Mining End-Of-Life Materials Suitable For Material Resynthesis And Discovering New Application Domains

Kristopher Doll, Conrad S. Tucker, Suja John

{krd174@psu.edu,ctucker4}@psu.edu; sujarj@gmail.com
PRESENTATION OVERVIEW

- Research Motivation
- Research Objectives
- Literature Review
- Methodology
- Results
- Path Forward
Research Motivation

• Over 2 million tons of electronic devices were discarded in the U.S in 2009 (also a global problem)

• Only 15-20% of electronic component based waste is treated with EOL decision-making, with the remainder of these electronics going directly to landfills and incinerators
Product Resynthesis

Utilizes existing waste from EOL products from diverse domains to create a new product distinct from its parent assemblies.
# Resynthesis as an EOL Strategy

## Operation

<table>
<thead>
<tr>
<th>Operation</th>
<th>Dispose</th>
<th>Reuse</th>
<th>Remanufacture</th>
<th>Recycle</th>
<th>Resynthesize</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collection</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Transportation to disposal centers</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dismantling</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Refining</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Machining</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Disposal of waste</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Assembling</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Decision

- **Dispose**
- **Reuse**
- **Remanufacture**
- **Recycle**
- **Resynthesize**

*Note: X indicates that the operation is relevant for the corresponding decision.*
Relevant Literature

Product Resynthesis
New products from EOL Products
Kang et al. (2014), Sane and Tucker (2013)

Properties of New Material?

Hybrid Materials
A + B + shape + scale
Effective Properties
Ashby et al. (2013)

Appropriate Material?

Materials Selection
Screening and Ranking, Kasaei et al. (2014), Chatterjee (2011)

Viable Application?

Application Selection
Search through Function
Substitution Matching Requirements
Smith et al. (2012)
Limitations of Product Resynthesis

- Only explored combinations of components of EOL products (form and function)
- Potential material combinations, acquired from the processing of EOL components are not explored
- Limited exploration of application domains suitable for resynthesized material
Research Objective

Identify materials suitable for material resynthesis that have the performance characteristics needed for certain application domains.
3.1: Resynthesized Material Generation

Material (i) \rightarrow \text{Resynthesized Material (k)}

Material (j)

3.2: Evaluation of Resynthesized Material

\[ \rho_e = \rho_1(1 - VF) + \rho_2(VF) \]

3.3-3.4: Resynthesized Material-Domain Matching

3.5: Final Application Selection (LSA)

<table>
<thead>
<tr>
<th>Strength</th>
<th>Stiffness</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material (i)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material (j)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material (k)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Performance Index q

Performance Index p

Potential Materials

Performance Gain:

Application Requirement

Unsuitable Materials
## Product Database

<table>
<thead>
<tr>
<th>Object</th>
<th>Image</th>
<th>3D Cad Image (Form data)</th>
<th>Function data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screwdriver</td>
<td><img src="image" alt="Screwdriver Image" /></td>
<td><img src="image" alt="3D Screwdriver Image" /></td>
<td>Screw, shank, handle, rotate, pry lever</td>
</tr>
<tr>
<td>Calculator</td>
<td><img src="image" alt="Calculator Image" /></td>
<td><img src="image" alt="3D Calculator Image" /></td>
<td>Mathematical computation, add, subtract, multiply, divide, numbers</td>
</tr>
</tbody>
</table>

Data Acquisition → Resynthesized Material Generation → Resynthesized Material Evaluation → Resynthesized Material-Application Matching
Aggregate Material

- Materials that can be easily ground into fine particles
  - E.g., wood

Binder Material

- Materials that can be converted into a liquid or semi-solid with the introduction of common solvents or heat
  - E.g., Thermoplastics
• Δthermal expansion coefficients of the materials < ε
• Melting or decomposition temperature of the aggregate < processing temperature of the binder.
Predicting properties of hybrid or composite material (Ashby and Bréchet (2000))

\[
\rho_e = \rho_1(VF_1) + \rho_2(VF_2) + \rho_3(VF_3)
\]  \hspace{1cm} (1)

Where,

- \(\rho_i\) is the density of material \(i\)
- \(VF_i\) is its volume fraction
- \(VF_1 + VF_2 + VF_3 = 1\)
Performance indices (PIs) for evaluating the effectiveness of material resynthesis

<table>
<thead>
<tr>
<th>Function</th>
<th>PI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lightweight Strong Axial</td>
<td>$\sigma / \rho$</td>
</tr>
<tr>
<td>Support</td>
<td></td>
</tr>
<tr>
<td>Lightweight Stiff Beam</td>
<td>$E^{1/3} / \rho$</td>
</tr>
<tr>
<td>Thermal insulator</td>
<td>$1/k$</td>
</tr>
</tbody>
</table>
## Quantifying Material-Application

### Research Methodology

<table>
<thead>
<tr>
<th>Functional Descriptive Terms</th>
<th>Material (i)</th>
<th>Material (j)</th>
<th>..</th>
<th>Application (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Term 1</td>
<td>$C_{1,1}$</td>
<td>$C_{1,2}$</td>
<td>..</td>
<td>$C_{1,n}$</td>
</tr>
<tr>
<td>Term 2</td>
<td>$C_{2,1}$</td>
<td>$C_{2,2}$</td>
<td>..</td>
<td>$C_{2,n}$</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>.</td>
<td>..</td>
<td>.</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>.</td>
<td>..</td>
<td>.</td>
</tr>
<tr>
<td>Term M</td>
<td>$C_{m,1}$</td>
<td>$C_{m,2}$</td>
<td>..</td>
<td>$C_{m,n}$</td>
</tr>
</tbody>
</table>

**Textual Data Base of Materials and Applications**

![Diagram showing the process of quantifying material-application with a textual data base.](http://www.engr.psu.edu/datalab/)
Latent Semantic Analysis

• Data Mining Algorithm for quantifying relationships between textual documents

Example of synonymy:

**Terms**
- Coining
- Piercing
- Milling
- Turning
- Drilling
- Embossing
- Drawing

**Processes**
- Shearing
- Machining
- Pressing
Quantifying Resynthesized Material-Application Compatibility

\[
similarity = \cos(\theta) = \frac{D_i \cdot D_j}{\|D_i\| \|D_j\|} = \frac{\sum_{q=1}^{Q} D_{q,i} D_{q,j}}{\sqrt{\sum_{q=1}^{Q} (D_{q,i})^2} \sqrt{\sum_{q=1}^{Q} (D_{q,j})^2}}
\]

Screening by Performance Indices

N Relevant Performance Metrics \( \rightarrow \) N Dimensional Space

- Unsuitable Materials
- Potential Materials
- Performance Gain: Euclidean Distance

Research Methodology

Data Acquisition
Resynthesized Material Generation
Resynthesized Material Evaluation
Resynthesized Material-Application Matching

http://www.engr.psu.edu/datalab/
Case Study: Material Resynthesis
Product Database

EOL Car

EOL Steering Wheel

EOL Tires

EOL Engine

Data Acquisition
Resynthesized Material Generation
Resynthesized Material Evaluation
Resynthesized Material Application Matching

Case Study

http://www.engr.psu.edu/datalab/
## Product Database

<table>
<thead>
<tr>
<th>Object</th>
<th>Image</th>
<th>3D Cad Image (Form data)</th>
<th>Function data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Screwdriver</td>
<td><img src="image" alt="Screwdriver" /></td>
<td><img src="image" alt="Screwdriver 3D" /></td>
<td>covers the wheel's rim to protect it.</td>
</tr>
<tr>
<td>Calculator</td>
<td><img src="image" alt="Calculator" /></td>
<td><img src="image" alt="Calculator 3D" /></td>
<td>Mathematical computation, add, subtract, multiply, divide, numbers</td>
</tr>
</tbody>
</table>
Case Study

Data Acquisition

Resynthesized Material Generation

Resynthesized Material Evaluation

Resynthesized Material-Application Matching

Rubber

Asphalt

Candidate Resynthesized Material

=Rubberized Asphalt
Predicting properties of hybrid or composite material

<table>
<thead>
<tr>
<th></th>
<th>$E/\rho$</th>
<th>$UTS/\rho$</th>
<th>Ductility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass-Asphalt</td>
<td>0.90</td>
<td>0.00</td>
<td>0.43</td>
</tr>
<tr>
<td>Glass-PVC</td>
<td>0.93</td>
<td>0.90</td>
<td>0.89</td>
</tr>
<tr>
<td>Glass-Concrete</td>
<td>1.00</td>
<td>0.25</td>
<td>0.27</td>
</tr>
<tr>
<td>Glass-Rubber</td>
<td>0.94</td>
<td>0.75</td>
<td>0.94</td>
</tr>
<tr>
<td>Concrete-Asphalt</td>
<td>0.85</td>
<td>0.07</td>
<td>0.44</td>
</tr>
<tr>
<td>Concrete-PVC</td>
<td>0.90</td>
<td>0.35</td>
<td>0.89</td>
</tr>
<tr>
<td>Concrete-Rubber</td>
<td>0.90</td>
<td>0.38</td>
<td>0.94</td>
</tr>
<tr>
<td>Rubber-Asphalt</td>
<td>0.45</td>
<td>0.11</td>
<td>0.94</td>
</tr>
<tr>
<td>Rubber-PVC</td>
<td>0.46</td>
<td>0.86</td>
<td>0.98</td>
</tr>
<tr>
<td>Asphalt-PVC</td>
<td>0.53</td>
<td>0.08</td>
<td>0.89</td>
</tr>
</tbody>
</table>
## Data Acquisition

- **Resynthesized Material Generation**
- **Resynthesized Material Evaluation**
- **Resynthesized Material Application Matching**

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Polypropylene + Brick</th>
<th>Asphalt + Concrete</th>
<th>Epoxy + Sawdust</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roof</td>
<td>0.30</td>
<td>0.31</td>
<td>0.23</td>
</tr>
<tr>
<td>Furniture</td>
<td>0.38</td>
<td>0.48</td>
<td>0.28</td>
</tr>
<tr>
<td>Load Bearing Wall</td>
<td>0.31</td>
<td>0.33</td>
<td>0.26</td>
</tr>
<tr>
<td>Road Surface</td>
<td>0.62 <em>(highlighted)</em></td>
<td>0.56</td>
<td>0.49</td>
</tr>
<tr>
<td>Footpath</td>
<td>0.28</td>
<td>0.38</td>
<td>0.19</td>
</tr>
<tr>
<td>Acoustic Board</td>
<td>0.24</td>
<td>0.18</td>
<td>0.19</td>
</tr>
<tr>
<td>Thermal Insulation</td>
<td>0.56</td>
<td>0.37</td>
<td>0.51</td>
</tr>
<tr>
<td>Window</td>
<td>0.37</td>
<td>0.54</td>
<td>0.28</td>
</tr>
</tbody>
</table>
Conclusion and Path Forward

Identified materials suitable for material resynthesis that have the performance characteristics needed for certain application domains.
Acknowledgement & References

Contributors:
• D.A.T.A. Lab: Kristopher Doll, Conrad S. Tucker, Suja John

References


Questions