Use of a Reprocessability Index System for the Environmental Scoring of Rotational Parts

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abstract
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ABSTRACT
A new concept in environmentally conscious design and manufacturing is explored and driven by the need to conserve resources and eliminate waste. The development of the Reprocessability Index (RPI) is aimed at providing a tool for comparing the potential for the reprocessing of product parts. The index is defined by specific physical attribute ratios of parts. The RPI model is applied to a set of basic parts established by the DCLASS Classification and Coding System. A more complete understanding of the RPI model is found through the results of several rotational parts from a washing machine that were analyzed with the RPI model.

INTRODUCTION
Manufacturing for the next century and beyond will be profoundly different from the immediate past. One may expect manufacturing processes to use energy and materials more efficiently in the next century. What one might not expect, however, is that the source of materials for manufacturing may change. It is known that several key raw material sources are nearing exhaustion and cannot support the demands of a growing affluent mankind. For example, it has been projected that if the present population of the earth were to use common metals such as aluminum, copper, lead and steel at the same quantities per capita as is currently the case in the United States, between five and sixteen times more resources would be needed to fulfill the demand. Known and projected sources of raw materials fall short of this demand. What is worse, the population of the earth is expected to double in the next fifty years further aggravating the problem of material supply [Homer-Dixon, 1993].

A “use and throw away” society has existed in the developed world since World War II. It has been estimated that 10 tons of material are needed per person per year, and that 94% of the material becomes waste within a few months after initial use [Ayres, 1989]. Japan, Germany, the Netherlands and other countries find that the real estate necessary for landfill disposal simply does not exist to support a continuance of a “use and throw away” society. Furthermore, landfills in the United States are associated with problems far beyond the immediate site contamination of the landfill site. Such problems include large scale contamination of ground waters, production of explosive quantities of methane, air pollution, and wildlife disease. The chemical soup of a landfill is unplanned and uncontrolled. It is no surprise that land owners will fight the siting of landfill in the vicinity of their properties.

These two factors drive and fuel a search for a more efficient use of product materials. One possible solution is to manufacture new parts for new purposes from existing parts. This is defined as reprocessing rather than the commonly known remanufacturing which is associated with recovery of parts for the purpose of reusing the parts
in their originally designed roles [Wentland et al., 1995]. It is expected that manufacturing for reprocessing results in parts with different geometries and different functions from that of the original plan. Reprocessing in this manner solves in part both the sourcing and the environmental problem by providing a level of recycling for manufacturing that is almost nonexistent today. Reprocessing offers a new challenge for engineers to identify and characterize the qualities that lend parts to be reprocessed. The Reprocessability Index (RPI) is an initial attempt to assist engineers in the task of designing for the future.

Reprocessability is not the total answer to making a company environmentally conscious. Reprocessing of materials through manufacturing operations is but one of the possible steps. Other possibilities that must be considered include product reuse and remanufacturing, and material recycling [Olson and Sutherland, 1993]. Reuse is the ideal post-use process; however, it is not often practical for complex products due to wear and tear. Recycling, while well established for metals and certain plastics may not be the most environmentally efficient. The last options, remanufacturing and reprocessing, offer a middle ground between reuse and recycling.

Remanufacturability and reprocessability must be designed into a product if a successful after-life is realized in this manner. Modern design techniques now include design for manufacturing and assembly at the concept to insure that both quality and cost effectiveness are built into products. The same attention must be given to design for remanufacturing and reprocessing to insure effective material and part reuse. To aid in the development of design for remanufacturing and reprocessing, an index or metric of reprocessability is needed. The proposed RPI is just such a metric.

REPROCESSABILITY INDEX

The Reprocessability Index (RPI) originated from a need to understand the environmental impacts of specific part shape at the design stage [Wentland et al., 1995]. A major function of design and later, manufacturing, is to establish and create part shape. An underlying hypothesis explored was that shape has an environmental impact in a product. Later, it was recognized that gross stress and moving contact areas had significant reprocessing impacts as well. The desire to give all parts a “preplanned” post-use focused the RPI on geometric attributes that may affect the post-use and provide an aid to design parts more environmentally friendly. It is known that material and initial process choices are also important in the environmental consideration, but the physical shape of a part is an indicator of the possible uses of it in its post-use life. Material and the necessary manufacturing processes typically fall into the costing problem that is important to all environmental work done. However, since this research is focused on design and manufacturing, the cost scenario is established as an issue that will be regarded in the future when actual application of the RPI evaluation is more feasible.

Reprocessability is a general term used to define any operation used on an existing part to produce a new part. Typically, machining is the most common operation associated with reprocessing, but other operations can be considered. Grinding, EDM, and ECM are a few of the other processes included under reprocessing. Figure 1 illustrates the products of reprocessing operations. The upper part is a round washer type part with several holes. Alternative reprocessed parts are shown along with the reduced amount of scrap which is denoted by excess material that has possible recycling potential. Similarly, the lower part is a shaft with slot and gear attributes. Several reprocessed part alternatives are shown along with the reduced scrap levels.

FIGURE 1 - REPROCESSED PARTS.
The RPI, as established here, consists of six additive terms. A small RPI value is considered preferable over a large value. The first and second terms of the RPI capture the material efficiencies of volume and surface area. The ratio of surface area to volume represents the environmental effects of overall shape relatively well. A high ratio typically indicates that a part is sheet-like or has many features. Sheet-like parts typically are difficult to reuse or reprocess because material content is minimal and the probability for corrosion and wear is increased. A low ratio indicates that a part is simple with few features and has relatively substantial volume. A low value is desired for environmental considerations because it indicates that a part has potential to be reprocessed. Even though this ratio is quite descriptive of a part, it is not a unitless term. Therefore, it is difficult to compare the ratio among different sized parts. To remove the problems posed by units, the surface area to volume ratio was separated into two unitless terms for the RPI.

These terms are created by a comparison with the volume and surface area of the bounding volume. For the rotational part example of Figure 2 the bounding volume is defined as the cylinder that encompasses the part. In general, cylinders are used as the bounding volume for rotational parts.

![Bounding Volume](image)

**FIGURE 2 - BOUNDING VOLUME.**

The first term, $R_1$, is created by dividing the volume of the bounding volume ($V_{BV}$) by the volume of the actual part ($V$). The second term, $R_2$, is the surface area of the actual part ($SA$) divided by the surface area of the bounding volume ($SA_{BV}$). These terms are shown in Eqs. (1,2), respectively.

$$R_1 = \frac{\text{Volume of Bounding Volume}}{\text{Volume}} = \frac{V_{BV}}{V} \quad [1]$$

$$R_2 = \frac{\text{Surface Area}}{\text{Surface Area of Bounding Volume}} = \frac{SA}{SA_{BV}} \quad [2]$$

$R_1$ provides insight into how much material is in the actual part as compared to the solid primitive shape. This term indicates if a part has many volume removing features associated with it, or was created with extremities that increase the size of the bounding volume. A value close to one indicates that the part is similar to the bounding volume. $R_2$ represents the complexity of the part. This ratio quantifies the difference between the bounding volume and the actual part, but can be influenced by features or overall shape. Generally more complex parts have less potential for reprocessing. As the ratio increases from one, the probability that the part is reprocessable decreases. Although, because of the nature of surface area, slopes and chamfers can produce misleading results. A part with several sloping surfaces can produce an $R_2$ term that is below one. This type of part will typically be handled by the remaining terms of the RPI, although most parts will have a ratio above one.

The third term in the RPI model, $R_3$, compares the minimum usable volume to the part volume. Since a small part requires more precise tooling and fixturing, a minimum practical volume ($V_{MIN}$) was established. This value may be set to reflect market and technology conditions. Any volume under this minimum level is denoted as unreprocesable and is given an infinite value. $R_3$ provides information about the size of the part in relation to other parts. Equation (3) indicates the third term of the RPI model.

$$R_3 = \frac{\text{Minimum Volume}}{\text{Volume of Part}} = \frac{V_{MIN}}{V} \quad [3]$$

The fourth term, $R_4$, is a specific analysis of blind holes, through holes, slots, and keyways in a part. Holes, keyways, and slots reduce the structural strength of a part and thus make a part more likely to fail in use. In addition, parts with these features will have inherent difficulties being converted unless these features match exactly with the new part to be created. It must be understood that when the RPI is used by the manufacturing engineer at concept, a proposed follow on part may not yet be known or defined. Extreme features such as holes and slots, severely limit any potential ability to create a new part from the existing part. These features represent an important amount of volume that is removed from the core of the part and may reduce the reprocessability. The most critical feature is a through hole. Blind holes and keyways are features that have less impact, but are still considered to reduce reprocessability. To account for these features, the volume of the part ($V$) is divided by the volume of the part ($V$) minus the volume of the feature ($V_f$). Each feature of these types is analyzed in this manner and then summed. The summation
indicates the possibility of features that cause unreprocessability. If the part has substantially less volume than the features within it, a negative value of R₄ may result. The use of the absolute value will account for this negative term, but will maintain the value’s influence in the RPI equation. Typically, when the ratio is negative, the R₄ value will be relatively large indicating that these specific features undermine the reprocessability of the part. As a more complete understanding of reprocessable parts is developed, other features can be added to the recognizable feature list.

\[
R₄ = \frac{\text{Volume of Part}}{|\text{Volume of Part} - \text{Volume of Feature}|} \quad [4]
\]

\[
= \sum \frac{V}{|V - V_i|}
\]

The preceding terms are based solely on the geometric attributes of the parts. While these provide an adequate description of the part, there are also physical condition concerns that must be considered when evaluating for reprocessing. These include the effects of stress and contact area wear.

The effects of stress originate from several sources. Design stress and cyclic stress are two sources of concern in the evaluation of the reprocessability of a part. Fatigue effects can be assimilated under the design stress with the assumption that the level of design stress produces the amount of fatigue effects that occur. Upon this assumption, fatigue effects are not further discussed here. The stress evaluated for the R₄ term is based on the maximum design stress (σ_DS) for the part. Typically, a low design stress will not cause any reprocessability problems because the stress has not caused plastic or brittle failure. As the design stress approaches the yield limit of the material, the chances of the part being reprocessable are reduced. The R₄ term is arranged so that an increase in maximum design stress will cause an increase in the unreprocessability of the part. Any resulting ratio of three or more indicates a considerable amount of design stress that may cause stress cracks or fatigue. Typically, this part would not be a candidate for reprocessability. Equation (5) shows the form of this term.

\[
R₅ = \frac{\text{Yield Stress}}{\text{Yield Stress} - \text{Maximum Design Stress}} \quad [5]
\]

\[
= \frac{\sigma_{YP}}{\sigma_{YP} - \sigma_{DS}}
\]

The final term of the RPI, R₆, evaluates wear. Since wear occurs predominantly on surfaces in moving contact, an evaluation of wear is based on the relative magnitude of moving contact surface area. Equation (6) shows the form of this term.

\[
R₆ = \frac{\text{Total Surface Area}}{\text{Total Surface Area} - \text{Moving Contact Areas}} \quad [6]
\]

\[
= \frac{SA}{SA - MCA}
\]

The complete equation is a linear assembly of the terms R₁ through R₆. Equation (7) shows the combination of the terms. By using this equation and the resultant categories for the RPI, a part design may be evaluated to determine its environmental manufacturing reprocessability. The resultant categories are defined by grouping the possible results from each RPI metric, and developing an overall RPI number that would represent the part and its properties properly. Table 1 gives a brief summary of the possible results of the RPI model.

\[
\text{RPI} = \sum_{i=1}^{6} R_i \quad [7]
\]

<table>
<thead>
<tr>
<th>RPI</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 7</td>
<td>Part is reproducible and has distinct possibilities for use as another function.</td>
</tr>
<tr>
<td>7 - 13</td>
<td>Part has limitations for reprocessability.</td>
</tr>
<tr>
<td>13 - 16</td>
<td>Reprocessability of the part is severely restricted.</td>
</tr>
<tr>
<td>&gt; 16</td>
<td>Part is most likely not reprocessable.</td>
</tr>
</tbody>
</table>

THEORETICAL APPLICATION OF THE RPI

To test the RPI model, it was applied to the DCLASS Part Family Classification and Coding System [Allen and Smith, 1979]. DCLASS was used because of its wealth of predetermined classified shapes. DCLASS uses a hierarchical and discrete classification system to establish an eight digit alphanumeric code. The classification system is focused on the basic shape, form features, size, precision, and material of the part. For the RPI model, the basic rotational shape indicators were the only information utilized. Many of the parts were previously analyzed in Wentland et al. The focus here has been directed at the rotational parts and their environmental attributes.
The initial purpose of the RPI was to evaluate shape effects on reprocessability. Terms $R_5$ and $R_6$ were added later. The DCLASS parts were used to test the shape concepts. A test of $R_5$ and $R_6$ is represented in the following section. AutoCAD was used as the CAD platform to draw the rotational parts of the DCLASS system. By using the solids AME package, all the necessary RPI information could be obtained. The calculation of the RPI was performed by an AutoLISP program designed to work with the various solids.

The parts were drawn, analyzed, and the RPI results were compared to each other. $V_{MIN}$ was set at 100 cm$^3$ for this evaluation. Several characteristic parts were chosen and displayed on an RPI axis shown in Figure 3. As shown, the parts provide a representative spread on the RPI axis. Table 2 provides a detailed breakdown of the RPI for several of the parts.

### Table 2 - RPI Evaluation of DCLASS Parts

<table>
<thead>
<tr>
<th>Part</th>
<th>RPI</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
<th>RPI</th>
<th>Part</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.80</td>
<td>1</td>
<td>1</td>
<td>0.80</td>
<td>1.10</td>
<td>0.80</td>
<td>1</td>
<td>0.50</td>
<td>4.01</td>
<td>1.41</td>
</tr>
<tr>
<td>4.86</td>
<td>2.04</td>
<td>1.11</td>
<td>0.41</td>
<td>1.30</td>
<td>1.37</td>
<td>5.98</td>
<td>1.37</td>
<td>5.98</td>
<td>3.41</td>
</tr>
<tr>
<td>20.52</td>
<td>3.57</td>
<td>1.05</td>
<td>2.14</td>
<td>13.76</td>
<td>1.90</td>
<td>1.90</td>
<td>5.57</td>
<td>1.90</td>
<td>1.64</td>
</tr>
</tbody>
</table>

### Example of the RPI

To illustrate a manufacturing usage, several representative rotational parts from a washing machine were drawn and analyzed. The five parts chosen for this example were: spacer, shaft, retaining ring, screw, and coupling. The minimum volume for $R_3$ was reduced to 15 cm$^3$ from 100 cm$^3$. Figure 4 shows the parts and the corresponding RPI value calculated. Table 3 is a breakdown of the various terms of the RPI. The shaft has the lowest RPI value and is most likely reprocessable. This generalization about the shaft's reprocessability fell into accordance with Table 1.

On the other end of the spectrum, the screw and the retaining ring were not reprocessable because they did not meet the minimum volume requirement. The other parts fell in between the screw and the shaft and have their associated terms shown in the table.

### Table 3 - Evaluated RPI Results

<table>
<thead>
<tr>
<th>Part</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
<th>RPI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Washer</td>
<td>1.3</td>
<td>1.2</td>
<td>0.8</td>
<td>1.1</td>
<td>4</td>
<td>1.0</td>
<td>9.4</td>
</tr>
<tr>
<td>Ret Ring</td>
<td>15.5</td>
<td>0.2</td>
<td>$\infty$</td>
<td>1.0</td>
<td>3</td>
<td>1.0</td>
<td>$\infty$</td>
</tr>
<tr>
<td>Shaft</td>
<td>1.1</td>
<td>1.1</td>
<td>0.1</td>
<td>1.1</td>
<td>2</td>
<td>1.0</td>
<td>6.3</td>
</tr>
<tr>
<td>Coupling</td>
<td>3.7</td>
<td>1.1</td>
<td>0.4</td>
<td>34.6</td>
<td>2</td>
<td>1.2</td>
<td>43.0</td>
</tr>
<tr>
<td>Screw</td>
<td>4.5</td>
<td>0.7</td>
<td>$\infty$</td>
<td>1.0</td>
<td>5</td>
<td>1.0</td>
<td>$\infty$</td>
</tr>
</tbody>
</table>
SUMMARY

The creation of environmentally conscious tools has been perceived as a positive contribution to both design and manufacturing. The Reprocessability Index was developed to evaluate various parts and induce an awareness of how the geometric attributes of any part can affect its post-use life.

The Reprocessability Index (RPI) is a metric that evaluates the shape related attributes of any part and provides a method of determining the possibility that a part is reprocessable. To expand the utility of the RPI, factors for stress and wear were added. The number generated from the RPI model has two distinct applications. The RPI can be used to compare existing parts for possible reprocessability. It can also be used at the concept design stage to build in a “preplanned” post-use. Either application aims at increasing the awareness of the environment and focuses on reducing future personal and industrial wastes.

The RPI model is made up of six terms. Several of the terms make use of a bounding volume entity which can be considered the ideal part. This bounding volume for the rotational parts is a simple cylinder that encompasses the part. The other terms make use of the stress applied, the moving contact zones, and the key features of the part. The resulting RPI values provide a distinct inference about the geometry of the part and its possible reprocessability. RPI values under 10 indicate that the part has a fairly high possibility of being reprocessed. Acceptance of these ideas could possibly lead to a system of part marking that could be in accordance with current trends in material identification. The cost effectiveness and efficiency are two other factors that have to be considered. However, the basis behind the RPI is to guide designers and manufacturers into a state of awareness that allows them to conserve the current resources and generate a new supply of material for the future.

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