CHAPTER 6

PRODUCT SUSTAINABILITY MODELLING AND EVALUATION

Sustainability of a product has gained significant importance in the design and development process. The product designers and manufacturers today are equally concerned about the incorporation of sustainability aspects in the product early at the design stage. The various parameters which influence the sustainability are identified and given below.

6.1 Sustainability Attributes of a Product

It is evident from the literature review that material characteristics have a significant role in the sustainability of products throughout its life cycle. Material characteristics which influence the product sustainability have been discussed thoroughly in the literature review. These are discussed in following subsections.

6.1.1 Mechanical Properties

The basic properties of any engineering material are its mechanical properties. There is a wide range of mechanical properties of a particular engineering material under consideration. However, the basic mechanical properties for a material are strength, stiffness, toughness, hardness and, density, etc. Mechanical properties of any engineering material are the basic properties which every candidate material must satisfy to meet the performance requirements. Materials like fibre reinforced plastics (FRP) have gained greater attention of researchers and manufacturers in the present day design and development process particularly in automobile sector due to their high strength and stiffness characteristics. Therefore, the first criterion for sustainability of a product is identified as Mechanical properties and is abbreviated as M. This criterion is termed as an
attribute of sustainability of a product. This attribute is shown in Table 6.1. Second and third column of the table show influencing parameters. The information given in column second and third will help designers in identifying the attributes of product, in a systematic and easier way.

### 6.1.2 Tribological Properties

It is important to note that at the operational stage, most of the failures of products are tribology related. It is also a fact that the consumption of energy is influenced by a tribological property – friction. Moreover at the operational stage, the lubrication of products play a pivotal role in its performance. Various tribological issues like wear, friction, lubrication, etc. play a significant role in selecting materials from tribology point of view. An analysis of various tribological studies reveal that the life of a system is highly influenced by various tribological properties and therefore, material selection from tribology point of view is also a major thrust area for the designers that must be considered while carrying out the material selection process for a product from life cycle engineering point of view. Moreover, material selection based on tribological properties is considered as an important aspect, at the product conceptual design stage. Therefore, the tribological properties are identified as the second attribute for sustainability of a product and is abbreviated as T. This attribute is shown in Table 6.1. Second and third column of the table shows the influencing parameters.

### 6.1.3 Economical Aspects

For many companies, the economic constraints are the main consideration while selecting a particular material from and among a list of various candidate materials available. It includes, Purchase Cost of raw materials, Processing or Manufacture Cost, and Recycle / Disposal Cost associated with a material. The recycling of materials, nowadays is
being considered an important issue and therefore, the materials are recycled using technologically advanced and innovative recycling methods. The recycled materials provide an improvement in the energy consumption during the production process when compared with the processing of raw material. The results have proven a major shift in overall cost particularly in the recycling of automotive parts. It has been observed that for an industry, the reduction in production cost is normally perceived as more important than a reduction in the in-use cost. Therefore, the third criterion for sustainability of a product is identified as Economical aspects and is abbreviated as E. This attribute is shown in Table 6.1. Second and third column of the table show influencing parameters.

6.1.4 Environmental Preservation

In the recent years, there has been much emphasis on preservation of environment. The environmental legislation has forced designers to design products having no or low environmental impact. The recent standards of ISO-14040 has made it necessary for manufacturers and end-user of the product to carry out sustainability analysis of products [20]. Previously, environmental problems were often considered as a single problem due to the impact of different phases of a product. However, in the present day design process, environmental properties of a material have become equally important. It includes energy consumption and recycle or reuse of the product. The endeavour of the designer in a material selection process is to choose non-toxic, bio compatible (green) materials in the design and development process of products or systems. For example, materials like natural fibres (flax, hemp and, jute) have been considered for reinforcing plastics as they require very minimum amount of energy to grow, are renewable and biocompatible. Therefore, the fourth criterion of sustainability of a product based on material characteristics is identified as Environmental Preservation and is abbreviated as
EP^M. This attribute is also shown in 4^{th} row in Table 6.1. The sustainability attributes identified above and given in Table 6.1 are represented mathematically as:

\[ A^s = (A^s_1, A^s_2, \ldots, A^s_Y) \]  \hspace{1cm} (6.1)

where \( A^s \) represents the sustainability attribute and \( A^s_Y \) represents \( y^{th} \) attribute.

These sustainability attributes are used in sustainability modelling and evaluation of a given product. Using this, a designer can evaluate sustainability of a product at system conceptual design stage. These are discussed in the following sections.
<table>
<thead>
<tr>
<th>S.No</th>
<th>Sustainability Attribute</th>
<th>Influencing Parameters</th>
<th>Nomenclature</th>
<th>Degree of Influence among attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Strong ($s_{ij}=3$)</td>
</tr>
<tr>
<td>1</td>
<td>Mechanical Properties</td>
<td>Strength, Toughness,</td>
<td>M</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stiffness, Hardness,</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Elasticity, Density,</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>etc</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Tribological Properties</td>
<td>Hardness, Toughness,</td>
<td>T</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wear resistance,</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Friction, Elasticity,</td>
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<td></td>
<td>Life Time</td>
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<tr>
<td></td>
<td></td>
<td>Lubrication, etc.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Economical Aspects</td>
<td>Raw material cost,</td>
<td>E</td>
<td>-</td>
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<tr>
<td></td>
<td></td>
<td>Manufacture cost,</td>
<td></td>
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<td>Longevity life,</td>
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<td></td>
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<td>Hardness, Wastage cost,</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Recycle /Disposal cost,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Environmental Preservation</td>
<td>Less emission of gases,</td>
<td>EP^M</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Recyclability, Bio</td>
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<td></td>
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<td></td>
<td></td>
<td>compatibility,</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Disposability, Low</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>weight, High wear</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>resistance, etc.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6.2 Sustainability Modelling

Sustainability attributes of a product have been identified in the previous section. Each attribute influences the sustainability aspects through its influencing factors/features. Each attribute possesses distinctive characteristics which helps to develop relationship among these attributes, i.e., how one attribute is related to the other in determining the sustainability of a product during its entire life cycle. The relationship among the attributes is called Degree of relationship. The relationship between the attributes varies. It may be taken as, strong, to none as two extremes of degree of relationship. In between, this is assumed as medium and weak relationship. For example, the degree of influence between two attributes M and T is determined on the basis of influencing parameters of these two attributes. In this case, influencing parameters, hardness, strength, toughness stiffness, etc. has strong influence on wear resistance and friction. Therefore, degree of influence between the two attributes is taken as strong and is shown in column 5th in Table 6.1 and is assigned a highest value of $s_{ij}=3$. However, the influencing parameters wear compatibility, friction and life time lubrication of the attribute T do not influence the attribute E in the same way. In this case, the degree of influence is taken as medium and is assigned a value of $s_{ij} = 2$ (as shown in Table 6.1). Similarly, the influence between any two sustainable attributes is determined on the basis of influencing parameters between the attributes and these are also shown in column 4th of the table. The degree of relationship for a sustainability attribute among the other attributes is shown against the attribute in its row entry as their serial number. It is however, mentioned again that the relationship among these attributes need to be derived by a team of designers and experts from other fields of sustainability or sustainable design. Sustainability therefore, requires consideration of various attributes and their relationship. This can be conveniently represented using graph–theoretical concepts, which have been applied in various fields of science and technology.
Sustainability attributes digraph $G^s (N^s, E^s)$ for a product is defined, where $N^s= (N^s_1, N^s_2, \ldots \ldots, N^s_Y)$ is a set of nodes representing product sustainability. Sustainability attributes digraph is abbreviated as $MS^s$. An edge $E^s = \{e^s_{12}, e^s_{13}, \ldots, e^s_{ij}\}$ is a set of edges among nodes representing degree of interrelationship e.g., the edge $e^s_{12}$ connects node $N^s_1$ to $N^s_2$. The direction of edge $e^s_{12}$ from node $N^s_1$ to $N^s_2$ indicates the relationship of $A^s_1$ and $A^s_2$, i.e., $A^s_1$ is related to $A^s_2$. It is possible that any two attributes ($A^s_1$ and $A^s_2$) of an attribute digraph are related to one another. This is represented by two directed edges ($e^s_{ij}$ and $e^s_{ji}$) in the opposite directions forming a closed loop. $MS^s$ in general, is developed considering the four attributes identified in above sections, and their relationship. This is shown in Fig. 6.1. In Fig. 6.1, the direction of edge $e^s_{12}$ from node $N^s_1$ to $N^s_2$ indicates the relationship of $M$ and $E$, i.e., $M$ is related to $E$. The direction of edge $e^s_{21}$ from node $A_2$ to $A_1$ indicates relationship of $M$ is related to $E$. In this way, the edge $e^s_{12}$ and $e^s_{21}$ from node $N^s_1$ to $N^s_2$ and node $N^s_2$ to $N^s_1$ respectively form a closed loop. In the similar way, edges between the nodes in Fig. 6.1 represent the relationship among the attributes.

$MS^s$ is a graphical representation of sustainability attributes and their interrelationship. The graphical representation augments further understanding the product sustainability attributes, which needs to be exploited at design stage. This shows a clear visual picture of product sustainability process. However, for handling the digraph conveniently it is represented by matrix due to the fact that presence of more number of nodes and edges may lead to a complex figure.
Fig. 6.1: Sustainability Attributes Digraph (MS\textsuperscript{8})
6.3 Matrix Representation of a Sustainability Attributes Digraph

Matrix representation of the MS\(^g\) consisting of all the important sustainability attributes e.g., M, T, EP\(^M\), and E is given here. In this case, the facilitation among all these attributes is considered to develop the sustainability expression. The MS\(^g\) of these four attributes is developed based on the discussion in section (6.2) and is shown in Fig.6.1.

Let the MS\(^g\) in general, with y nodes be represented by y\(^th\) order binary matrix \([s_{ij}]\), where \(s_{ij}\) represents relationship of i\(^{th}\) attribute with j\(^{th}\) attribute with \(s_{ij} = 1\), if i\(^{th}\) attribute is related to j\(^{th}\) attribute, otherwise \(s_{ij} = 0\), as an attribute cannot have relationship with itself. Product sustainability matrix for the MS\(^g\) is shown in of Fig.1 and is written as

\[
Q^s = \begin{bmatrix}
0 & 1 & 1 & 1 \\
1 & 0 & 1 & 1 \\
1 & 1 & 0 & 1 \\
1 & 1 & 1 & 0 \\
\end{bmatrix}
\]  
\quad (6.2)

The diagonal elements in the matrix have value 0 and off diagonal elements have value 0 or 1. This implies that in this matrix only relationship among attributes is considered and value of the attributes is not taken into account. To incorporate this, a new matrix called Sustainability Attributes Relationship Permanent Matrix is defined. A Sustainability Attributes Relationship Permanent Matrix representing the sustainability attributes digraph shown in Fig. 6.1 is written as:

\[
Q^p = [AI^s + R^s] = \begin{bmatrix}
S & 1 & 1 & 1 \\
1 & S & 1 & 1 \\
1 & 1 & S & 1 \\
1 & 1 & 1 & S \\
\end{bmatrix}
\]  
\quad (6.3)

Where I\(^s\) is identity matrix and S is value of the attributes. It is noted from the matrix expression (6.3), that all the diagonal elements have been assigned the value of S i.e., each
attribute has equal value in the system. However, this is not true in actual practice. Also, the relationship of one attribute with the other attribute (i.e., $s_{ij}$) may take any value rather than extreme value 0 and 1. Thus, there is a need for considering general attribute value (i.e., diagonal elements $S_i$) as well as degree of relationship (i.e., off diagonal elements $s_{ij}$) to develop matrix expression which is a characteristic of the product.

These are taken into consideration through a new matrix called Variable Sustainability Attributes Relationship Permanent Matrix (VMS$^{\text{per}}$). Let the off diagonal elements of matrix $Q'$ is represented as $s_{ij}$ instead of 1, where $i^{th}$ attribute is related to $j^{th}$ attribute. Let us also define a diagonal matrix, $H^s$, with diagonal elements $S_i$ representing variable value of $i^{th}$ attribute. If an attribute is excellent in a product, it is assigned a maximum value. If an attribute is weak, it is assigned a minimum value. In general, most of the attributes are assigned intermediate values of the interval scale, as attribute may have medium contribution in material selection. The attribute value may be assigned qualitatively or quantitatively.

Variable MS$^s$ Attributes Relationship Permanent Matrix for the digraph shown in Fig. (6.1) is given as

$$Q' = [H^s + F^s] = \begin{bmatrix} S_1 & s_{12} & s_{13} & s_{14} \\ s_{21} & S_2 & s_{23} & s_{24} \\ s_{31} & s_{32} & S_3 & s_{34} \\ s_{41} & s_{42} & s_{43} & S_4 \end{bmatrix} \quad (6.4)$$

It may be noted that any matrix expression (6.4), represents value of attributes ($S_i$’s) and their relationship ($s_{ij}$’s) for the given material. Permanent of this matrix (or $\text{Per} (S)$) i.e., VMS$^{\text{per}}$, is called variable sustainability attributes relationship permanent function, abbreviated as VPF-$s$. VPF-$s$ is characteristic of the given product as it contains number of terms, which are its variant. Use of this concept in product sustainability modelling will help
in representing structural information from combinatorial consideration. This is desirable to associate proper physical meaning to the structural components and their combinations. Moreover, using this no negative sign will appear in the expression and hence no information is lost.

VPF-s of matrix, expression (6.4) is written in sigma form as

\[
Per(S) = \sum_{i=1}^{4} S_i + \sum_{i} \sum_{j} \sum_{k} \sum_{l} (s_{ij} \cdot s_{jl}) S_k \cdot S_l \\
+ \sum_{i} \sum_{j} \sum_{k} \sum_{l} (s_{ij} \cdot s_{jk} \cdot s_{kl} + s_{ik} \cdot s_{jl} \cdot s_{jl}) S_l \\
+ \left( \sum_{i} \sum_{j} \sum_{k} \sum_{l} (s_{ij} \cdot s_{jl} \cdot s_{kl} \cdot s_{il} + s_{il} \cdot s_{ik} \cdot s_{kl} \cdot s_{jl}) \right) \ldots (6.5)
\]

The equation consists of number of terms. These are arranged in eight (i.e., \(Y+1 = 5\), with \(Y=4\) in this case) groupings in descending order of number of attributes value. The first grouping contains only one term and is a product of four attribute values, (i.e., \(S_i S_j S_k S_l\)). The second grouping is absent as there are no self loops present in the digraph. The third grouping contains number of terms and each term is a multiple of two attribute values, (i.e., \(S_k S_l\)) and a 2-attribute relationship loop \((s_{ij} s_{ji})\). The fourth grouping is a multiple of 1-attribute value i.e., \((S_i)\) and two-attribute relationship loops i.e., \((s_{ij} s_{jk} s_{ik})\) and \((s_{ik} s_{kj} s_{ji})\). The fifth grouping contains two subgroupings. The first subgrouping contains two attribute relationship loops \((s_{ij} s_{ji})\) and \((s_{kl} s_{lk})\). The second subgrouping contains a 4-attribute relationship \((s_{ij} s_{jk} s_{kl} s_{li})\) or its pair \((s_{il} s_{lk} s_{kj} s_{ji})\). This shows that VPF-s represents all terms of matrix. From this it is clear that VPF-s is a powerful expression for material selection. As it takes into account all terms and thus no information is lost.
6.4 Product Sustainability Index

Sustainability index for a product is a measure of sustainability of a product design alternative based on material properties. This is represented as $I^s_i$. If the material alternative is better, its $I^s_i$ should be higher and vice-versa. The index for the sustainability of a product under consideration needs to take into account the value of attributes for the product and the degree of interrelationship among the attributes. VPF-s, developed earlier is a characteristic of the product based on material characteristics and this can be used for evaluation of index as it meets the requirements. Moreover, all terms of the VPF-s are positive. Therefore, increase in the value of attribute and their degree of relationship will result in increased value of VPF-s. VPF-s, i.e., permanent of $VMS^{per}$ is therefore, considered for evaluation of $I^s_i$ of a product. The index can be evaluated if $S_i$ and $s_{ij}$ are assigned quantitative or qualitative values. The values can be assigned on appropriate scale. In this case, Tables, (6.2-6.3) have been for assigning values to attributes. It is suggested that the designer / user may develop similar scoring Tables (6.2-6.3) for evaluation of criterion. However, methodologies already developed by various researchers may also be used for assigning score values to sustainability attributes, as is given in [103, 121]. An attribute ($A^s_i$) is therefore assigned a value on a scale e.g. 0 to 4 based on system design features for the attribute or using the existing scales from the literature. The attribute takes the value 4, if the material used for product under consideration favours the sustainability requirements to the maximum extent. For example, the value to attribute M is given on the basis of Table 6.3. The scale for each attribute is developed on the basis of the understanding of the material properties. The degree of interrelationship $s_{ij}$ is also assigned value 0 to 4.

Numerical value of permanent, i.e., VPF-s becomes a powerful means for evaluation of product sustainability as it contains various structure invariant of product. An index called sustainability index ($I^s$) is defined as the numerical value of the permanent ($VMS^{per}$). Based
on the index value, the product alternatives are evaluated. The best alternative is the one having the highest index value and is selected. The alternatives are thus evaluated in terms of index \( I_i \). The ideal value of \( I_i \) is obtained from VPF-s, i.e., expression (6.4) by taking the value of diagonal elements (\( S_1 \) to \( S_4 \)) to be equal to 4, i.e., highest score value. The values of off diagonal elements are obtained from Table 6.1 on the basis of degree of relationship.

The ideal value \( (I_i^{ideal}) \) of MS\(_1\) is calculated to be \( 1.81 \times 10^3 \). Comparison of index value of a product \( (I_i) \) can be relatively made with ideal value \( (I_i^{ideal}) \). This comparison shows the relative closeness of index value to the ideal value. This is obtained as:

\[
I_i' = \frac{I_i}{I_i^{ideal}} \times 100 \%
\]

(6.6)

where, \( I_i' \) is the relative product sustainability index value, which represents sustainability value of the product based on material characteristics as \% of the ideal value of index. A scale 0-4 is proposed for assigning value to attributes and their degree of relationship. The user may select an appropriate scale e.g., 0-5, 0-10 or 0-100. However, it is desirable to select lower scale value to obtain manageable value of index and also to reduce subjectivity. This is done so that there is limited range of score values before the designer to select. The final result will not be changed if the user chooses a different scale. The relative sustainability index value \( (I_i') \) i.e., Eq. (6.6) will be useful in this regard.
Table 6.2: Scoring Criteria for product sustainability attribute - M

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Description of Scoring Criterion</th>
<th>Score (S&lt;sub&gt;i&lt;/sub&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Fulfils all the mechanical properties</td>
<td>4</td>
</tr>
<tr>
<td>2.</td>
<td>Fulfils a few of the above requirements</td>
<td>2</td>
</tr>
<tr>
<td>3.</td>
<td>None of the above.</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 6.3: Scoring Criteria for product sustainability attribute - T

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Description of Scoring Criterion</th>
<th>Score (S&lt;sub&gt;i&lt;/sub&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Fulfils all the tribological properties</td>
<td>4</td>
</tr>
<tr>
<td>2.</td>
<td>Fulfils a few of the above requirements</td>
<td>2</td>
</tr>
<tr>
<td>3.</td>
<td>None of the above.</td>
<td>0</td>
</tr>
</tbody>
</table>
6.5 Steps in a Sustainability Analysis and Evaluation Approach

The procedure proposed previously for sustainability evaluation of a product is given now. Consider the given product design alternative from the various available alternatives (u= 1,2,……). Study its functional requirements and other necessary details from sustainability point of view.

21. Consider the first design alternative of material (i.e., u=1). Identify the sustainability attributes (A_i^s, i=1,2,3……,y) of the material (Refer section 6.2) and also assign values to attributes i.e., S_i, i= 1,2,……,y (Refer section 6.5 and also use Table 6.3 - 6.4).

22. Identify the relationship among attributes i.e., in terms of degree of relationship (s_{ij}). Assign value to s_{ij} using Table 6.2.

23. Develop MS^g for the design alternative (Refer section 6.3)

24. Write VMS^per (refer sections 6.3 and 6.4). This will be y x y matrix with diagonal elements S_i’s and off diagonal elements s_{ij}’s.

25. Derive sustainability expression (VPF-s) or permanent function i.e., permanent (VMS^per) on the lines of expression (6.5). Refer section 6.4 for details.

26. Evaluate the ideal value I^ideal from VPF-s obtained in step 6 by substituting S_i= 4 and s_{ij} as obtained in step 3.

27. Use VPF-s and substitute the value of S_i and s_{ij} obtained in step 2^{nd} and 3^{rd} to evaluate sustainability index value (I^s_i). Determine also the value of I^s using equation (6.5). Refer section 6.5.

28. Consider the 2^{nd} alternative (i.e., u=2) and repeat step 2 to 5 and 7.
29. Carry out step 8 for all other alternatives i.e., \( u = 3, 4, \ldots \)

30. Compare the sustainability index of all alternatives based on step 6 to 8 and identify the best alternative from sustainability point of view.
6.6 Example

The proposed methodology can be used for both new and existing product design alternatives for selection and evaluation of various product design alternatives. An example of an automobile brake disk has been considered to illustrate the proposed procedure.

6.6.1 Example – Automobile disk brake

An example of an automobile disk brake is considered here for illustrating the above procedure [71]. Two candidate materials are available for this purpose. The first material is a conventional brake material and the other material is a recently developed material in a composite form. These candidate materials available are grey cast iron BS 50 and, F3K20S Duraclan (aluminium matrix compound). First of all, it is necessary to study the various details of each candidate material. The primary objective of a brake disk with respect to the vehicle’s condition is its efficient braking action. The secondary objective of the brake disc is low weight and less cost. The first candidate material i.e., grey cast iron BS 50 has high strength, high toughness, and a higher value of hardness. The brake disk is manufactured using green sand casting process and has low cost, easy to recycle/remanufacture. In this case, all the attributes identified in sec. 2 are taken into consideration for carrying out the evaluation. These sustainability attributes are M, T, E and, EP\textsuperscript{M}. The value to various attributes is assigned on the basis score values using Table 6.3- 6.4. For example, the value of attribute EP\textsuperscript{M} is obtained from Table 6.3. In this case, grey cast iron BS 50 fulfills the primary requirements i.e., efficient braking action however, it is more in weight and has relatively higher cost. Moreover, it also involves more friction and therefore, more heat is generated during its operation which is not desirable. This means the candidate material does not fulfil all the requirements, hence it is assigned a score value of 2 on the basis Table 6.3- 6.5 i.e., S\textsubscript{1}=2, S\textsubscript{2}=2, S\textsubscript{3} = 2 and S\textsubscript{4}= 2. Therefore, the values assigned to various
material selection attributes in case of first material alternative i.e., grey cast iron BS 50 are $S_1=2$, $S_2=2$, $S_3=2$, $S_4=2$. This completes step 2 of the suggested procedure.

The relationship among these attributes, i.e., the degree of interrelationship $m_{ij}$ are also identified. The value of $s_{ij}$’s is obtained on the basis of degree of relationship, from Table 6.2 (Section 6.2). From the table, we get $s_{12}=3$, $s_{13}=2$, $s_{14}=2$, $s_{21}=3$, $s_{23}=2$, $s_{24}=2$, $s_{31}=2$, $s_{32}=2$, $s_{34}=2$, $s_{41}=2$, $s_{42}=2$, $s_{43}=2$. This completes step 2, of the procedure. The $MS^g$ is developed on the basis of steps 1 and 2 carried out earlier. In this example, $MS^g$ shown above in Fig. 6.1 remains same. The $VMS^{per}$ is obtained as

$$Q' = \begin{bmatrix} S_1 & s_{12} & s_{13} & s_{14} \\ s_{21} & S_2 & s_{23} & s_{24} \\ s_{31} & s_{32} & S_3 & s_{34} \\ s_{41} & s_{42} & s_{43} & S_4 \end{bmatrix} \quad (6.7)$$

This completes step 4. The MS expression $VPF$-s is obtained. In this example, the sustainability expression, written above may be used for this purpose with $Y=4$, (Refer (6.5)).This completes step 5.

The ideal value of index, $I^i_{\text{ideal}} = 0.1236 \times 10^4$ is obtained from matrix expression (6.6) and this completes step 6 of the design procedure. By substituting the value of $S_i$ and $s_{ij}$ in expression (6.7), $I^i_1$ is obtained as

$$I^i_1 = \begin{bmatrix} 2 & 3 & 2 & 2 \\ 3 & 2 & 2 & 2 \\ 2 & 2 & 2 & 2 \\ 2 & 2 & 2 & 2 \end{bmatrix} \quad (6.8)$$

Therefore, $I^i_1 = 0.584 \times 10^3$. The value of $I^i_r$ in this case is 32.31%. This completes step 7.
Now, the second material alternative (F3K20S Duraclan (aluminium matrix compound) is considered on the lines of first alternative. In this case, the value of $S_1=4$ as it has less weight, greater hardness and high toughness. The material also has excellent strength properties. The disk made up of this material is manufactured using squeeze casting method (liquid metal forging) and therefore involves high cost. For recycle/remanufacture, it is difficult to recycle/remanufacture and thus requires more complicated procedure and therefore additional high cost. However, it shows better Tribological properties and therefore on the basis of these aspects, it is assigned the values as $S_1=4$, $S_2=2$, $S_3= 2$, $S_4=4$. The $I_{m2}$ is obtained as

$$I_{s2} = \begin{bmatrix} 4 & 3 & 2 & 2 \\ 3 & 2 & 2 & 2 \\ 2 & 2 & 2 & 2 \\ 2 & 2 & 2 & 4 \end{bmatrix}$$

(6.9)

So, $I_s = 0.748*10^3$. The value of $I_s$ in this case is 60.69%. This completes step 8.

This completes the step 9 of the procedure. It is observed that the sustainability index increases from $0.584*10^3$ to $0.748*10^3$ for the two material alternatives considered here in this example. The relative index value also increases from 32.31% to 60.69%. The alternative with highest value of $I_2 = 0.748*10^3$ is considered as the best material alternative from sustainability point of view. Therefore, in this case, material alternative-II i.e., (F3K20S Duraclan (aluminium matrix compound) is the best material alternative among the available alternatives. This procedure provides a convenient method to determine the best material alternative from material selection point of view. These sustainability aspects are therefore very vital for the product’s performance throughout its operation.
Table 6.4: Brake Disk System – Material Selection Comparison

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Design Alternative</th>
<th>Index Value ($I_1$)</th>
<th>$I_4$ Value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Grey Cat Iron (BS40)</td>
<td>0.584</td>
<td>47.25</td>
</tr>
<tr>
<td>2.</td>
<td>Composite Material (F3K20S)</td>
<td>0.748</td>
<td>60.52</td>
</tr>
</tbody>
</table>

This simple example has been elaborated for the benefit of readers. Although the procedure may appear troublesome and time consuming if performed manually, however it is not so when using a computer and more so using an expert system.

Sustainability of a product based on material characteristics is evaluated. The sustainability attributes for a product, in general, have been identified on the basis of material characteristics. These attributes have been modelled in terms of sustainability attributes digraph. The sustainability index ($I_1$) which evaluates the product sustainability from VPF-s is obtained. The proposed procedure is useful for practising engineers and environmental designers for evaluating the sustainability of products at product design and operational stage.