Application of Reverse Engineering (RE) for Different Rapid Prototyping Techniques (RP) and its Comparative Analysis

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Abstract To grab market and meeting deadlines has increased the scope of new methods in product design and development. Industries continuously strive to optimize the development cycles with high quality and cost efficient products to maintain market competitiveness. Thus the need of Reverse Engineering (RE) and Rapid Prototyping Techniques (RPT) has started to play pivotal role in rapid product development cycle for complex product. This paper describes reverse engineering methodology and applications. Reverse engineering is done for a complex profile and RP parts are developed of the obtained scanned file to reduce the overall time. Nowadays, various techniques of RPT are used for mould development to reduce the overall time. Dimensional accuracy, surface finish and time are the corner stone of Rapid Prototyping (RP) especially if they are used for mould development. However selection of best RP system is a tedious work due to involvement of various objective or attributes in the decision making process. Thus, the Multi-criteria Decision Making (MCDM) becomes a useful approach to solve this kind of problem. Therefore, this thesis also deals with the development of parts by SLA, SLS and FDM process and presents a strategic approach for developing decision support system for RP process selection. A framework of MCDM such as Analytical Hierarchy Process (AHP) and Technique of Order Preference by Similarity to Ideal Solution (TOPSIS) is used which provides logical procedure to evaluate the three RP processes in terms of various attributes or criteria such as surface finish, cost and time.

Keywords- Reverse Engineering, Rapid Prototyping Techniques, Mould development, MCDM, AHP, TOPSIS.

I. Introduction

The competition in the world market due to globalization for manufacturing products has intensified tremendously in recent year. Even, the change in market requirements towards a large variety of products in small batch size and short life cycle has increased the needs for time reduction during mould development. To remain competitive, the overall time-to-market is a crucial factor. It requires revolutionary changes rather than incremental improvements in product development. Reverse Engineering (RE), Computer-Aided-Design (CAD) and Rapid Prototyping (RP) process can reduce the time to market of the products.

1) Reverse Engineering – Tool to Expedite the Design of a New Product

Reverse engineering can be used as an initial step in product design and development (PDD) to generate product concepts. After identifying a set of customer needs and establishing target product specification or changes in the existing part can be made or new product can be developed. The existing part or a product can be recreated by reverse engineering (RE) by acquiring the CAD model of the existing part and designs can be modified to generate various new concept of a product [1-2].

2) Rapid Prototyping

The term rapid prototyping(RP) refers to a class of technologies that can automatically construct physical models from Computer Aided Design (CAD) data. Rapid prototyping is widely used in various fields such as prototyping, rapid tooling and rapid manufacturing, automotive, medical and aerospace. Therefore, there is need that RP parts should have high accuracy in order to ensure proper functional requirements [3-5]. There are a large numbers of RP technologies available in the market but proper selection of a rapid prototyping is difficult even for experienced users. To increase the use of RP process and for proper process selection, a decision support system needs to be developed keeping in view the end use of part. Decision making is the process of finding the best option from all feasible alternatives. The aim of the thesis is to study and implement tools such as RE, various RP process and selection of best among them using the concepts of MCDM (Multi-Criteria Decision Making) technique.

3) Analytical Hierarchy Process (AHP) method

Thomas L. Saaty (1980) originally developed the Analytic Hierarchy Process (AHP) to enable decision making in situations characterized by multiple
attributes and alternatives. AHP is one of the Multi Criteria decision making techniques. AHP has been applied successfully in many areas of decision-making. In short, it is a method to derive ratio scales from paired comparisons. We have used the following steps of AHP (Saaty, 1980) to help us to measure the relative importance or the weighted values of several criteria [6-9].

1. Define the problem and determine the criteria.
2. Structure the decision hierarchy taking into account the goal of the decision.
3. Develop a pair wise comparison matrix in which the set of elements is compared with itself (size n x n) by using the fundamental scale of pair-wise comparison shown in Table 3.
4. Assign the reciprocal value in the corresponding position in the matrix. Total n (n-1)/2 number of comparison required to develop the set of matrices instead.
5. The hierarchy synthesis function is used to weight the Eigenvectors by the weights of the criteria and the sum is taken over all weighted eigenvector entries corresponding to those in the next lower level of the hierarchy.
6. After all the pair wise comparisons are completed the consistency of the comparisons is assessed by using the Eigen value, λ, to calculate a consistency index, CI: (λ max-n)/ (n-1), Where n is the matrix size.
7. The new final consistency ratio (CR) is calculated as the ratio of the CI and the random index (RI), as indicated.

\[ CR = \frac{CI}{RI} \]

CR=RI/RI where R.I. Stands for Random Consistency Index.

Saaty (1980) suggests that the C.R. is acceptable if it does not exceed 0.10. If the CR is greater than 0.10, the judgment matrix should be considered inconsistent. To obtain a consistent matrix, the judgments should be reviewed and repeated.

### Table 1: Fundamental Scale of Pair-Wise comparison for AHP [12]

<table>
<thead>
<tr>
<th>Relative importance</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equal importance</td>
</tr>
<tr>
<td>3</td>
<td>Moderate importance of one factor over another</td>
</tr>
<tr>
<td>5</td>
<td>Strong or essential importance</td>
</tr>
<tr>
<td>7</td>
<td>Very Strong importance</td>
</tr>
<tr>
<td>9</td>
<td>Extreme importance</td>
</tr>
</tbody>
</table>

4) **Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS)**

TOPSIS was first presented by Yoon (1980) and Hwang and Yoon (1981), for solving Multiple Criteria Decision Making (MCDM) problems based on the concept that the chosen alternative should have the shortest Euclidian distance from the Positive Ideal Solution (PIS) and the farthest from the Negative Ideal Solution (NIS). For instance, PIS maximizes the benefit and minimizes the cost, whereas the NIS maximizes the cost and minimizes the benefit. It assumes that each criterion require to be maximized or minimized. TOPSIS is a simple and useful technique for ranking a number of possible alternatives according to closeness to the ideal solution.

The TOPSIS procedure is based on an intuitive and simple idea, which is that the optimal ideal solution, having the maximum benefit is obtained by selecting the best alternative which is far from the most unsuitable alternative, having minimal benefits [10-13].

Mathematically, the application of the TOPSIS method involves the following steps [10-13].

**Step 1:** Establish the decision matrix
The first step of the TOPSIS method involves the construction of a Decision Matrix (DM).

\[ DM = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \]

Where ‘i’ is the criterion index (i = 1 . . . m); m is the number of potential sites and ‘j’ is the alternative index (j = 1 . . . n). The elements C_{ij}, C_{i2}, C_{in} refer to the criteria: while L_{1}, L_{2}, . . . , L_{n} refer to the alternative locations. The elements of the matrix are related to the values of criteria i with respect to alternative j.

**Step 2:** Calculate a normalized decision matrix
The normalized values denote the Normalized Decision Matrix (NDM) which represents the relative performance of the generated design alternatives. This step transforms various attribute dimensions into non-dimensional attributes, which allows comparisons across criteria.

\[ NDM = R_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \]

**Step 3:** Determine the weighted decision matrix
Not all of the selection criteria may be of equal importance and hence weighting were introduced from AHP (Analytical Hierarchy Process) technique to quantify the relative importance of the different selection criteria. The weighting decision matrix is simply constructed by multiplying each element of each column of the normalized decision matrix by the random weights.

\[ V = V_{ij} = W_{ij} \times R_{ij} \]

**Step 4:** Identify the Positive and Negative Ideal Solution
The positive ideal (A+) and the negative ideal (A−) solutions are defined according to the weighted decision matrix via Equations (4) and (5) below

\[ PIS = A^+ = \{V_{1}, V_{2}, \ldots, V_{n}\}, \text{where:} V_j = \{\max_i (V_{ij}) \text{ if } j \notin \mathcal{E}_j \} \]

\[ NIS = A^- = \{V_{1}^-, V_{2}^-, \ldots, V_{n}^-\}, \text{where:} V_j^+ = \{\min_i (V_{ij}) \text{ if } j \notin \mathcal{E}_j \} \]

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Where, J is associated with the beneficial attributes and J’ is associated with the non-beneficial attributes.

**Step 5:** Calculate the separation distance of each competitive alternative from the ideal and non-ideal solution.

\[ S = \left( \sum_{j=1}^{n} (V_j - V_i)^2 \right)^{1/2} \]

\[ S' = \left( \sum_{j=1}^{n} (V'_j - V'_i)^2 \right)^{1/2} \]

Where, i = criterion index, j = alternative index.

**Step 6:** Measure the relative closeness of each location to the ideal solution.

For each competitive alternative the relative closeness of the potential location with respect to the ideal solution is computed.

\[ C_i^* = \frac{S_i}{S_i + S_i}, 0 \leq C_i^* \leq 1 \]

**Step 7:** Rank the preference order

The higher the value of the relative closeness \( C_i^* \), the higher the ranking order and hence the better the performance of the alternative. Ranking of the preference in descending order thus allows relatively better performances to be compared.

### II. Experimental Study

An industrial component Fluid Premixer used for mixing purpose of fluids is considered for experimental study. The objective of this project is to build the CAD model using Reverse Engineering (RE) approach. Later this CAD model is used to print three prototypes by different three rapid prototyping processes such as SLS, SLA and FDM process. Then these three prototypes are measured on few attributes such as Surface finish, Time and Cost to select which process is best out of three by using MCDM technique.

Reverse Engineering has been carried out using Blue Light Scanning system with model name COMET. The information obtained by RE has been post processed using the integrated software within the system. The scanned .STL file which is obtained is then used to develop the rapid prototype (RP) component using FDM, SLS and SLA process.

**Model building with Rapid Prototyping (RP)**

It has been identified that SLA, SLS and FDM are three techniques widely used and hence they have been taken for the study. Fluid Premixer prototypes were built by using three different rapid prototyping techniques (RP). Figure 1 shows prototype build using fused deposition modelling (FDM) process and material used is ABS (Acrylonitrile Butadiene Styrene). Figure 2 shows prototype build using Selective Laser Sintering (SLS) process SLS Duroform PA (polyamide) is the material used and in Figure 3 Stereolithography Apparatus (SLA) process is used to generate and the material used is Accura 25 (Polypropylene Equivalent).

### III. Result and Discussion

**Comparison of Surface Roughness among the three different Prototypes**

To compare the surface roughness of three different prototypes, the surface roughness of each three types of part was measured by using Mitutoyo Surface Roughness Tester mounted on Metzer Optical profile projector. Because of the geometry limitations, only the top surfaces of Section 1, the periphery surface (Ribs surface) of Section 2 as shown in Figure 5 were measured. The measured surface roughness is given in Table 2.

**Table 2:** Measured surface roughness of three different RP parts

<table>
<thead>
<tr>
<th></th>
<th>FDM</th>
<th>SLS</th>
<th>SLA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Section 1 (Top Surface)</strong> Ra value in µm</td>
<td>1.25</td>
<td>9.41</td>
<td>2.32</td>
</tr>
<tr>
<td><strong>Section 2 (Rib surface i.e. Periphery)</strong> Ra value in µm</td>
<td>25.12</td>
<td>18.70</td>
<td>2.94</td>
</tr>
</tbody>
</table>

**Comparison of various other parameters for three different RP parts**

Table 3 is a comparison table in terms Cost, Machine Setting Time and Build Time of various methods that could be used in fabricating an RP Fluid Premixer.
If this statement is true, you are on the right track.

Cost is less important than Surface Finish.

Rapid Prototyping Process Selection

Application of AHP method used for definition of scales and to evaluate weight for the alternatives

1. Data collection of Pair-Wise comparison of attributes based on rating factor. Selection of a rapid prototyping process depends on many factors. In this phase, the experts of industries are given the task of forming individual pair-wise comparison matrix for major attributes such as surface finish, cost, and time.

2. Pair-wise comparison matrix and Normalization After rating, next step is to normalize the matrix. This is done by totalling the numbers shown in Table 4.

Table 4: Pair-wise comparison matrix for criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Surface Finish</th>
<th>Cost</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Finish</td>
<td>1.0000</td>
<td>1.0000</td>
<td>5.0000</td>
</tr>
<tr>
<td>Cost</td>
<td>1.0000</td>
<td>1.0000</td>
<td>0.3330</td>
</tr>
<tr>
<td>Time</td>
<td>0.2000</td>
<td>3.0000</td>
<td>1.0000</td>
</tr>
<tr>
<td>sum</td>
<td>2.2000</td>
<td>5.0000</td>
<td>6.3330</td>
</tr>
</tbody>
</table>

3. Synthesizing Procedure

Table 5: Weight calculation for attributes

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Surface Finish</th>
<th>Cost</th>
<th>Time</th>
<th>Weights</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Finish</td>
<td>0.454545455</td>
<td>0.2</td>
<td>0.7895</td>
<td>0.481</td>
</tr>
<tr>
<td>Cost</td>
<td>0.454545455</td>
<td>0.2</td>
<td>0.0525</td>
<td>0.236</td>
</tr>
<tr>
<td>Time</td>
<td>0.090909091</td>
<td>0.6</td>
<td>0.1579</td>
<td>0.283</td>
</tr>
<tr>
<td>checksum</td>
<td>1.0000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Application of TOPSIS method for ranking of the three rapid prototyping techniques of SLA, SLS and FDM

The procedural steps of TOPSIS method are enlisted as below:

1. Establishment of the decision matrix

The three rapid prototyping process SLS, SLA and FDM are evaluated on the basis of surface finish, cost and time. The rating scale 1 to 9 is used in order to rank parameters Surface finish, Cost and Time. The input to rank parameters for three different processes is the observation table obtained by measuring the surface finish (Table 2), Cost and Building time (Table 3)

Table 3: Comparison of process methods to create RP Fluid Premixer

<table>
<thead>
<tr>
<th>Process Method</th>
<th>Time Taken</th>
<th>Cost in Rupees/part</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>FDM</td>
<td>2hrs/part</td>
<td>733</td>
<td>ABS</td>
</tr>
<tr>
<td>SLS</td>
<td>5hrs/part</td>
<td>1392</td>
<td>Duraform Polyamide (nylon)</td>
</tr>
<tr>
<td>SLA</td>
<td>4hrs/part</td>
<td>2468</td>
<td>25(Polypropylene Equivalent)</td>
</tr>
</tbody>
</table>

Table 6: Evaluation of alternatives and attributes

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Surface Finish</th>
<th>Cost</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternatives</td>
<td>SLS</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>SLA</td>
<td>9</td>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>FDM</td>
<td>6</td>
<td>9</td>
<td>9</td>
</tr>
</tbody>
</table>

- Construct a normalized decision matrix
  Divide each column by ($\sum x_{ij}^2)^{1/2}$ to get $R_{ij}$

Table 7: Normalized values of Decision Matrix

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Surface Finish</th>
<th>Cost</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternatives</td>
<td>SLS</td>
<td>0.419590679</td>
<td>0.56225</td>
</tr>
<tr>
<td>SLA</td>
<td>0.755263222</td>
<td>0.40161</td>
<td>0.5232</td>
</tr>
<tr>
<td>FDM</td>
<td>0.503508815</td>
<td>0.7229</td>
<td>0.67269</td>
</tr>
</tbody>
</table>

- Construct the weighted decision matrix
  Multiply each column by $W_{ij}$ to get $V_{ij}$ as shown in Table 8

Table 8: Weighted values of decision matrix

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Surface Finish</th>
<th>Cost</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternatives</td>
<td>SLS</td>
<td>0.201823117</td>
<td>0.13213</td>
</tr>
<tr>
<td>SLA</td>
<td>0.36328161</td>
<td>0.09438</td>
<td>0.14754</td>
</tr>
<tr>
<td>FDM</td>
<td>0.24218774</td>
<td>0.16988</td>
<td>0.1897</td>
</tr>
</tbody>
</table>

- Identify the Positive and Negative Ideal Solution according to the weighted decision matrix via equations where $J$ is associated with the beneficial attributes and $J'$ is associated with the non-beneficial attributes

$A^+ = \{0.36328161, 0.16988, 0.1897\} $
$A^- = \{0.201823117, 0.09438, 0.14754\} $

- Calculate the separation distance of each competitive alternative from the ideal and non-ideal solution. Therefore (Eq.6 and 7)

$S'_i = (0.1710879, 0.0864737, 0.121093) $
$S'' = (0.0377513, 0.1614584, 0.0954307) $

- Calculate the relative closeness to the ideal solution $C_i = S'_i / (S'' + S'_i)$

$C_i = (0.1807673, 0.6512201, 0.4407384)$

Therefore the maximum value is the best one. If the value is lesser than the value of 1, then it is acceptable condition.

Conclusion

This study explain the implementation of RE to create a 3D CAD model by directly scanning an industrial component Fluid Premixer. The main aim of
the application of RE was to investigate whether scanning of complex intricate profile is feasible. There is various scanning technique but for the study digital camera was used for scanning the part. It is clear that using digital camera and image processing method the part can be reversed easily. Thus the scanning and surface model creations are done easily and any error in the surface model can be easily rectified during modelling through integrated software. Due to the application of RE there was a steep reduction in overall time as compared to the 3D CAD model obtained by solidwork. CAD model made in solid works software is quite tedious and time consuming. This has completely eliminated by using reverse engineering. Thus this will increase the productivity.

A study was also been conducted to investigate the parameters such as surface roughness, cost and time of three RP parts made by FDM, SLS and SLA processes and to select the best process with the aim of validating the system for mould development. Therefore, in this study MCDM method such as AHP and fuzzy TOPSIS is used for selecting the best RP process. Based on closeness coefficient values, the ranking of alternatives in descending order are SLA, FDM and SLS. Proposed model results that SLA is the best alternative with higher performance index value of 0.65. For more researchers, the findings of the present study or for other different types of RP processes with other various parameters can be compared with other optimization methods.

References