METHODOLOGY FOR INCLUDING ENVIRONMENTAL CONCERNS IN CONCURRENT ENGINEERING

Charles I. Whitmer II, Walter W. Olson, and John W. Sutherland
Department of Mechanical Engineering - Engineering Mechanics
Michigan Technological University
Houghton, MI

ABSTRACT

In the traditional concurrent engineering process marketing, finance, design and manufacturing are considered simultaneously. Due to the changing marketplace it is believed that environmental concerns should be included in the concurrent engineering process. Because a product's environmental friendliness ultimately depends on its design, a Pairwise Comparison Analysis (PCA) methodology for determining the relative importance of design factors is presented. A sensitivity analysis is then presented to show that the global importance of the design factors as suggested by the PCA are stable when changes are made to the comparison matrices used in the PCA.

INTRODUCTION

Under the traditional system of concurrent engineering marketing, finance, design, and manufacturing have been considered simultaneously. These four activities have not always been considered to have equal importance, however. According to Skinner (1986), manufacturing is regarded by managers as a sort of dirty business that must be done so that the "real" activities of business, such as marketing and finance, will have meaning. This attitude seems to have been reflected in universities where manufacturing is often not considered a suitable intellectual activity nor a fruitful career path in industry (Nevins and Whitney, 1989). However, declining trade balances over the last fifteen to thirty years have shown this attitude to be incorrect. In an effort to reduce trade balances and increase productivity, considerable attention has been given to design and manufacturing engineering. Computer modeling in the early stages of design now allows models to be made available to many functional groups early in the product design process (Ulerich, 1992). This allows for revisions to be generated earlier in the design cycle reducing the time and cost of implementation. It is at this point that environmental concerns should be considered.

Recent trends in environmental law (U.S. Congress, 1989) suggest that manufacturers may be required to take back their products after its useful life. This is true regardless of the post-use process the product may have been designed for. Such laws, combined with rising consumer environmental awareness and economic concerns, introduce a large amount of uncertainty when predicting a products post-use process. As a result of this uncertainty, it is believed that all four post-use processes (Olson and Sutherland, 1993) should be considered concurrently in the design process.

PROBLEM DEFINITION

Rising consumer environmental awareness, changing economic conditions, and recent government regulations have made the environment an important consideration for manufacturers. Because environmental concerns affect not only the design, but manufacturing, marketing, and finance also, it is important to include these concerns in the concurrent engineering process. Ultimately, however, it is the responsibility of the designer to produce a product that not only meets the standard requirements of form, fit, and function, but also requires no environmentally harmful manufacturing processes, can be marketed as environmentally conscious, and is financially

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feasible to produce. For the designer to succeed in this task, guidelines are needed to show the relative importance of how the design factors rank with respect to the environment.

To find these relative importance’s, a Pairwise Comparison Analysis (PCA) is used. Under this method, a hierarchy showing the relationships between the overall goal of designing an environmentally conscious product, the four post-use processes, and the design factors is constructed. An example of such a hierarchy is shown in Figure 1. Pairwise comparisons are then made between two design factors with respect to a post-use process and placed in a comparison matrix, $F_m$. The matrix $F_m$ is then used to solve an optimization problem where the resulting vector shows the relative importance of each design factor with respect to a post-use process. This process is repeated for all of the post-use processes, and the resulting matrices are combined into a level matrix, $L_n$, where the columns are the design factor relative importance’s. Next, pairwise comparisons are made between the post-use processes with respect to the design goal of an environmentally conscious product. These comparisons are placed in a matrix, $P$, and a process relative importance vector is calculated. Multiplying the level matrix, $L_n$, by the process importance vector, $p^*$, the global importance of the design factors, $g$, can be found regardless of which post-use process is used.

Questions have been raised regarding the validity of the PCA recommendations. These questions result from the subjective manner in which the comparisons are made. Because the pairwise comparisons are made on experience and judgment, the comparisons have a high amount of uncertainty. This uncertainty would allow for changes in the comparison matrix to be made after the solution methodology has been performed. For this reason it is desirable to find the sensitivity of the global importance vector to changes in the comparison matrix.

With the relative importance of the design factors estimated, the sensitivity of the solution must be checked. This will show how making changes in the comparison matrix will change the importance of the global importance of the design factors. If the solution methodology is found to have a low sensitivity, then the high levels of uncertainty will not effect the confidence with which the designer can interpret the global importance of the design factors.

**PAIRWISE COMPARISON ANALYSIS**

To build the hierarchy needed, each post-use process was studied to understand what factors play a role in the ease or difficulty with which the process is completed. Five design factors were identified that play an important role in the process completion. These are disassembly time, processing cost, material selection, processing energy, and the modularity of the assembly. The goal of an environmentally conscious product, post-use processes, design factors, and their interactions are shown graphically in the hierarchical structure shown in Figure 1 for an environmentally conscious product.

The group in level 1 is the overall objective of the system. Level 2 contains four groups which represent the post-use process alternatives which can be employed to achieve this objective. These post-use processes are reuse, remanufacture, recycle, and disposal. The five groups in level 3 are design factors which can be made to ease the post-use processes and in turn accomplish the overall goal. These five design factors are time, cost, materials, energy, and modularity. It is assumed that each group in the hierarchy is independent of the other groups in the same level. Also, each group is influenced by and influences only one group at a time on the level directly above and below it respectively. This allows direct comparisons without considering interrelationships with groups on the same level. Following are the definitions used in creating the hierarchy:

- **Reuse** - The act of using the returned product in a new product with no major modifications being made.
- **Remanufacture** - The act of building a new product on the base of a used product. This may include technological improvements where possible.
- **Recycle** - The act of recovering the material content from a product that has reached the end of its useful life.
- **Disposal** - The act of placing a used product in a landfill where no further action will be taken.
- **Time** - The time required to deal with a product after its useful life. (i.e. Disassembly time)
- **Cost** - The cost required to deal with a product after its useful life. (i.e. Transportation, Hazardous waste disposal)
- **Materials** - The importance of choosing materials that are easily dealt with after the products useful life. (i.e. Metal vs. Plastic, Recyclable plastics)
- **Energy** - The energy required to deal with a product after its useful life. (i.e. Power for disassembly tools, Transportation)
- **Modularity** - The importance of using assemblies in a products design to ease
dealing with a product after its useful life.
(i.e. Designing with a base part)

With the hierarchy established, the next step is to make
pairwise comparisons. These comparisons are made
between two groups on the same level in the hierarchy
with respect to a group on the next higher level. The
result of these comparisons is a ranking of the
importance of one group over the other. These
preferences are determined by comparing the two groups
and entering the importance intensity factor (x for level 2
and y for level 3) into a comparison matrix P for level 2
and F_m for level 3. This process of pairwise comparison
is repeated for all possible combinations throughout the
entire hierarchy. It should be noted that because the
comparisons are opinion based the transitive property may
be violated in the matrix. These violations will be dealt
with in the solution process. If the transitive property did
apply, the matrix would be consistent and the solution
methodology presented would be trivial. The correct
weighting factors would be a normalized column of the
comparison matrix. Pairwise comparisons were made for
the hierarchy above and will be used as an example to
demonstrate the PCA process.

When making comparisons it is important to have an
agreed upon rating system or importance intensity factors.
For a hierarchy where relative importance is compared a
scheme employing the numerical values, shown in Table
1, is often employed. By convention the comparison
matrix in which the importance intensity factors are
placed is always read as the relative importance of the
group in column j on the top against the

group in row i on the left. The importance of one group,
y_j, over another group on the same level, y_i, can be
expressed as:

\[ y_i = f_{m,i,j} y_j \]  \hspace{1cm} [1]

where the importance intensity factor, \( f_{m,i,j} \), expresses
how much more important group i is than group j. A
group is equally important when compared to itself, so
when i and j are equal, a 1 is placed. If the group i has a
number assigned to it when compared with group j, then j
has the reciprocal value when compared with i. This
result can be seen from equation 1 by solving for y_j as a
function of y_i and f_{m,i,j}.

The matrix F_j shows that y_i can be expressed as:

\[ y_i = f_{1,1,2} y_1 \]
\[ y_i = f_{1,1,2} y_2 \]
\[ y_i = f_{1,1,2} y_3 \]
\[ y_i = f_{1,1,2} y_4 \]
\[ y_i = f_{1,1,2} y_5 \]  \hspace{1cm} [2]

If the equations are summed, the result should be:

\[ 5 y_i = \sum_{j=1}^{n} f_{m,1,i} y_j. \]  \hspace{1cm} [3]

We know from inconsistencies in the matrix F_m that this
is not the case, however. With the analysis expanded to n
equations, the total error for group i can then be expressed as:

\[ e_i = \frac{1}{n} \sum_{j=1}^{n} f_{m,i,j} y_j + (1 + \lambda_i / n) y_i. \]  \hspace{1cm} [4]

If we define \( f'_{m,i,j} = n (1-1/n) \), then the column vector
expressing the total error can be expressed as the product
of the adjusted comparison matrix, \( F'_m \), and the column
vector showing the importance of each group, y:

\[ e = F'_m y \]  \hspace{1cm} [5]

where the adjusted comparison matrix, \( F'_m \), is:

\[ F'_m = F_m + (n-2) \lambda. \]  \hspace{1cm} [6]

The objective is to find importance values of group i, \( y_i \),
that minimizes the error values resulting from equation
violations. This can be accomplished by solving the
following constrained optimization problem:

\[ \min \ e^T e = y^T F'_m y \]
sub. to \[ y^T y = 1. \]  \hspace{1cm} [7]

The constraint in equation 6 was added to reduce the
number of solutions and scale the solution to a unit vector.
This constrained optimization problem can be solved
using the method of Lagrange multipliers (Reklaitis et.
1983). The solution then takes the form:

\[ (F'_m^T F'_m - \lambda I) y = 0. \]  \hspace{1cm} [8]

In this solution form the Lagrange multipliers, \( \lambda \), are the
eigenvalues, and the solution vectors, y, are eigenvectors.
The final solution vector for each comparison matrix, \( y'_m \),
for \( F_m \) is taken as the eigenvector with all positive
elements. This vector is chosen because the elements
represent importance's, which must be positive. A similar
methodology substituting \( P \) for \( F_m \) and \( x \) for \( y \) in the
equations should be used to evaluate level 2. The
resulting vectors show the relative importance of the
design factors with respect to the post-use processes, and
the post-use processes with respect to designing an environmentally conscious product.
To find the importance of the design factors in level 3 with respect to the overall goal in level 1, a level matrix \( L_3 \) is formed where the column \( j \) is equal to the solution vector \( y_m^* \) for each group in the level 2:
\[
L_3 = \begin{bmatrix} y_1^* \vdots y_2^* \vdots y_3^* \vdots y_4^* \end{bmatrix}. \tag{9}
\]
The matrix \( L_3 \) is then multiplied by the solution vector \( x^* \) to find \( g \), the global importance of each design factor in level 3 with respect to the overall design goal. It is the designer's responsibility to complete the pairwise comparisons for the hierarchical system developed for the product being considered. Sample comparisons were made, and the following results were obtained:
\[
\begin{align*}
x^* = & \begin{bmatrix} 0.74 \\ 0.54 \\ 0.36 \\ 0.17 \end{bmatrix} & \begin{bmatrix} 0.20 \\ 0.44 \\ 0.41 \\ 0.61 \end{bmatrix} & \begin{bmatrix} 0.24 \\ 0.62 \\ 0.20 \\ 0.60 \end{bmatrix} \\
y_1^* = & \begin{bmatrix} 0.19 \\ 0.44 \\ 0.73 \\ 0.24 \\ 0.41 \end{bmatrix} & \begin{bmatrix} 0.59 \\ 0.61 \\ 0.33 \\ 0.34 \\ 0.24 \end{bmatrix} & \begin{bmatrix} 0.26 \\ 0.52 \\ 0.51 \\ 0.32 \\ 0.55 \end{bmatrix} \\
L_3 = & \begin{bmatrix} 0.20 & 0.24 & 0.19 & 0.59 \\ 0.44 & 0.62 & 0.44 & 0.61 \\ 0.48 & 0.40 & 0.73 & 0.33 \\ 0.41 & 0.20 & 0.24 & 0.34 \\ 0.61 & 0.60 & 0.41 & 0.24 \end{bmatrix} & g = \begin{bmatrix} 0.51 \\ 0.52 \\ 0.51 \end{bmatrix}.
\end{align*}
\]
Taking the square of the elements in a solution vector gives the relative importance of the groups. In the vector \( x^* \), the relative importance's are: 0.55 for reuse, 0.29 for remanufacture, 0.13 for recycling, and 0.03 for disposal. Similarly, the relative importance's in \( g \) are: 0.07 for time, 0.27 for cost, 0.26 for materials, 0.10 for energy, and 0.30 for modularity.

**SENSITIVITY ANALYSIS**

To understand how changes in the comparison matrix affects the global importance vector, a sensitivity analysis was run changing one element and its corresponding reciprocal in a comparison matrix at a time. The initial sensitivity analysis was performed assuming small variations about the decided upon relative importance's.

The first level to be compared was level 2 which contains the four post-use processes. The adjusted comparison matrix used for the example given above is:
\[
P^* = \begin{bmatrix} 3.00 & 0.33 & 0.17 & 0.11 \\ 3.00 & 3.00 & 0.25 & 0.14 \\ 6.00 & 4.00 & 3.00 & 0.20 \\ 9.00 & 7.00 & 5.00 & 3.00 \end{bmatrix}
\]
Applying a variation of \( \pm 1 \) to the relative importance of reuse and remanufacturing with respect to an environmentally conscious product (\( x_{2,1} = 3 \pm 1 \)) gives the following results:
\[
\begin{align*}
x^* = & \begin{bmatrix} 0.73 \\ 0.37 \\ 0.20 \end{bmatrix} & g = \begin{bmatrix} 0.51 \\ 0.32 \\ 0.55 \end{bmatrix} & \text{for } x_{2,1} = 2 \\
\end{align*}
\]
and
\[
\begin{align*}
x^* = & \begin{bmatrix} 0.75 \\ 0.35 \\ 0.16 \end{bmatrix} & g = \begin{bmatrix} 0.51 \\ 0.32 \\ 0.55 \end{bmatrix} & \text{for } x_{2,1} = 4.
\end{align*}
\]
This shows that small changes in the relative importance of reuse and remanufacturing with respect to an environmentally conscious product has little effect on the global importance of the design factors. The process of varying the relative importance vectors by \( \pm 1 \) was completed for each of the elements with integer values not on the diagonal in the matrix. Similar differences were observed in the global importance of design factors as a result of the variations.

The vector showing the importance of reuse, remanufacturing, recycling, and disposal is:
\[
\begin{bmatrix} 0.74 \\ 0.54 \\ 0.36 \end{bmatrix}
\]
showing that the post-use process with the largest importance is reuse, with a value of 0.55. This shows that changes in the matrix comparing design factors with respect to reuse will have the largest effect on the global solution vector.

To find the maximum effect of changing one element in matrix \( F^*_1 \), small variations were analyzed in the
comparison matrices for design factors with respect to reuse:

\[
F_1^* = \begin{bmatrix}
4.00 & 3.00 & 7.00 & 4.00 & 7.00 \\
0.33 & 4.00 & 0.20 & 0.33 & 0.50 \\
0.14 & 5.00 & 4.00 & 4.00 & 5.00 \\
0.25 & 3.00 & 0.25 & 4.00 & 2.00 \\
0.14 & 2.00 & 0.20 & 0.50 & 4.00
\end{bmatrix}
\]

Similar to the analysis shown above, variations of ±1 were applied to the comparison of cost and modular design with respect to reuse. The result of this analysis is:

\[
y^* = \begin{bmatrix}
0.18 \\
0.45 \\
0.43 \\
0.49 \\
0.59
\end{bmatrix}
\text{ and } g = \begin{bmatrix}
0.25 \\
0.53 \\
0.49 \\
0.35 \\
0.54
\end{bmatrix}
\text{ for } f_{1,5,2} = 3
\]

\[
y^* = \begin{bmatrix}
0.19 \\
0.41 \\
0.45 \\
0.48 \\
0.60
\end{bmatrix}
\text{ and } g = \begin{bmatrix}
0.25 \\
0.52 \\
0.50 \\
0.35 \\
0.55
\end{bmatrix}
\text{ for } f_{1,5,2} = 1.
\]

The results of these tests show that even changes in the matrix that will yield the maximum variation on the global importance vector are minimal. Variation in the three remaining matrices comparing design factors with respect to post-use processes will result in similar changes in the global importance vector with smaller magnitudes.

In an effort to further understand the stability of the global importance vectors, large variations were made in the comparison matrices. In the matrix comparing design factors with respect to recycling:

\[
F_3^* = \begin{bmatrix}
4.00 & 5.00 & 9.00 & 3.00 & 5.00 \\
0.20 & 4.00 & 6.00 & 0.20 & 3.00 \\
0.11 & 0.17 & 4.00 & 0.33 & 0.25 \\
0.33 & 5.00 & 3.00 & 4.00 & 2.00 \\
0.20 & 0.33 & 4.00 & 0.50 & 4.00
\end{bmatrix}
\]

the relative comparison between cost and time was given a importance intensity factor of 8. The results of the change are:

\[
y_3^* = \begin{bmatrix}
0.19 \\
0.55 \\
0.23 \\
0.39
\end{bmatrix}
\text{ and } g = \begin{bmatrix}
0.25 \\
0.55 \\
0.31 \\
0.54
\end{bmatrix}
\text{ for } f_{3,1,2} = 8.
\]

These results show that even large changes in the comparison matrix have a minimal effect on the global importance of the design factors. This stability is limited by the requirement that the order of importance for the factors in the matrix being varied is not changed. If the order of importance is changed, there will be a large change in the global importance of the design factors.

CONCLUSIONS

To compete in the changing marketplace it has been shown that environmental concerns need to be considered simultaneously with the traditional topics of marketing, finance, design, and manufacturing. A methodology based on Pairwise Comparison Analysis has been presented which shows the global importance of design factors with respect to the design of an environmentally conscious product without knowing the post-use process of the product. The pairwise comparisons used to find the global importance of the design factors are based on experience and judgment only. This reliance on human judgment is inherently filled with uncertainty. For this reason, a sensitivity analysis has been performed on the results of the PCA by substituting alternate values into the comparison matrices. The results of the sensitivity analysis show that the global importance of the design factors are stable if there is no change in the order of relative importance in the comparison matrix.

ACKNOWLEDGMENTS

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REFERENCES


Figure 1. Hierarchy for Designing an Environmentally Conscious Product.

TABLE 1. TABLE SHOWING RANKING SYSTEM FOR PAIRWISE COMPARISONS. [SAATY, 1990]

<table>
<thead>
<tr>
<th>Importance factor</th>
<th>Intensity</th>
<th>Definition</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Equal importance.</td>
<td>Two activities contribute equally to the objective.</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>Weak importance of one over another.</td>
<td>Experience and judgment slightly favor one activity over another.</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>Essential or strong importance.</td>
<td>Experience and judgment strongly favor one activity over another.</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>Very strong or demonstrated importance.</td>
<td>An activity is favored very strongly over another, its dominance is demonstrated in practice.</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>Absolute importance.</td>
<td>The evidence favoring one activity over another is of the highest possible order of affirmation.</td>
</tr>
<tr>
<td>2,4,6,8</td>
<td></td>
<td>Intermediate values between adjacent scale values.</td>
<td>When compromise is needed.</td>
</tr>
<tr>
<td>Reciprocals of above non-zero numbers.</td>
<td></td>
<td>If the activity $i$ has one of the above non-zero numbers assigned to it when compared with activity $j$, then $j$ has the reciprocal value when compared with $i$.</td>
<td>A reasonable assumption.</td>
</tr>
</tbody>
</table>