CHAPTER 10
MATERIALS SUBSTITUTION
Chapter 10: Goal and objectives

The goal of this chapter is to analyze the various incentives and constraints involved in substituting one material for another in making an existing component.

The main objectives are to get better understanding about:
1. Materials audit
2. Constraints and incentives in materials substitution.
3. Life cycle energy impact of materials substitution
5. Some quantitative methods of initial screening, comparing alternatives and making final decision for materials substitution.
The audit process could start by asking questions such as:

- When were the materials last selected and specified?
- Who initiated the last changes in materials?
  Was it company, personnel or materials suppliers?
- Why was the material changed?
  Was it legislation, to reduce cost, or improve?
- What feedback do you have on the performance of your product?
- What progress has been made in materials since the last change?
- Has new processes been introduced since the last change?
Materials audit II

- Is the advantage of adopting a new and untried material worth the risk of abandoning the current and established material?
- Is the cost of conversion to the new material less than the benefits?
- Would new equipment and plant be needed?
- Assuming that substitution has been made, what are the implicates of that substitution on the system at large?
- What are the institutional, legal, social, and environmental consequences?
Forces resisting substitution

There are usually powerful arguments for not changing the status quo unless the benefits can be seen to be considerable. Forces that make substitution difficult include:

1. Company policy.
2. Lack of design guidelines and in-service experience for new materials.
3. High cost of redesign and investment required for new equipment.
4. Cost of increased inventory required for more spare replacements.
Forces encouraging substitution

1. Engineering products are subject to continual evolution to meet increased performance demands and to lower manufacturing costs. To stand still is to invite the competition to overtake.

2. New and improved materials and processes can contribute to improved competitiveness, and the opportunities should be continuously assessed.
Considerations in materials substitution I

Simple substitution of one material for another does not usually provide optimum utilization of the new material. Redesigning the part exploits the properties and manufacturing characteristics of the new material.

Hangers:
1. Wood and steel hook
2. Steel wire
3. Plastic and steel hook with no redesign.
4. All plastic and introduces additional features that are possible with injection molding.
Considerations in materials substitution II

a) Technical performance advantage, as a result of introducing a stronger, stiffer, tougher, or lighter material.

b) Economic advantage over the total life cycle of the product:
   cheaper material
   lower cost of processing
   better recycleability and lower cost of disposal
   lower running cost of the product.

c) Improving the aesthetics of the product:
   using a more attractive material,
   providing more comfort (e.g. sound or heat insulation)

d) Environmental and legislative considerations
## Screening of substitution alternatives

### Table (10.1) Example of the Use of the Pugh Decision Matrix for Materials Substitution

<table>
<thead>
<tr>
<th>Property</th>
<th>Currently used material</th>
<th>New material (1)</th>
<th>New material (2)</th>
<th>New material (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Property (1)</td>
<td>C1</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Property (2)</td>
<td>C2</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Property (3)</td>
<td>C3</td>
<td>+</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Property (4)</td>
<td>C4</td>
<td>0</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Property (5)</td>
<td>C5</td>
<td>-</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Property (6)</td>
<td>C6</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Property (7)</td>
<td>C7</td>
<td>-</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td>Property (8)</td>
<td>C8</td>
<td>-</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Property (9)</td>
<td>C9</td>
<td>-</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Total (+)</th>
<th>Total (-)</th>
<th>Total (0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total (+)</td>
<td>2</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Total (-)</td>
<td>5</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Total (0)</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
</tbody>
</table>
A manufacturer of tennis rackets is introducing a new model.

The main evaluation criteria racket are power, damping and cost.

Analysis

The current material is epoxy-50% carbon fibers.

Substitute candidates are in Table 10.2.

Power is taken as \((E/\rho)\), where \(E\) is elastic modulus and \(\rho\) is density.

Damping is inversely proportional to \(E\) (material with the lowest \(E\) is given a damping of 10).

The cost is taken as cost of the material per unit mass.
Table (10.2) Characteristics of tennis racket materials

NP = normalized power, ND = normalized damping, NC = normalized cost

<table>
<thead>
<tr>
<th>Material</th>
<th>E (GPa)</th>
<th>Density ρ (g/cc)</th>
<th>Cost ($/kg)</th>
<th>Power</th>
<th>Damping</th>
<th>N P</th>
<th>ND</th>
<th>NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy+50%CF</td>
<td>136</td>
<td>1.87</td>
<td>93</td>
<td>73</td>
<td>10</td>
<td>82</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Epoxy+55%CF</td>
<td>146.4</td>
<td>1.873</td>
<td>101</td>
<td>78</td>
<td>9.3</td>
<td>88</td>
<td>93</td>
<td>92</td>
</tr>
<tr>
<td>Epoxy+60%CF</td>
<td>156.8</td>
<td>1.876</td>
<td>109</td>
<td>84</td>
<td>8.7</td>
<td>94</td>
<td>87</td>
<td>85</td>
</tr>
<tr>
<td>Epoxy+65%CF</td>
<td>167.2</td>
<td>1.879</td>
<td>117</td>
<td>89</td>
<td>8.1</td>
<td>100</td>
<td>81</td>
<td>80</td>
</tr>
</tbody>
</table>
Case study 10.1 Material substitution in a tennis racket II

Cost of performance method:

The performance index $\gamma$ in Table 10.3 is calculated by giving weights of 0.7 for the power and 0.3 for damping.

$\Delta\gamma\%$ and $\Delta C\%$ are percent increase in $\gamma$ and cost relative to the base material, respectively.

Epoxy+65%CF is a preferable substitution material as it has the highest $(\Delta\gamma\%/\Delta C\%)$. Epoxy+60%CF comes as a close second.
Case study 10.1 Material substitution in a tennis racket III

Compound performance function method (CPF)

CPF in Table 10.4 is calculated by giving the weights of 0.55 for power, 0.2 for damping, and 0.25 for cost.

Epoxy+65%CF is a preferable substitution material as it has the highest CPF.

Epoxy+60%CF is a close second.
### Table 10.3 Cost of performance method

<table>
<thead>
<tr>
<th>Material</th>
<th>γ</th>
<th>Δγ%</th>
<th>ΔC%</th>
<th>(Δγ%/ ΔC%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy+50%CF</td>
<td>87.4</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Epoxy+55%CF</td>
<td>89.5</td>
<td>2.40</td>
<td>8.6</td>
<td>0.28</td>
</tr>
<tr>
<td>Epoxy+60%CF</td>
<td>91.9</td>
<td>5.15</td>
<td>17.2</td>
<td>0.3</td>
</tr>
<tr>
<td>Epoxy+65%CF</td>
<td>94.3</td>
<td>7.9</td>
<td>25.8</td>
<td>0.31</td>
</tr>
</tbody>
</table>

### Table 10.4 Compound performance function method

<table>
<thead>
<tr>
<th>Material</th>
<th>0.55NP</th>
<th>0.20 ND</th>
<th>0.25 NC</th>
<th>CPF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy+50%CF</td>
<td>45.1</td>
<td>20</td>
<td>25</td>
<td>90.1</td>
</tr>
<tr>
<td>Epoxy+55%CF</td>
<td>48.4</td>
<td>18.6</td>
<td>23</td>
<td>90.0</td>
</tr>
<tr>
<td>Epoxy+60%CF</td>
<td>51.7</td>
<td>17.4</td>
<td>21.25</td>
<td>90.35</td>
</tr>
<tr>
<td>Epoxy+65%CF</td>
<td>55</td>
<td>16.2</td>
<td>20</td>
<td>91.2</td>
</tr>
</tbody>
</table>
Case study 10.2: Materials substitution for a cryogenic tank I

In the case of the cryogenic tank of case study 9.2, SS 301-FH is the optimum material and is therefore used in making the tank.

Suppose that at a later date a new fiber reinforced material is available and can be used to manufacture the tank by filament winding.

The properties of the new fiber reinforced material are given in Table 10.5 together with the properties of SS 301-FH.
Case study 10.2: Materials substitution for a cryogenic tank II

Table 10.6 Scaled values of properties and performance index

<table>
<thead>
<tr>
<th>Material</th>
<th>Scaled properties</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>Performance index (γ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS 301-FH</td>
<td></td>
<td>100</td>
<td>91</td>
<td>95</td>
<td>25</td>
<td>71</td>
<td>12.5</td>
<td>100</td>
<td>70.9</td>
</tr>
<tr>
<td>Composite</td>
<td></td>
<td>23</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>80</td>
<td>77.4</td>
</tr>
</tbody>
</table>
Case study 10.2: Materials substitution for a cryogenic tank III

Analysis:

Using the procedure in Section 9.5, the properties are first scaled. Using the weighting factors in Table 9.5, the performance index is given in Table 10.6. The composite material is technically better.

Final comparison is carried out according to CPF method on the basis of the figure of merit, as in Section 9.5. The cost of unit strength is shown in Table 10.7.

Table 10.7 Relative cost and cost of unit strength for candidate materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative cost</th>
<th>Cost of unit strength x 100</th>
<th>Figure of merit $(\gamma/cost \ of \ unit \ strength) \times 10^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS 301-FH</td>
<td>1.4</td>
<td>0.81</td>
<td>87.53</td>
</tr>
<tr>
<td>Composite</td>
<td>7</td>
<td>0.93</td>
<td>83.23</td>
</tr>
</tbody>
</table>
Case study 10.2: Materials substitution for a cryogenic tank IV

Conclusion

As the figure of merit of SS 301-FH is higher than that of the composite material, the basis material still gives better value than the new material and no substitution is required.

If the relative cost of the new composite material decreases to 6.6 instead of 7, the cost of unit property becomes $0.837 \times 100$ instead of $0.93 \times 100$.

In this case, the figure of merit of the composite material becomes $92.5 \times 10^{-2}$, which means that it gives better value and is therefore, a viable substitute.
Reaching a final decision on substitution

Cost-benefit analysis

When the new material is technically better but more expensive the economic gain as a result of improved performance $\Delta \gamma_e$ should be more than the additional cost ($\Delta C_t$):

$$\Delta \gamma_e - \Delta C_t > 1$$  \hspace{1cm} (10.4)

Economic advantage of improved performance

The economic gain as a result of improved performance $\Delta \gamma_e$ can be related to the difference in performance index of the new and currently used materials, $\gamma_n$ and $\gamma_o$.

$$\Delta \gamma_e = A \ (\gamma_n - \gamma_o)$$  \hspace{1cm} (10.5)

$A$ is the benefit of improved performance of the component expressed in $\$ per unit increase in material performance index $\gamma$. 
Case study 10.3 – Reaching final decision on material substitution for the sailing boat mast component I

In case study 9.5, AA 2024 T6 was selected for the sailing-boat mast component since it gives the least expensive solution, Table 9.21.

Table (9.21) Designs Using Candidate Materials With Highest Performance Indices.

(Based on Farag and El-Magd)

<table>
<thead>
<tr>
<th>Material</th>
<th>Da (mm)</th>
<th>S (mm)</th>
<th>A (mm²)</th>
<th>Mass (kg)</th>
<th>Cost/kg ($)</th>
<th>Cost of Component ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA 6061 T6 (UNS A96061)</td>
<td>100</td>
<td>3.4</td>
<td>1065.7</td>
<td>2.88</td>
<td>8</td>
<td>23.2</td>
</tr>
<tr>
<td>AA 2024 T6 (UNS A92024)</td>
<td>88.3</td>
<td>2.89</td>
<td>801.1</td>
<td>2.22</td>
<td>8.3</td>
<td>18.4</td>
</tr>
<tr>
<td>AA 2014 T6 (UNS A92014)</td>
<td>85.6</td>
<td>2.89</td>
<td>776.6</td>
<td>2.17</td>
<td>9</td>
<td>19.6</td>
</tr>
<tr>
<td>AA 7075 T6 (UNS A97075)</td>
<td>78.1</td>
<td>2.89</td>
<td>709.1</td>
<td>1.99</td>
<td>10.1</td>
<td>20</td>
</tr>
<tr>
<td>Epoxy-70% glass fabric</td>
<td>78</td>
<td>4.64</td>
<td>1136.3</td>
<td>2.39</td>
<td>30.8</td>
<td>73.6</td>
</tr>
<tr>
<td>Epoxy-63% carbon fabric</td>
<td>73.4</td>
<td>2.37</td>
<td>546.1</td>
<td>0.88</td>
<td>99</td>
<td>87.1</td>
</tr>
<tr>
<td>Epoxy-62% aramid fabric</td>
<td>75.1</td>
<td>3.99</td>
<td>941.6</td>
<td>1.30</td>
<td>88</td>
<td>114.4</td>
</tr>
</tbody>
</table>
Case study 10.3 – Reaching final decision on material substitution for the sailing boat mast component II

From Table 9.21, AA 6061 T6, Epoxy-70% glass fabric, and Epoxy-62% aramid fabric are heavier and more expensive, rejected.

The other three materials

AA 2014 T6,
AA 7075 T6,
Epoxy-63% carbon fabric

result in progressively lighter components at progressively higher cost than AA2024 T6.
Case study 10.3 – Reaching final decision on material substitution for the sailing boat mast component III

Analysis

From Eq (10.5) the performance index $\gamma$ is considered as the weight, $\Delta C$ is the difference in cost of component, and $A$ is the benefit expressed in dollars, of reducing the mass by 1 kg.

- For $A < $7/kg saved, AA2024 T6 is the optimum material.
- For $A = $7 - $60.5/kg saved, AA 7075 T6 is a better substitute.
- For $A > $60.5/kg saved, Epoxy-63% carbon fabric is optimum.
Total cost of substitution

The additional cost ($\Delta C_t$) of substitution can be divided into:

a) Cost of redesign and testing, 

b) Cost differences in materials, 

c) Cost of new tools and equipment, 

d) Cost differences in labor.

\[
\Delta C_t = (P_n M_n - P_o M_o) + f \left( \frac{C_1}{N} \right) + \left( \frac{C_2}{N} \right) + (T_n - T_o) + (L_n - L_o)
\]

- $P_n$ & $P_o$ = Price/unit mass of new and original materials
- $M_n$ & $M_o$ = Mass of new and original materials
- $f$ = Capital recovery factor; about 15%
- $C_1$ = Cost of transition to new materials including cost of new equipment.
- $C_2$ = Cost of redesign and testing.
- $N$ = Total number of new parts produced.
- $T_n$ & $T_o$ = Tooling cost per part for new and original materials.
- $L_n$ & $L_o$ = Labor cost per part using new and old materials.
This case study gives an analysis of the different factors involved in materials substitution in aerospace industry. $(E^{1/3}/\rho)$ is the design parameter for comparing materials for panels.

Table 10.8 Properties of candidate materials for aircraft body panels

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus of elasticity (GPa)</th>
<th>Density (mg/m$^3$)</th>
<th>$E^{1/3}/\rho$ (SI units)</th>
<th>Cost ($/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum alloy (average of 2xxx and 7xx series)</td>
<td>71</td>
<td>2.7</td>
<td>71.2</td>
<td>4.3$^b$</td>
</tr>
<tr>
<td>Epoxy-33% carbon fabric +30% carbon fibers</td>
<td>100</td>
<td>1.61</td>
<td>134.65</td>
<td>110$^a$</td>
</tr>
</tbody>
</table>

$^a$ McAfee  
$^b$ Aluminum alloys’ cost is based on the average of 2024 and 7075 alloys, 1987 prices (Charles and Crane 1989)
Case study 10.4-Materials substitution of a panel in aircraft II

The thickness \((t)\) of panels of width \((b)\) for equal stiffness under in-plane compressive load \((P)\) is given as:  \[ t = \left( \frac{Pb}{3.62 \, E} \right)^{1/3} \]

The mass \((M)\) of a panel of length \((l)\) is:  \[ M = \rho t bl \]

Table 10.9 Estimates for aircraft panel substitution

<table>
<thead>
<tr>
<th></th>
<th>Aluminum</th>
<th>CFRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness for equal buckling resistance in (mm)</td>
<td>0.59 (15)</td>
<td>0.53 (13.4)</td>
</tr>
<tr>
<td>Mass of panel lb (kg)</td>
<td>44.64 (20.25)</td>
<td>23.79 (10.79)</td>
</tr>
<tr>
<td>Cost of material in panel ($)</td>
<td>87.08</td>
<td>1186.90</td>
</tr>
<tr>
<td>Cost of transition per panel ($)</td>
<td>--</td>
<td>1002.51*</td>
</tr>
<tr>
<td>Cost of labor/lb of panel material ($)</td>
<td>10 - 50**</td>
<td>50 – 300*</td>
</tr>
<tr>
<td>Cost of labor per panel ($)</td>
<td>446.4 - 2232</td>
<td>1189.5 - 7137</td>
</tr>
<tr>
<td>Cost savings/panel to due to less weight ($)</td>
<td>--</td>
<td>5671.20</td>
</tr>
</tbody>
</table>

* source: Shipp (1990)
** estimated
Variations in the labor rate can affect the economic feasibility of substitution.

At a labor rate of $440/kg for CFRP, Al is more attractive if its labor rate is $44/kg, but not attractive if its labor rate is $88/kg.

Similarly, at a labor rate $44/kg for Al, CFRP is more attractive if its labor rate is $330/kg, but not if its labor rate is $440/kg.

Figure 10.2 Effect of labor rate variations on the total cost of substitution for a panel in the upper wing surface of an aircraft.
Case study 10.4-Materials substitution of a panel in aircraft IV

Conclusion

As the long-range behavior of the new materials is not well established, the present design codes require higher factors of safety in design and extensive testing programs when adopting FRP for critical components.

This adds to the economic disadvantage of FRP. Such difficulty can only be solved gradually because engineers need to be more familiar with the unusual behavior of the new materials and to gain more confidence in their long-range performance.
Chapter 10: Summary I

1. Materials substitution is an on-going process and materials used for a given product should be reviewed regularly through a materials audit process.

2. In substituting a new material for an established one, the characteristics of the new material should be well understood and that advantages outweigh drawbacks of adopting it.

Risk, cost of conversion and equipment needed, as well as the environmental impact need to be carefully evaluated.
Chapter 10: Summary II

3. The economic parameters involved in material substitution are:
   • direct material and labor,
   • cost of redesign and testing,
   • cost of new tools and equipment,
   • cost of change in performance,
   • overheads.
Chapter 10: Summary III

4. The major stages of materials substitution are:
   • screening of alternatives
   • comparing and ranking alternative substitutes
   • reaching a final decision.

The initial stages involve only rough estimates, which become more elaborate as the substitution process progresses to the screening and then the final selection stages.
Chapter 10: Summary IV

5. The use of quantitative methods ensures that decisions are made rationally and that no viable alternative is ignored.

These methods include:

• Pugh’s method for initial screening,
• cost of performance and compound performance function methods for ranking alternative solutions
• cost-benefit analysis for reaching final decision.