
Prepared by: Meshal Hamdi
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Outline

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- E-waste Problem
- Ethical Issues
- E-waste Recycling Statistics
- Causes of the Problem
- Objective and Top-Level Requirements
- Stakeholders Definitions
- Concept of Operations
- Systems of systems concept
- E-waste Management System – Operational View
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- Measures of Effectiveness
- Risk and Opportunity Analysis
- Proposed Solution Approach
- Lean Methods
- The Selected System
- Proposed System Architecture – Operational View
- Concentrations of metals
- Cost Analysis
- Verification and validation processes
- Lesson learned and conclusion
What is E-waste?

A popular name for electronic products nearing the end of their useful life (Lifecycle)
Why is E-waste dangerous?

Because it contains toxic and hazardous materials that pose a threat to human health and the environment

<table>
<thead>
<tr>
<th>Hazardous Component</th>
<th>Electronic Components and Devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead</td>
<td>Cathode ray tubes and solder</td>
</tr>
<tr>
<td>Mercury</td>
<td>Switches and housing</td>
</tr>
<tr>
<td>Antimony trioxide</td>
<td>Flame retardant</td>
</tr>
<tr>
<td>Polybrominated flame retardants</td>
<td>Circuit boards, plastic casings, and cables</td>
</tr>
<tr>
<td>Selenium</td>
<td>Circuit boards</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Circuit boards and semiconductors</td>
</tr>
<tr>
<td>Chromium</td>
<td>Corrosion protection for steel</td>
</tr>
<tr>
<td>Cobalt</td>
<td>Structural strength and magnetivity in steel</td>
</tr>
</tbody>
</table>
Addressing the Problem

Although e-waste represents less than 2% of America's landfill mass, it contains 70% of overall toxic waste (EPA Statistics, 2009)
Ethical Issues

- It is estimated that 50% to 80% of e-waste collected in the U.S. is exported to developing countries such as China, India and Pakistan. (Silicon Valley Toxic Coalition)
Women manually sorting e-waste!
Unhealthy conditions for workers!
Open burning and smelting with no control on the emissions!
Child doing the burning process!
E-waste Recycling Statistic in the U.S.


<table>
<thead>
<tr>
<th>Year</th>
<th>Tons of E-waste</th>
<th>Total e-waste generated</th>
<th>E-waste trashed</th>
<th>E-waste recycled</th>
<th>Percent Recycled</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>500,000</td>
<td>1,900,000</td>
<td>1,710,000</td>
<td>190,000</td>
<td>10.0%</td>
</tr>
<tr>
<td>2005</td>
<td>500,000</td>
<td>2,630,000</td>
<td>2,270,000</td>
<td>360,000</td>
<td>13.7%</td>
</tr>
<tr>
<td>2007</td>
<td>500,000</td>
<td>3,010,000</td>
<td>2,460,000</td>
<td>550,000</td>
<td>18.3%</td>
</tr>
<tr>
<td>2009</td>
<td>500,000</td>
<td>3,190,000</td>
<td>2,590,000</td>
<td>600,000</td>
<td>18.8%</td>
</tr>
<tr>
<td>2010</td>
<td>500,000</td>
<td>3,320,000</td>
<td>2,670,000</td>
<td>650,000</td>
<td>19.6%</td>
</tr>
<tr>
<td>2011</td>
<td>500,000</td>
<td>3,410,000</td>
<td>2,560,000</td>
<td>850,000</td>
<td>24.9%</td>
</tr>
<tr>
<td>2012</td>
<td>500,000</td>
<td>3,420,000</td>
<td>2,420,000</td>
<td>1,000,000</td>
<td>29.20%</td>
</tr>
</tbody>
</table>
Root Causes of the problem

- High cost of recycling
- Not enough e-waste recycling capacity
- Insufficient e-waste collection activities
- Lack of federal laws mandating e-waste recycling
- Lack of awareness
Objective
To find and design a system solution for the e-waste problem using systems engineering approaches and satisfying the top-level requirements.

Top-Level Requirements
1. The system shall be environmentally friendly
2. The system shall be safe for workers in operation
3. The system shall be profitable and cost effective
4. The system shall reduce the quantity of toxic materials that is being dumped in landfills
5. The system shall use the latest developed technologies related to e-waste
Stakeholders Definitions

- Each stakeholder has different interests and influences.
- Business leaders in the electronic industry can make a significant impact to help in the e-waste problem but they need to be motivated to make a change.
**Concept of Operations**

**Product Flow Cycle**

- **Manufacturing of electronic products** → **Distribution Process** → **Inventory/Sales** → **Consumers** → **Recycling Process** → **Landfill**

- **Raw materials**

- **Landfill** → **Disposal** → **Collection**

- **Raw Materials**

- <1% of total weight
System of Systems Concept

**SUBSYSTEM: Manufacturing/Assembling System**
- Stakeholders:
  - Suppliers/Manufacturers of electronics
  - Raw Materials Producers
  - Retailers
  - State Government
  - Federal Government

**SUBSYSTEM: Recycling System**
- Stakeholders:
  - Recycling Companies
  - Retailers
  - Local Governments
  - State Government

**SUBSYSTEM: Collecting System**
- Stakeholders:
  - Collecting Companies
  - Retailers
  - Local Governments
  - State Government

**SUBSYSTEM: Government Regulations System**
- Stakeholders:
  - State Government
  - Environmental Agencies
  - Tax Payers

**SYSTEM: E-waste Management Sys.**
- Subsystems:
  - Manufacturing/Assembling sys.
  - Recycling sys.
  - Collecting sys.
  - Government regulations sys.

**EXTERNAL SYSTEMS**
- Stakeholders:
  - Community
  - International Corporations
  - Cities
  - Tax Payers

**SUBSYSTEM: Retailers System**
- Stakeholders:
  - Suppliers/Manufacturers of electronics
  - Businesses/Corporations
  - Local Governments

**SUBSYSTEM: Funding System**
- Stakeholders:
  - Privet industry
  - End customers
  - State government
E-waste Management System

Operational View

- Externalities
- E-waste Management System
  - Government Regulations System
  - Manufacturers/Assemblers System
  - Retailers System
  - Collection System
  - Recycling System
  - Consumers
  - Landfills
  - Funding System
Alternative Analysis

- The alternative analysis was done by analyzing the previous figures (Product Flow Cycle, the conceptual and operational views of the e-waste management system)

- Three alternatives were chosen after the analysis
First Alternative

- Using different materials that are not hazardous in manufacturing electronic products
- According to the report of the Army Corrosion Summit in 2010 in Huntsville, there are many non-toxic alternative materials that can replace the toxic materials used in electronics
- For example, cadmium can be replaced with zinc or aluminum for coating in electronics
- The challenges are in design, maintenance, supply, cost and efficiency of these alternative materials
Second Alternative

- Using Mono-disposal landfills for e-waste as temporary storage for future recycling
- Monofills are landfills dedicated solely to waste of similar characteristics and typically used for tires
Third Alternative

- Developing the capabilities and performance of the current recycling system for electronics.
- This approach will be focusing on improving the recycling sub-system because it is the major and most critical sub-system in the e-waste management system.
## Measures of Effectiveness (MoE)

<table>
<thead>
<tr>
<th>Factor/Alternatives</th>
<th>Alternative 1 Replacing the materials “out of 5”</th>
<th>Alternative 2 Mono-disposal landfills “out of 5”</th>
<th>Alternative 3 Developing current system “out of 5”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial cost</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Environmental conservation</td>
<td>4</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Safety in operation</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Toxic materials reduction in landfills</td>
<td>5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Revenue streams (Income)</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Long-term benefits</td>
<td>5</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Execution simplicity</td>
<td>3</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Interface with current system</td>
<td>3</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>27</strong></td>
<td><strong>19</strong></td>
<td><strong>29</strong></td>
</tr>
</tbody>
</table>
Risk and Opportunity Analysis

Traditional 5x5 Risk Matrix is used
# Risk and Opportunity results

<table>
<thead>
<tr>
<th>Risk Factor/Alternatives</th>
<th>Alternative 1</th>
<th>Alternative 2</th>
<th>Alternative 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Technical/Technology risk</strong></td>
<td>H(5,4)</td>
<td>L(2,2)</td>
<td>H(5,4)</td>
</tr>
<tr>
<td><strong>Integration/Interface risk</strong></td>
<td>H(4,4)</td>
<td>H(5,4)</td>
<td>M(4,2)</td>
</tr>
<tr>
<td><strong>Cost risk</strong></td>
<td>H(5,5)</td>
<td>H(5,4)</td>
<td>H(5,4)</td>
</tr>
<tr>
<td><strong>Design risk</strong></td>
<td>H(5,4)</td>
<td>H(4,4)</td>
<td>M(4,3)</td>
</tr>
<tr>
<td><strong>Political risk</strong></td>
<td>H(4,4)</td>
<td>H(4,4)</td>
<td>M(4,2)</td>
</tr>
<tr>
<td><strong>Cultural risk</strong></td>
<td>L(2,3)</td>
<td>M(4,3)</td>
<td>L(2,2)</td>
</tr>
<tr>
<td><strong>Laws and regulations risk</strong></td>
<td>H(5,4)</td>
<td>H(5,5)</td>
<td>L(3,2)</td>
</tr>
<tr>
<td><strong>Scope uncertainty risk</strong></td>
<td>H(5,5)</td>
<td>H(5,4)</td>
<td>M(3,4)</td>
</tr>
<tr>
<td><strong>Environmental impact risk</strong></td>
<td>L(1,4)</td>
<td>M(2,4)</td>
<td>M(2,3)</td>
</tr>
<tr>
<td><strong>Financial income risk</strong></td>
<td>H(4,5)</td>
<td>H(5,5)</td>
<td>H(4,4)</td>
</tr>
<tr>
<td><strong>Implementation risk</strong></td>
<td>H(5,4)</td>
<td>H(5,5)</td>
<td>M(4,3)</td>
</tr>
</tbody>
</table>
**Proposed Solution Approach**

- The proposed solution approach is a combination between the first and third alternatives (Replacing the materials and developing the current system)

- The second alternative is rejected. Mainly because of its high risk factors, low effectiveness and the limited revenue streams possibilities

- The first alternative requires an advanced LAB and experienced team about the materials used in electronics. Therefore, the focus will be on the third alternative and specifically on the recycling sub-system because it is a fundamental sub-system in e-waste management system
**Risk and Opportunity Management**

- Applying the risk calculations to the third alternative
- Technical/Technology, cost and financial income are the high risk factors and should be mitigated if possible.
The selected solution approach focuses on two particular e-waste categories (computers and mobile devices) with the possibility of expanding to more categories in the future.

This strategy will remove costly steps "waste" because the latest and most economical technologies will be used on the selected categories which is hard to be accomplished when recycling wide range of products.
**Selected Technology for the System**

- Developed by ATMI Corporation in 2013 (American Textile Manufacturers Institute)

- Focuses on the Printed Wiring Board (PWB) because it contains most of both the hazardous materials and the precious metals

- Uses green chemicals to do automatically the dismantling process and raw-materials recovery process

- Does not require any burning or smelting processes to recover the metals because it is done using green chemicals and collected in bars
The Selected System
The Selected System
Proposed System Architecture - Operational View

Electronic Products Consumption

E-waste Collection

E-waste Transport

E-waste Sorting

Recycling System Boundary

Plastics, Aluminum & Steel

Primary Components Separation

Printed Wiring Boards

Chemical Separation

Electronic Components Recovery

Additional Chemical Processing

Raw Materials Recovery

Specialized Recycling Facilities

Reuse
After the Chemical Separation of Components

DESOLDERED
After the Chemical Gold Leaching

DESOLEDERED & GOLD LEACHED
**Component Percentages of Printed Wiring Boards by Weight**

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage of PWB by weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiberglass</td>
<td>45% - 50%</td>
</tr>
<tr>
<td>Copper</td>
<td>15% - 20%</td>
</tr>
<tr>
<td>Components/Integrated Circuits</td>
<td>10% - 25%</td>
</tr>
<tr>
<td>Precious Metals</td>
<td>0.4%</td>
</tr>
<tr>
<td>Lead, tin &amp; other base metals</td>
<td>Remainder</td>
</tr>
</tbody>
</table>

One metric ton of circuit boards can contain 40 to 800 times the amount of gold, and 30 to 40 times the amount of copper mined from one metric ton of ore. (EPA Statistics, 2009)
**Concentration of Metals in Electronics**

<table>
<thead>
<tr>
<th>Electronic</th>
<th>Copper (% by weight)</th>
<th>Silver (ppm)</th>
<th>Gold (ppm)</th>
<th>Palladium (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Television (TV) Board</td>
<td>10%</td>
<td>280</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Personal Computer (PC) Board</td>
<td>20%</td>
<td>1000</td>
<td>250</td>
<td>110</td>
</tr>
<tr>
<td>Mobile Phone</td>
<td>13%</td>
<td>3500</td>
<td>340</td>
<td>130</td>
</tr>
<tr>
<td>Portable Audio Scrap(^{(2)})</td>
<td>21%</td>
<td>150</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>DVD Player Scrap(^{(2)})</td>
<td>5%</td>
<td>115</td>
<td>15</td>
<td>4</td>
</tr>
</tbody>
</table>

- The cost analysis is based on the above table by focusing on personal computers and mobile devices.
- The remaining materials (plastics, aluminum, steel and batteries) is assumed to be
  - 80% of total weight for **personal computers**
  - 87% of total weight for **mobile devices**
Cost Analysis

Value of printed wiring boards by weight

Value of printed wiring board – dollars per pound

[Graph showing the value of printed wiring boards from January 2008 to March 2012, with values ranging from $0.00 to $9.00 per pound.]
**Cost Analysis**

- The estimations for cost is based on a system capacity of 2,000 short tons per year.

<table>
<thead>
<tr>
<th>Description</th>
<th>Millions U.S. Dollars</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Expenses</strong></td>
<td></td>
</tr>
<tr>
<td>Equipment &amp; Installation cost</td>
<td>50 – 60</td>
</tr>
<tr>
<td>Operational Cost</td>
<td>30 per year</td>
</tr>
<tr>
<td>e-waste scrap cost (2000 short tons)</td>
<td>2 per year</td>
</tr>
<tr>
<td><strong>Income Streams</strong></td>
<td></td>
</tr>
<tr>
<td>Precious metals (gold, silver and palladium)</td>
<td>50 per year</td>
</tr>
<tr>
<td>Remaining materials (plastics, aluminum, steel and batteries)</td>
<td>1.1 per year</td>
</tr>
<tr>
<td><strong>Total Income</strong></td>
<td>51.1 per year</td>
</tr>
</tbody>
</table>
Cost Analysis

Return on Investment (ROI) = (Net profit / Cost of investment) x100

- Assumptions
  - $55 million investment
  - 7% Royalty
  - Prices for plastics, aluminum, steel and batteries are $0.15/lbs, $0.75/lbs, $0.14 and $0.25/lbs respectively

- Results
  - Net Profit = $8.463 million/year
  - Return on Investment (ROI) = 15.7% (less than 7 years)
Verification Process

- Satisfying the top-level requirements.

- Environmentally friendly system
- Safe for workers during operation
- Profitable and cost effective system
- Reduce the quantity of toxic materials that is being dumped in landfills
- Use of latest developed technologies
Validation Process

- Meeting the operational needs of the customers and stakeholders

✓ Market Driven Solution
✓ Practical and Scalable System
✓ Profitable Business Proposition
✓ Minimize Manual Work

- Further detailed analysis in system logistics with an experienced company in green chemistry technologies is needed to finalize the model
Lesson Learned

• Understanding the interfaces among the sub-systems is a key factor in comprehending the structure and functionality of the e-waste management system because it is a global, large and complex system of systems and includes large subsystems.

• Analyzing the possible alternatives and the concept of operations for the system carefully before jumping into solutions is such an important and critical step in analyzing complex systems.

• Solving the e-waste problem require cooperation between the privat sector, including business leaders in recycling industry, and the government.
Lesson Learned

- The lack of federal laws or policies for mandating e-waste recycling is a major challenge in the U.S. e-waste management and recycling systems.
- The financial and business model is a major challenge in the e-waste recycling systems.
- There is a lack of infrastructure for e-waste recycling in the U.S. because traditional recycling systems are costly and require regularity support, formal recycling infrastructure and a skilled workforce.
- The manufacturers/producers of electronic products can make a significant help by designing the products in a way that makes the recycling process easy and replace the hazardous materials with nonhazardous.
Conclusion

- The green chemistry technology is such an efficient way to drive the recycling cost down in a safe, environmentally friendly, cost effective and practical manner.

- It is probably the most efficient recycling technique for electronic products so far but it still needs more testing and improvements.

- The proposed recycling system is a contribution to solve part of the e-waste problem and with more contributions from different groups and entities, the e-waste problem will be potentially solved.
References


Thank you !!!

Q & A

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