarni S (2004, 2005), risk mitigation by Faisal M.N et al. (2007) and in other areas also. Digraph and matrix approach is a well systematic one, which considers all the influencing factors (attributes) and their relative importance of one factor on the other. This consideration of relative importance is missing in all other techniques discussed above. This paper presents the analysis, evaluation and selection of product design through design aspects using digraph and matrix approach.
Table 7.4 Common evaluation methods and techniques

<table>
<thead>
<tr>
<th>Evaluation methods/Techniques</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>CAD simulation models</td>
<td>To evaluate design and its perceived use during the different stages of a design process.</td>
</tr>
<tr>
<td>Checklists</td>
<td>To define operations of a product/system and identify users’ needs.</td>
</tr>
<tr>
<td>Mock-up evaluation</td>
<td>To evaluate product usage with users participation</td>
</tr>
<tr>
<td>Motion studies</td>
<td>To evaluate motion performances and identify critical conditions</td>
</tr>
<tr>
<td>Protocol analysis</td>
<td>To evaluate a design, user’s expertise level and understand users’ concept of products.</td>
</tr>
<tr>
<td>Prototype evaluation</td>
<td>To verify a design outcome under real conditions.</td>
</tr>
<tr>
<td>Task-analysis</td>
<td>To define and evaluate operational procedures of a human/product/system.</td>
</tr>
<tr>
<td>Interviewing users</td>
<td>To identify users’ needs</td>
</tr>
</tbody>
</table>

There are many design aspects that affect (factors) the design process. They are called as design selection attributes. They are

1. Design for manufacturing
2. Design for assembly
3. Design for environment
4. Design for safety
5. Design for reliability
6. Design for maintenance
7. Design for aesthetic features
8. Design for economy
9. Design for ergonomics

The above said product design evaluation attributes are listed based on the discussions in focus group (brain storming session) and from the literatures [Otto K. and Wood K. (2000), Ulrich K.T. and Eppinger S.D. (2008), Chitale A.K., Gupta R.C. (2001)]. A focus group is a collection of individuals that has been brought together to discuss a particular topic, issue or concern. This focus group technique as one approach enables the designer to explore user desires and needs.

In general, these design aspects are innumerable and are referred to as design for X (DFX) where X represents a broad variety of design considerations which influence the design selection and are referred to as design selection attributes. All these attributes and their importance on design selection are explained in the forthcoming section.

7.2.2 Product design evaluation attributes

a. Design for manufacturing (DFM)

DFM refers to the general engineering art of designing products in such a way that they are easy to manufacture. The basic idea exists in almost all engineering disciplines, but of course the details differ wildly depending on the manufacturing technology. Traditionally, DFM method evaluates the feasibility and cost of manufacturing of the product at the operation level. Bralla J.G. (1986), Anderson D.M. (1990), Corbett J. et al. (1991), and Boothroyd G. et al. (2002) provide detailed discussions on manufacturability and design. Design guidelines such as those provided by Parmer C. and
Steve Laney (1993), Singh K. (1996), and Fagade A. and Kazmer D. (1998) are examples of DFM method. As new DFX methods are explored, the definition of DFM has expanded to become synonymous with DFX and concurrent engineering. Various guidelines for DFM are given in the appendix A.

b. Design for assembly (DFA)

DFA is a process by which products are designed with ease of assembly in mind. If a product contains fewer parts, it will take less time to assemble, thereby reducing assembly costs. In addition, if the parts are provided with features, which make it easier to grasp, move, orient and insert them, assembly time and assembly costs reduce. DFA guidelines adapted from several sources such as Andreasen D.M. (1983), Baldwin S. (1996), Huthwaite B. (1990), Iredale R. (1964) and Xerox (1986). DFM and DFA are most of the time considered simultaneously as DFMA (design for manufacturing and assembly). But, they have conflicting nature among them. DFMA is important for design because it has three beneficial impacts. First and foremost, it reduces part count and also reduces cost and time. For example, Motorola introduced DFMA and reduced its part count from 217 to 97 and thereby assembly time is reduced from 2,700 to 1,350 s [Otto K., Wood K. (2000)]. Secondly, DFMA increases reliability [Bralla J.G. (1991), Barkan P., Hinckley C. (1993)]. Finally, DFMA increases the quality of the design. Various guidelines for the DFA are given in appendix B.

c. Design For Environment (DFE)

The present problem of global warming is a challenging one for the manufacturing industries. DFE is a product design approach for reducing the impact of the products on the environment. Products can have adverse impact on the environment during manufacturing through the use of highly polluting
processes and consumption of large quantities of raw materials and energy and disposal of waste. Because of these issues, one must consider the entire life cycle of the product from creation to disposal. In this life cycle, there are many events of creating pollution and many opportunities for recycling, remanufacturing, reuse, and reducing environmental impact. Designer must bring all his ingenuity to keep in mind all the challenging problems while creating efficient products. Various guidelines for the DFE are given in appendix C.

d. Design for Safety (DFS)

The goals of the design process are usually manifold. The resulting system must not only satisfy its functional requirements but also have to fulfill certain non-functional requirements. One such requirement is safety. A safe product is one that does not cause injury or property loss and does not pollute the environment. There are three aspects to design for safety.

1. Make the product safe.
2. If it is not possible to make the product inherently safe, then design the proactive devices like guards, automatic cutoff switches, pressure relief valves, to mitigate the hazard.
3. If step 2 cannot remove all the hazards, then warn the user of the product with appropriate warnings like labels, flashing and loud sounds. Various guidelines for the design for safety are given in appendix D.

e. Design for Reliability (DFR)

Reliability engineering is the discipline of ensuring that a system will be reliable when operated in a specified manner. Reliability engineering is performed throughout the entire life cycle of a system, including development, test, production and operation. Reliability may be defined in several ways as:


- Idea that something is fit for a purpose with respect to time.
- Capacity of a device or system to perform as designed.
- Resistance to failure of a device or system.
- Ability of a device or system to perform a required function under stated conditions for a specified period of time.
- Probability that a functional unit will perform its required function for a specified interval under stated conditions.

Reliability engineers rely heavily on statistics, probability theory, and reliability theory. Many engineering techniques are used in reliability engineering, such as reliability prediction, Weibull analysis, thermal management, reliability testing and accelerated life testing. Because of the large number of reliability techniques, their expense, and the varying degrees of reliability required for different situations, most of the projects develop a reliability program plan to specify the reliability tasks that will be performed for that specific system. Various guidelines for the design for reliability are given in the appendix E.

f. Design for Maintenance (Serviceability) (DFMn)

Serviceability is concerned with the ease with which maintenance can be performed on a product. Products often have parts that are to be replaced at periodic intervals. It is important to anticipate the required service operations during the design of the product. Provision must be made for disassembly and assembly. For example, don’t make an automobile design that requires the removal of the panel to access the oil filter. Also, remember that service usually will be carried out in “the field” where special tools and fixtures used in factory assembly are not available. The best way to improve serviceability is to reduce the need for service by improving reliability of the
components and systems. Various guidelines for the design for maintenance are given in appendix F.

g. Design for Aesthetic Features (DFAF)

Designers have many aesthetic qualities to improve the marketability of the manufactured products: smoothness, shine/reflectivity, texture, pattern, curviness, color, simplicity, usability, velocity, symmetry, naturalness, and modernism. The staff of the design aesthetics section focus on design, appearance and the way people perceives products. Design aesthetics is interested in the appearance of products; the meaning of appearance is studied mainly in terms of social and cultural factors. The distinctive focus of the section is research and education in the field of sensory modalities in relation to product. These fields of attention generate design baggage that enables engineers to design products, systems, and services, and match them to the correct field of use. Various guidelines for the design of aesthetic features are given in appendix G.

h. Design for Economy (DFEc)

It is important to note that cost is also a dimension of the quality. Economically successful products are profitable; that is, they generate more cumulative inflows than the cumulative outflows. The main objective of all manufacturers is to make profit. So, the producer should give a cost effective design. Based on the cost and other considerations, the designer should select material or manufacturing processes. Various guidelines for the design for economy are given in appendix H.
**i. Design for Ergonomics (DFEr)**

Ergonomics (or human factors) is the application of scientific information concerning humans to the design of objects, systems and environment for human use. (Definition adopted by the International Ergonomics Association in 2007). Ergonomics is the study of the interaction of a person with a machine. Information derived from Ergonomists contributes to the design and evaluation of tasks, jobs, products, environments and systems in order to make them compatible with the needs, abilities and limitations of people (International Ergonomics Association in 2000). Ergonomics comes into everything, which involves people. Work systems, sports and leisure, health and safety should all embody ergonomics principles if well designed. (International Ergonomics Association in 2007). It is the applied science of equipment design intended to maximize productivity by reducing operator fatigue and discomfort. The field is also called biotechnology, human engineering, and human factors engineering. The role of human factors in a product assumes importance in three respects.

1. Man, the operator, as occupant of space that is to operate a machine, should have adequate space as dictated by human body dimensions or anthropometry.

2. Man, as reader of display from the machine. This is based on the display data; man processes the data and takes action.

3. Man, as one who takes action through operating controls which form a part of the machine. It will be obvious that human engineering in design should consider application of forces and study of displays and controls.

Various guidelines for the design for ergonomics are given in the appendix I. Design for X (DFX), where X corresponds to one of dozens of quality criteria, which are listed earlier. This list is not an exhaustive one and
the same may be extended further for dozens of criteria. They may be specifically related to the product or processes. For example, design for handling, design for flow ability (casting process), design for recycle ability, design for remanufacturing, design for energy efficiency and design for regulations and standards, etc.

### 7.2.3 Product design Evaluation Digraph (PED) model

A digraph is used to represent the factors and their interdependencies in terms of nodes and edges. In a digraph, direction is assigned to edges in the graph. Thus, product design evaluation attributes’ digraph consists of set of nodes, \( S = \{ P_i \} \) with \( i = 1, 2, \ldots, M \) and set of edges, \( E = \{ r_{ij} \} \). A node \( P_i \) represents \( i^{th} \) product design evaluation attribute and the \( r_{ij} \) edge represents relative importance among the attributes. The number of nodes \( M \) is equal to the number of product design evaluation attributes considered for the selection of design. If a node \( i \) has relative importance over another node \( j \) in the selection, then, a directed edge (arrow) is drawn from node \( i \) to \( j \) (i.e., \( r_{ij} \)). If \( j \) has relative importance over \( i \), then the directed edge (arrow) is drawn from node \( j \) to \( i \) (i.e., \( r_{ji} \)). The most common representation of a graph is a diagram in which the vertices are represented as points and edges as line segments joining the end vertices. A universal product evaluation digraph model is constructed as shown in figure 7.4 by considering the attributes described in section 7.2.2 as nodes and the relative importance between the attributes as edges.
7.2.4 Product design Evaluation Matrix (PEM)

Since a digraph representation is a visual one, it helps to analyze the simple system with few attributes. When a system becomes complex (i.e., when it has more attributes), the digraph becomes clumsy and inconvenient for visualization. To overcome these difficulties, the digraph is represented in matrix form. Matrix representation of PED presents a one-to-one representation. If a digraph has ‘N’ factors, the matrix representation will be a $N \times N$ matrix, which considers all the product design evaluation attributes and their relative importance ($r_{ij}$). The PEM is given in matrix equation 7.5 in which $P_i$ is the value of the $i$th attribute and $r_{ij}$ is the relative importance of $i$th attribute over the $j$th attribute. In general, diagonal elements carry the value of attributes and the off diagonal elements carry the value of relative importance.
7.2.5 Product design Evaluation Function (PEF)

It is a permanent function of standard matrix and is used in combinatorial mathematics described by Jarkat W.B and Rayser K.J. (1996)). It is a desirable function, which interprets the design characteristics of the system. The PEF is a function in which all system and their interdependence and structural complexity are accounted. Moreover, PEF does not contain any negative sign and hence no information is lost. The PEF is written in the form of equation 7.6 as per. \[ S = \]

\[
\begin{array}{cccccccccc}
P_1 & r_{12} & r_{13} & r_{14} & r_{15} & r_{16} & r_{17} & r_{18} & r_{19} \\
r_{21} & P_2 & r_{23} & r_{24} & r_{25} & r_{26} & r_{27} & r_{28} & r_{29} \\
r_{31} & r_{32} & P_3 & r_{34} & r_{35} & r_{36} & r_{37} & r_{38} & r_{39} \\
r_{41} & r_{42} & r_{43} & P_4 & r_{45} & r_{46} & r_{47} & r_{48} & r_{49} \\
r_{51} & r_{52} & r_{53} & r_{54} & P_5 & r_{56} & r_{57} & r_{58} & r_{59} \\
r_{61} & r_{62} & r_{63} & r_{64} & r_{65} & P_6 & r_{67} & r_{68} & r_{69} \\
r_{71} & r_{72} & r_{73} & r_{74} & r_{75} & r_{76} & P_7 & r_{78} & r_{79} \\
r_{81} & r_{82} & r_{83} & r_{84} & r_{85} & r_{86} & r_{87} & P_8 & r_{89} \\
r_{91} & r_{92} & r_{93} & r_{94} & r_{95} & r_{96} & r_{97} & r_{98} & P_9 \\
\end{array}
\]

\[ \sum_{i} \sum_{j} \sum_{k} \sum_{l} r_{ij} r_{kl} r_{lk} P_m P_7 P_8 P_9 \]

\[ \sum_{i} \sum_{j} \sum_{k} \sum_{l} r_{ij} r_{kl} r_{lk} r_{ik} P_m P_7 P_8 P_9 \]

\[ \sum_{i} \sum_{j} \sum_{k} \sum_{l} r_{ij} r_{kl} r_{lk} r_{ik} r_{jk} P_m P_7 P_8 P_9 \]

\[ \sum_{i} \sum_{j} \sum_{k} \sum_{l} r_{ij} r_{kl} r_{lk} r_{ik} r_{jk} r_{ki} P_m P_7 P_8 P_9 \]

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\[
\begin{array}{cccccccccc}
P_1 & r_{12} & r_{13} & r_{14} & r_{15} & r_{16} & r_{17} & r_{18} & r_{19} \\
r_{21} & P_2 & r_{23} & r_{24} & r_{25} & r_{26} & r_{27} & r_{28} & r_{29} \\
r_{31} & r_{32} & P_3 & r_{34} & r_{35} & r_{36} & r_{37} & r_{38} & r_{39} \\
r_{41} & r_{42} & r_{43} & P_4 & r_{45} & r_{46} & r_{47} & r_{48} & r_{49} \\
r_{51} & r_{52} & r_{53} & r_{54} & P_5 & r_{56} & r_{57} & r_{58} & r_{59} \\
r_{61} & r_{62} & r_{63} & r_{64} & r_{65} & P_6 & r_{67} & r_{68} & r_{69} \\
r_{71} & r_{72} & r_{73} & r_{74} & r_{75} & r_{76} & P_7 & r_{78} & r_{79} \\
r_{81} & r_{82} & r_{83} & r_{84} & r_{85} & r_{86} & r_{87} & P_8 & r_{89} \\
r_{91} & r_{92} & r_{93} & r_{94} & r_{95} & r_{96} & r_{97} & r_{98} & P_9 \\
\end{array}
\]

\[ \sum_{i=1}^{9} P_i + \sum_{i} \sum_{j} \sum_{k} \sum_{l} r_{ij} r_{kl} r_{kl} \sum_{9} (r_{ij} r_{kl}) P_i P_j P_k P_l P_m P_s \]

\[ \sum_{i} \sum_{j} \sum_{k} \sum_{l} r_{ij} r_{kl} r_{kl} \sum_{9} (r_{ij} r_{kl}) P_m P_s P_i P_k P_l P_m P_s \]

\[ \sum_{i} \sum_{j} \sum_{k} \sum_{l} r_{ij} r_{kl} r_{kl} r_{ij} r_{kl} r_{ij} \sum_{9} (r_{ij} r_{kl} r_{ij} r_{kl} r_{ij} r_{kl}) P_m P_s P_i P_k P_l P_m P_s \]

\[ \sum_{i} \sum_{j} \sum_{k} \sum_{l} r_{ij} r_{kl} r_{kl} r_{ij} r_{kl} r_{ij} \sum_{9} (r_{ij} r_{kl} r_{ij} r_{kl} r_{ij} r_{kl}) P_m P_s P_i P_k P_l P_m P_s \]
The product design evaluation function \( \text{Per.}(S) \) contains terms arranged in \((M + 1)\) groupings and these groupings represent the presence of attributes and the relative importance loops. The first grouping represents the presence of all product design attributes. In general, the second grouping is absent due to the absence self loop in product design attributes digraph. The third grouping contains 2-attributes relative importance loops and the presence of \((M - 2)\) attributes. Fourth grouping represents a set of 3-attributes relative importance loops or its pairs and presence of \((M - 3)\) attributes. The fifth grouping contains two sub-groupings. The terms of the first sub-grouping are a set of two 2-attributes relative importance loops and the presence of \((M - 4)\) attributes. Each term of the second sub-grouping is a set of 4-attributes relative importance loops or its pairs and the presence of \((M - 4)\) attributes. The sixth grouping contains two sub-groupings. The terms of the first sub-grouping are a set of 2-attributes relative importance loops and 3 attributes relative importance loops or its pairs and presence of \((M - 5)\) attributes. The term of second sub-grouping is a 5-attributes relative importance loop or its pairs and the presence of \((M - 5)\) attributes. Similarly, other terms of the expression are defined. Thus, product design evaluation function characterizes the product design as it contains all attributes and their relative importance.

### 7.2.6 Product design Evaluation Index (PEI)

PEI is a numerical value that defines the overall effectiveness of the product design with respect to design aspects and provides the information of the product design with respect to customer satisfaction. PEI is obtained from
the product design evaluation function (equation 7.6) by substituting the
values of attributes $P_i$ and the values of relative importance between the
attributes $r_{ij}$. The values for attributes $P_i$ are obtained from the data provided
by the industries and expertise. The value of many attributes cannot be
expressed as numerical values. If a quantitative value is not available, then a
ranked value judgment on a scale, e.g., from 0 to 10 scales, is adopted. It is
seen that many of the attributes are not easy to measure in terms of qualitative
scale. Hence, a questionnaire has been designed to measure each attribute in
terms of weightage (questionnaire is given in appendix). The numerical values
obtained through questionnaire are normalized on the same scale, i.e., 0–10. If
$P_i$ has a range $P_{il}$ and $P_{iu}$, the value 0 is assigned to the lowest range value
($P_{il}$) and 10 is assigned to the highest range value ($P_{iu}$). The other intermediate
values $P_i$ of the product design attribute are assigned values between 0 and 10
as follows:

$$
P_i = \left\{ \frac{10}{P_{iu}} \right\} \times P_{ii} \text{ for } P_{il} = 0
$$

$$
P_i = \left\{ \frac{10}{(P_{iu} - P_{il})} \right\} \times (P_{ii} - P_{il}) \text{ for } P_{il} > 0
$$

(7.7)

Equation 7.7 is applicable for general beneficial attributes only. A
beneficial attribute i.e., design for safety, means its higher attribute values are
more desirable for the given product design, whereas a non beneficial attribute
i.e., design for economy is one for which lower attribute values are desirable.
Therefore, in case of non beneficial product design attributes, the value 0 and
10 are assigned to the highest range value ($P_{iu}$) and the lowest range value ($P_{il}$
) respectively. The other intermediate values $P_{ii}$ of the product design attribute
are assigned between 0 and 10 as follows:

$$
P_i = 10\{ 1 - (P_{ii} / P_{iu}) \} \text{ for } P_{il} = 0
$$

$$
P_i = \left\{ \frac{10}{P_{iu} - P_{il}} \right\} \times (P_{iu} - P_{ii}) \text{ for } P_{il} > 0
$$

(7.8)
For example, the attribute design for safety with the higher value is much safer to use. So, the value for the attribute design for safety with higher value is beneficial to customers as well as manufacturers. So, the quantitative value obtained from the appendix for DFS is substituted in equations 7.7 for normalizing. On the other hand, the attribute design for economy means total cost of the product involved in product development. If the total cost is higher, both the customer and the manufacturer will not be benefited. So, the attribute DFE is considered as non-beneficial attribute and it should have minimum value. So, the value obtained from appendix for DFE is substituted in equation 7.8 for normalizing.

The relative importance between the two attributes (i.e., \( r_{ij} \)) for a given product design is also assigned a value on the scale 0–10 and is arranged in six classes. The relative importance implies that an attribute ‘i’ is compared with another attribute ‘j’ in terms of its relative importance for the given product design. The relative importance between \( i, j \) and \( j, i \) is distributed on the scale 0–10. This means, a scale is adopted from 0 to 10 on which the relative importance values are compared. If \( r_{ij} \) represents the relative importance of the \( i \)th attribute over the \( j \)th attribute, then the relative importance of the \( j \)th attribute over the \( i \)th attribute is evaluated using equation \( r_{ji}=10-r_{ij} \). For example, if \( j \) th attribute is slightly more important than the \( i \)th attribute, then \( r_{ji} = 6 \) and \( r_{ij} = 4 \). Comparative scale for assigning the values of \( r_{ij} \) and \( r_{ji} \) is given in the table 7.5. The product design evaluation index value for all design alternatives is evaluated by substituting the values of \( P_i \)'s and \( r_{ij} \)'s in equation 7.6. The product designs can be arranged in the descending or ascending order of PEI, to rank them for their performance. The product design, for which the value of PEI is highest, is considered to be the best. The value of the relative importance between the attributes is assigned based on table 7.5 and is given in table 7.6.
### Table 7.5 Relative importance of product selection attributes

<table>
<thead>
<tr>
<th>Class Description</th>
<th>( r_{ij} )</th>
<th>( r_{ji} = 10 - r_{ij} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two attributes are of equal importance</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>One attribute is slightly more important than the other</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>One attribute is more important than the other</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>One attribute is much more important than the other</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>One attribute is extremely more important than the other</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>One attribute is exceptionally more important than the other</td>
<td>10</td>
<td>0</td>
</tr>
</tbody>
</table>

### Table 7.6 Value of relative importance

<table>
<thead>
<tr>
<th></th>
<th>DFM</th>
<th>DFA</th>
<th>DFE</th>
<th>DFS</th>
<th>DFR</th>
<th>DMn</th>
<th>DFAF</th>
<th>DF Ec</th>
<th>DF Er</th>
</tr>
</thead>
<tbody>
<tr>
<td>DFM</td>
<td>***</td>
<td>5</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DFA</td>
<td>5</td>
<td>***</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>7</td>
<td>7</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>DFE</td>
<td>3</td>
<td>3</td>
<td>***</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>6</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>DFS</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>***</td>
<td>5</td>
<td>7</td>
<td>7</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>DFR</td>
<td>4</td>
<td>4</td>
<td>5</td>
<td>5</td>
<td>***</td>
<td>6</td>
<td>7</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>DMn</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>***</td>
<td>6</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>DFAF</td>
<td>2</td>
<td>3</td>
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7.2.7 Example

In order to select the optimum product design model, it is necessary to evaluate all the models of a certain product. An example of kicker models of motor bike (product) is considered for illustrating the procedure for obtaining the PEI and is shown in figure 7.5.

![Figure 7.5 Various models of the product (motor bike kicker)](image)

**Step 1: Identification of the attributes**

To simplify the illustration, the following main attributes are considered. They are

1. Design for manufacturing-P1
2. Design for assembly-P2
3. Design for maintenance-P3
4. Design for economy-P4

For the example considered, the above said steps are followed for analyzing and for obtaining evaluation index.
Step 2: Construction of digraph model

By considering the mentioned attributes, the digraph model is constructed and is shown in figure 7.6.

![Figure 7.6 Digraph model for the given example](image)

Step 3: Development of product design evaluation matrix

Product design evaluation matrix shown in figure 7.9 is developed by considering the attributes \([P_1, P_2, P_3, P_4]\) as diagonal elements and the relative importance between the attributes as off diagonal elements.

\[
S = \begin{pmatrix}
P_1 & r_{12} & r_{13} & r_{14} \\
r_{21} & P_2 & r_{23} & r_{24} \\
r_{31} & r_{32} & P_3 & r_{34} \\
r_{41} & r_{42} & r_{43} & P_4
\end{pmatrix}
\]  

(7.9)

Note: The values for the attributes are arrived by filling the questionnaires given in the appendix.

Description to obtain the value for attribute is as follows:

1. Considering the attribute DFM and assigning the value in the appendix against each guideline for the considered design alternative.
2. Assigning the minimum possible value for the each guide lines of DFM and summing up all the values and assuming as the $P_{ii}$ (lower value of the $i$th attribute). For this example $P_{ii} = 25$.

3. Assigning the maximum possible value for the each guide lines of DFM and summing up all the values and assuming as the $P_{iu}$ (higher value of the $i$th attribute). For this example, $P_{iu} = 115$

4. Assigning the value for each guide lines of DFM of the considered product design and summing up all the values and assuming as $P_{ii}$ (value of the attribute of the considered product design) For the product design given in figure 7.5, $P_{ii} = 65$

5. Substituting this value in the equation 7.7 to get the normalized value on 0–10 scale.

$$P_i = \frac{10}{(P_{iu} - P_{ii})} \times (P_{ii} - P_{il}) \text{ for } P_{ii} > 0$$

$$= \frac{10}{(115 - 25)} \times (65 - 25)$$

$$= 0.111 \times 40 = 4.4$$

Similarly, the other attribute values are normalized.

**Step 4: Obtaining product design evaluation function**

In this step, product design evaluation function is obtained which is nothing but the determinant of the given matrix. The PEF can be written in the expanded form as shown in equation 7.10.

$$S_1 = \begin{pmatrix}
4.4 & 5 & 6 & 6 \\
5 & 5.4 & 6 & 6 \\
4 & 4 & 1.6 & 5 \\
4 & 4 & 5 & 1.6
\end{pmatrix} \quad S_2 = \begin{pmatrix}
3.8 & 5 & 6 & 6 \\
5 & 4.2 & 6 & 6 \\
4 & 4 & 1.2 & 5 \\
4 & 4 & 5 & 1.2
\end{pmatrix}$$
\[ \text{Per}(S) = P_1P_2P_3P_4 + \left\{ (r_{12}r_{21}P_3P_4 + r_{13}r_{31}P_2P_4 + r_{14}r_{41}P_2P_3 + r_{23}r_{32}P_1P_4 + r_{24}r_{42}P_1P_3 + r_{34}P_4P_1P_2) \right\} \\
+ \left\{ (r_{12}r_{23}r_{31}P_4 + r_{13}r_{32}r_{21}P_4 + r_{14}r_{42}r_{21}P_3 + r_{14}r_{43}r_{31}P_2 + r_{23}r_{34}r_{42}P_1 + r_{24}r_{43}r_{32}P_1) \right\} \\
+ \left\{ (r_{12}r_{21}r_{34}r_{43} + r_{13}r_{31}r_{24}r_{42} + r_{14}r_{41}r_{23}r_{32} + r_{12}r_{23}r_{34}r_{41} + r_{14}r_{43}r_{32}r_{21} + r_{13}r_{34}r_{42}r_{21} + r_{12}r_{24}r_{43}r_{31} + r_{14}r_{42}r_{23}r_{31} + r_{13}r_{32}r_{24}r_{41}) \right\} \] 

(7.10)

**Step 5: Evaluation of index**

In this step, the values of the attributes and relative importance of one attribute over the other is substituted in Eq. (7.2.5) for both the models.

\[
\text{PEI}(S1) = 60.82 + 1410.64 + 3120 + 5329 \\
\text{PEI}(S2) = 22.92 + 895.8 + 2136 + 5329
\]

(Values are calculated for each subgroup)  

\[ = 9920.46 \]

\[ = 8381.72 \]

**Step 6: Arranging the PEI in ascending order and selection of best one**

Hence, from the indices (PEI) of the product models, it is understood that the product in figure 7.5(a) is the best (i.e., whose PEI is 9920.46). The reason is the diagonal elements value in matrix s1 are higher than the diagonal elements value in matrix s2 (step 4). These diagonal elements represent the values of attributes DFM, DFA, DFMn and DFEc. Because of simplicity, less number of components and less manufacturing processes model ‘a’ compared to the model ‘b’ these attributes values are higher. So the index for model ‘a’ is higher than for model ‘b’.