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A Decision-Making Model for Materials Management of End-of-Life Products in the Pantex Plant

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AMARILLO NATIONAL RESOURCE CENTER FOR PLUTONIUM/
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An Interim Report on

A Decision-Making Model for Materials Management of End-of-Life Products in the Pantex Plant

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A Decision-Making Model for Materials Management of End-of-Life Products in the Pantex Plant

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ABSTRACT

This report is concerned with a proposed system architecture for decision-making model for material management of non-nuclear dismantled components – PMM (Proactive Material Management) model. The subsystems of the model is discussed in detail, including classification/separation, shredding/separation, and recycling plan generation.. To facilitate decision making of recycling plan for dismantled components, three major factors are considered: cost, environmental impacts, and recoverable materials. Environmental impact analysis is performed by utilizing a consistent environmental assessment method – EDIP (Environmental Development of Industrial Products).

Based on the refined system architecture, the research group performed data collection on two important material categories: PCB (Printed Circuit Board) and plastics. Among dismantled non-nuclear components, PCB and plastics are important categories that influence decision-making in terms of material management and recycling plan generation. The group utilizes EDIP method to evaluate the environmental impacts of these two material categories. The assessment data will help to finalize system architecture and decision making scheme.

The prototype model based on the refined system architecture and collected data is under development and is scheduled to be completed by the end of March. The database structure of the prototype model has already been established.

1. SYSTEM ARCHITECTURE

Combined with the results from the first-year research, the refined system architecture of PMM is proposed as the basis for future prototyping model development (Figure 1). The refined system architecture still focuses on decision-making support for material management of dismantled non-nuclear components.

1.1 Input and Output

At the outset, the input and output of the system should be clarified. Pantex plant utilizes a Disassembly Information System (DIS) as a centralized tracking system to trace all disassembled parts along with all parts inventory. The functionality of the disassembly process consists of a reverse bill

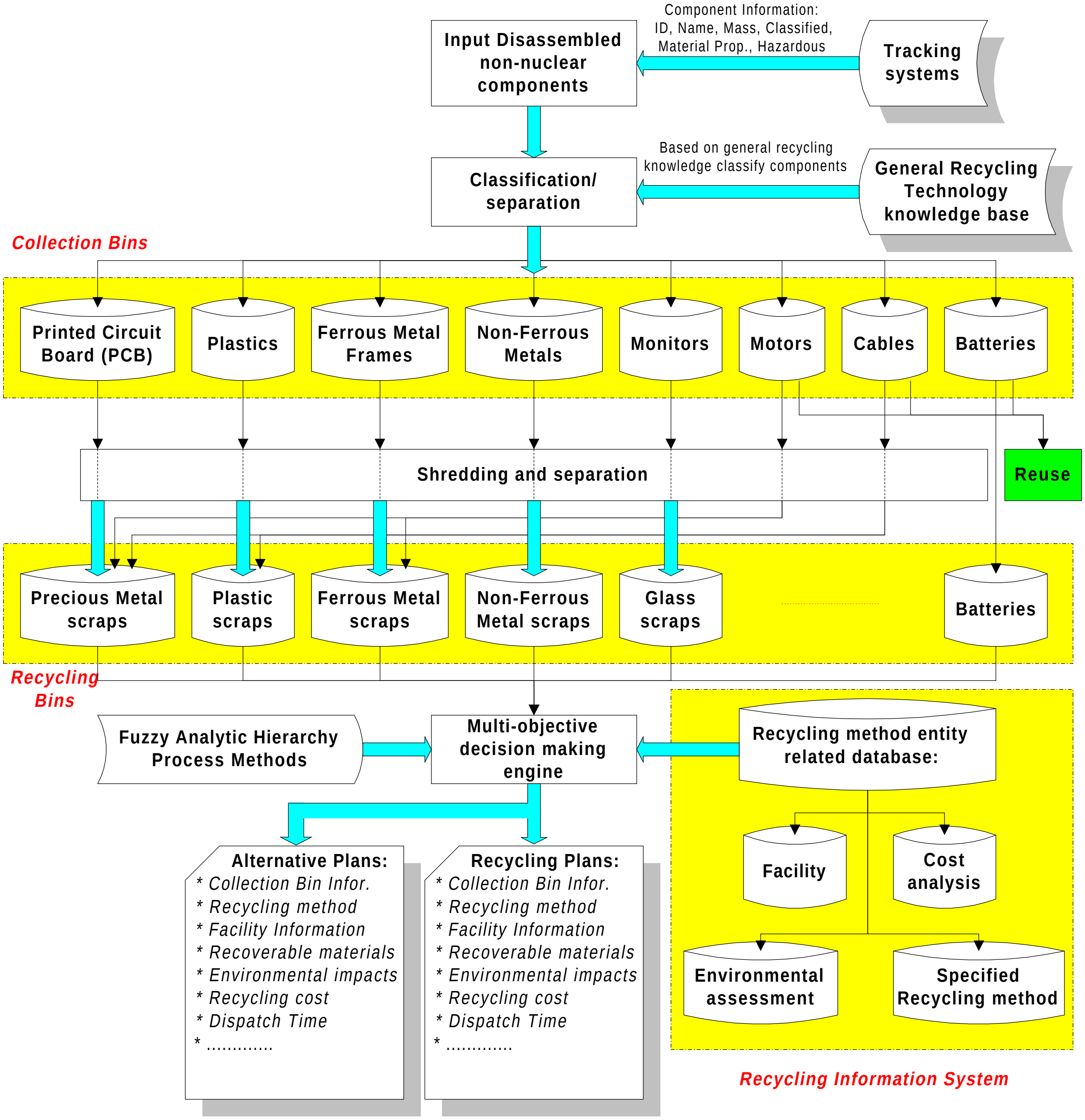

Figure 1: Refined System Architecture of PMM Model

of material with part disposition definitions and also automatic order generation. The proposed PMM model will utilize this tracking system as the disassembled component input. The DIS system may include many data fields including: ID, name, mass, classified information, dispatch time, and so on. To minimize integration work with existed tracking systems, PMM model only requires the basic data as model input. The data include component name and mass information. These two data fields are necessary to construct eight collection bins in the model. Other data are built into the PMM model database, such as recycling method, recycling facility information, recycling cost and recycling bin information. The advantage of adopting minimal data input is to keep the model as independent as possible, thus leading to ease of implementation and integration.

The output of the PMM model includes a set of recycling plans for dismantled non-nuclear components. The contents of recycling plans are listed in the Table 1. The suggested recycling plan will be generated by multi-objective decision making engine. Alternative recycling plans will also be listed for users' choice.

1.2 Phase I: Component Sorting and Separation

After dismantled non-nuclear component information is retrieved from the existed Disassembly Information System in the Pantex plant, the first phase in the system architecture is to classify or group these components into eight Collection Bins (CBs) based on general recycling knowledge.

There are many components in a nuclear warhead – including nuclear materials, other toxic and hazardous materials (chemicals and metals), and classified materials (switches, electronic components) – all of which require careful handling and attention as to environment, safety, and health issues. The physical components of a nuclear warhead may include:

- Fighting parts: Detonators, High explosives, Beryllium, Depleted uranium, Highly enriched uranium, Plutonium, Lithium deuteride, Plastic foam, Neutron generators, Tritium/deuterium, Gas canister.
- Electronic Packages (encapsulated/unencapsulated): Lead solder and other metals, Thermal batteries, Encapsulating materials, Electrical components (PCBs), Asbestos, Cables.
- Other Component: Electromechanical devices, Functional mechanical devices, Electronic components, Electric cables, Parachutes and explosives, Nonfunctional mechanical parts, Residuals: O-rings, seals, fasteners, etc.

According to the general recycling technology, the above non-nuclear components are currently grouped into eight Collection Bins, namely, Printed Circuit Board (PCB), Plastics, Ferrous Metal Frames, Non-Ferrous Metals, Monitors, Motors, Cables, and Batteries. The generation of Collection Bins is to facilitate to develop further recycling or treatment plans. The number and name of Collection Bins can be modified based on different user intent. In the prototype model, we try to group components with similar recycling scenarios into the same Collection Bin.

Table 1: Output of PMM Model

Categories	Details
Recycling Bin Basic Information	• Recycling Bin ID; • Recycling Bin Name; • Recycling Bin Type; • Recycling Bin Establishing Date; • Recycling Bin Net Weight (LBs).
Recycling Bin Dispatch Information	• Recycling Bin Dispatch Date; • Recycling Facility information: - Facility ID; - Facility name; - Facility address; - Contact person; - Contact phone; • Quote price or cost for this recycling bin; • Distance and transportation cost.
Recycling Method Information	• Recycling method name; • Recycling method description; • Environmental impact – Person Equivalent score: - Global warming score; - Ozone depletion score; - Acidification score; - Photosmog score; - Solid waste score; - Crude Oil score; - Natural Gas score; - Coal score.
Recycling Plan	• Recommended recycling method for each recycling bin. • Alternative recycling methods for each recycling bin.
Overall environmental impacts and cost analysis	• Total cost analysis (recycling cost, transportation cost, etc.) for a batch of recycling bins. • Total environmental impact report for all recycling plans.

1.3 Phase II: Shredding and Separation

After Phase I, all dismantled components are grouped into various Collection Bins. We believe the next step is to pre-treat these Collection Bins, that is, using shredding or other simple separation methods to separate different materials. In this phase, we use another term - Recycling Bins – to illustrate the output of shredding and separation operation. Thus the input of this phase is various Collection Bins and the output is generated Recycling Bins. We provide six general Recycling Bins according to common recycler's jargon. They are Precious Metal Scraps, Plastic Scraps, Ferrous Metal Scraps, Non-Ferrous Metal Scraps, Glass Scraps, and Batteries.

For some Collection Bin, there is only one Recycling Bins corresponding to it. For example, "Printed Circuit Board (PCB)" is shredded and sent into the corresponding Recycling Bin – "Precious Metal Scraps." For some Collection Bin, they need to be separated into several Recycling Bins after shredding. For example, "Motors" might be shredded and separated into "Precious Metal

Scraps," "Ferrous Metal Scraps," and "Non-Ferrous Metal Scraps." For some Collection Bins, they may be reused or remanufactured, or they cannot be shredded because of their hazardous material content. In this case, they will be sent directly into special Recycling Bins. For example, some of batteries and motors may be reused after testing. Most batteries contain hazardous materials, thus they will be sent directly into Recycling Bin "Batteries".

1.4 Phase III: Recycling Plan Generation

After formulation of various Recycling Bins, the material management and recycling plans for individual components are transformed into management of those Recycling Bins. According to the previous research, there exist various treatment methods or recycling plans for these bins. The optimal choice of recycling plans needs a multi-objective decision making engine. In the model, three factors are considered decision objectives, namely, cost, environmental impacts, and recoverable materials. The recycling plan contents have been discussed in the input/output section. The detail decision making scheme will be discussed later.

1.5 Prototype Model Implementation and Database Construction

The prototype model based on refined system architecture is under development. The flowchart of the prototype model is illustrated in Figure 2.

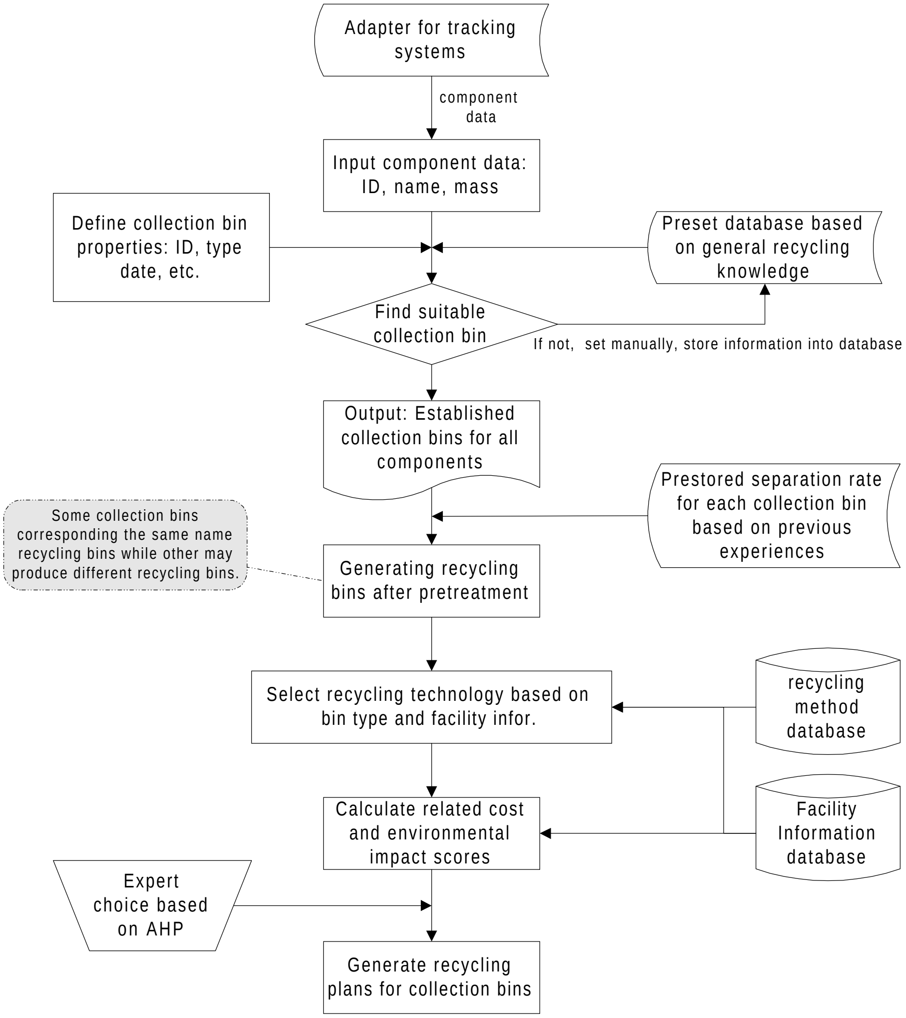

Figure 2: Flowchart of PMM Prototype Model

The database of this prototype model should be constructed firstly to provide essential information to generate optimal recycling plans. The Entity-Related database model is illustrated in Figure 3. There are totally 13 tables for prototype model construction. Some sample data will be stored to test the prototype.

Pantex Project Database Entity Related Model

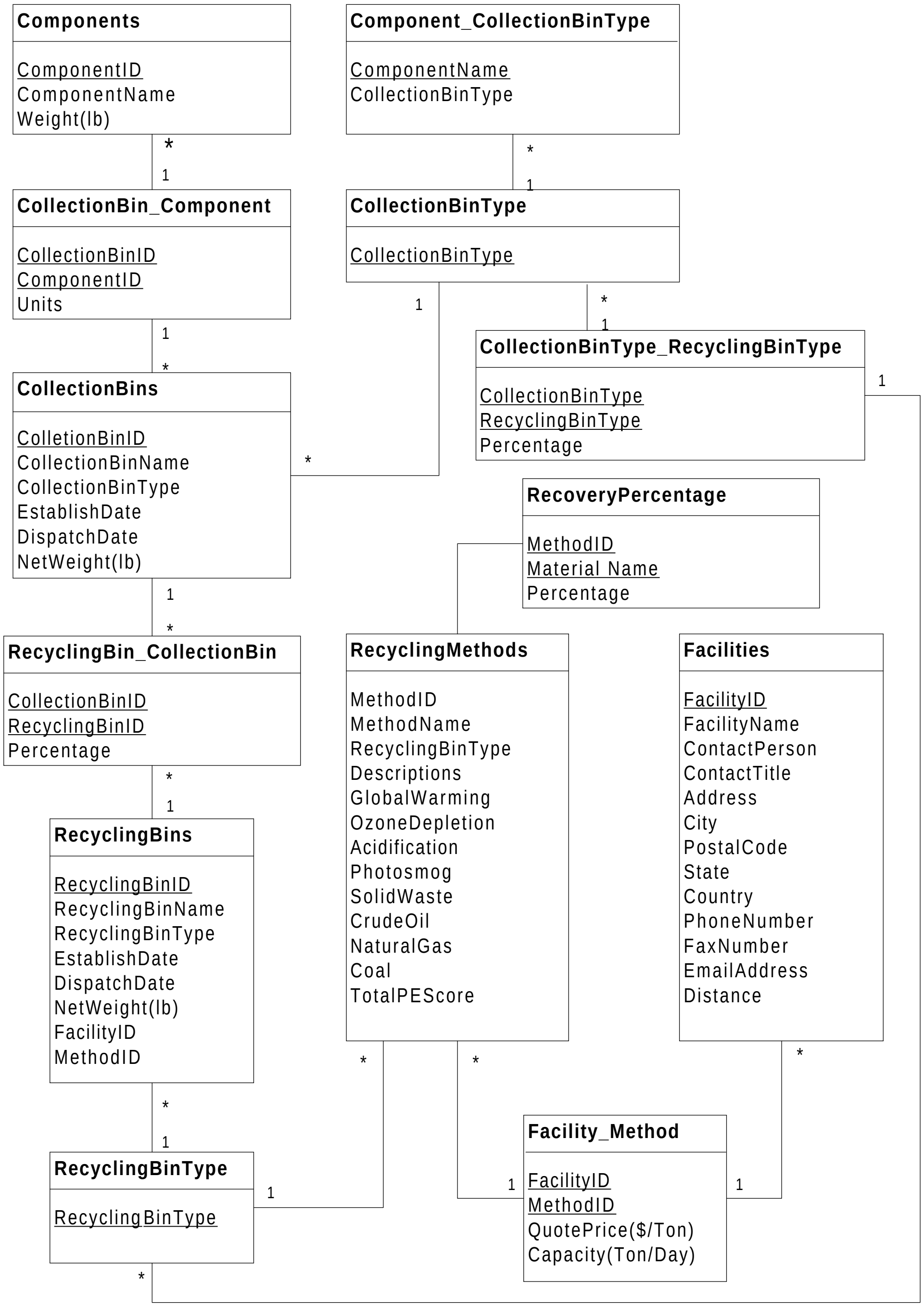

Figure 3: ER Database Model for PMM

2. ENVIRONMENTAL IMPACT ANALYSIS

In Phase III, in order to obtain multi-objective decision making of recycling plans, three factors are introduced. Among them, environmental impact factors will be discussed in this section.

In the past two decades a new discipline in environmental engineering has emerged, called the environmental assessment methods. Environmental assessment methods are methods with which the environmental impacts from human activities can be quantified. When environmental assessment methods are utilized in a recycling scenario, they will provide environmental impacts assessment of various waste management and recycling plans, thus facilitate decision making scheme for end-of-life products treatment.

In this report, we utilize a consistent environmental assessment method – EDIP (Environmental Development of Industrial Products) to evaluate the environmental impacts of end-of-life products treatment in the Pantex Plant.

Before discussion, general environmental effects are introduced briefly. The effects on the external environment are traditionally divided into global effects (global warming and ozone depletion), regional effects (acidification, nutrient enrichment, smog creation and certain toxicity effects) and local effects (waste generation and certain effect categories for human toxicity and eco-toxicity).

Based on these effects, EDIP method operates with seven overall environmental impact categories for emissions to the external environment, as following:

- Global warming:
  There are several gases contributing to global warming. The most common of these so-called global warming gases is carbon dioxide (CO_2). The global warming potential (GWP) is applied to measure a gas's potential for preventing heat from escaping into the universe, in terms of the kilograms of CO_2 that would have the same effect as one kilogram of the substance. Thus:

$$Global\,warming\,score\,(kg\,CO_2) = \sum_i GWP_i \times kg\,substa_i$$

- Stratospheric ozone depletion:
  Stratospheric ozone depletion may be caused by a number of different substances, mostly CFCs, HCFCs and halones. The most common of these substances is the CFC-11. The ozone depletion potential (ODP) is applied to measure the potential of a substance for stratospheric ozone depletion, in terms of the kilogram of CFC-11 that would have the same effect as one kilogram of the substance. Thus:

$$Ozone\,depletion\,score\,(kg\,CFC-11) = \sum_i ODP_i \times kg\,substan_i$$

- Acidification:
  The reference substance in acidification is sulphur dioxide (SO_2). The acidification potential (AP) is applied to measure the potential of a substance for acidification, in terms of the kilogram of SO_2 that would have the same effect as one kilogram of the substance. Thus:

$$Acidification\,score\,(kg\,SO_2) = \sum_i AP_i \times kg\,substance_i$$

- Photochemical ozone creation (photosmog):
  Photosmog is created when volatile organic compounds react to form ozone in the troposphere. The reation is influenced by the amount of NO_x in the troposphere. The EDIP method divides the photosmog category into two sub-categories, depending on the NO_x level in the troposphere: A low NO_x level category and a high NO_x level category. Photochemical ozone creation potential (POCP) has the reference substance as

ethylene (C_2H_4) and the score is calculated by:

$$Photosmog\ score(kg\ C_2H_4) = \sum_i POCP_i \times kg\ substance_i$$

- Eutrophication:
  Eutrophication is caused by either biologically accessible nitrogen or phosphorous. The calculation of a single effect score for eutrophication follows the same general procedure as above. Eutrophication potential (EP) has the reference substance as the nitrate ion (NO_3). The score is calculated by:

$$Eutrophication\ score(kg\ NO_3) = \sum_i EP_i \times kg\ substance_i$$

- Toxicity towards eco-systems (eco-toxicity):
  Eco-toxicity is not a simple environmental effect in a single environmental compartment, but rather a collection of different toxicity effects in more than one environmental compartment caused by a greater variety of toxic chemical substances. To get a properly detailed treatment, the EDIP method divides the overall eco-toxicity effect into four individual effect categories: Acute toxicity towards aquatic eco-systems, chronic toxicity towards aquatic eco-systems, chronic toxicity towards terrestrial eco-systems and toxicity towards micro-organisms in waste water treatment plants. The eco-toxicity potential (ETEQ) are calculated as a product of two factors. This factor is under research and not available yet.

- Toxicity towards humans (human toxicity).
  The other toxicological effect treated by the EDIP method is human toxicity. The EDIP method uses the same general principle to treat eco-toxicity and human toxicity.

The total contribution to the respective environmental effects are now expressed as single effect scores either as kilograms of a reference substance or as cubic meters of critical volume. The effect scores for resource draws and waste generation is simply kilograms of resource drawn or waste generated. Then the effect scores should be normalized by dividing each effect score with a normalization reference. The normalization reference is the total effect score per person for all human activities in the area affected by the effect. The general formula for the normalization is:

$$NES_j(in\ person\ equivalents) = ES_j / (L \times NR_j)$$

NES_j is the normalized effect score for an environmental effect or a resource draw, measured as person equivalents. ES_j is the characterized effect score for the environmental effect or resource draw. L is the life time of the product being studied in the LCA (Life Cycle Assessment). In the report, L is set to one year. NR_j is the normalization reference. Table 2 shows the normalization references relevant for the report.

After normalization step, the EDIP method applies a set of weighting factors for the environmental impact and waste generation categories based on distance to target philosophy. The weighting factors relevant for the report are given in the Table 3.

After the weighting, the scores are aggregated into one index describing the environmental performance of the specific treatment method. The unit is person equivalents (PEs). This index will be applied in the following discussion of PCB and plastics waste management and recycling plan generation. For each possible recycling scenario, an eco-profile is generated to compare the environmental impacts and provide data resource for further decision-making.

Table 2: Normalization References for this Report

Effect	**Normalization Reference**	**Effect**	**Normalization Reference**
Slag and ash	350 kg/person	Lignite (brown coal)	254 kg/person
Volume waste	1350 kg/person	Natural gas	309 kg/person
Global warming	9000 kg CO_2-eqv./person	Crude oil	592 kg/person
Acidification	139 kg SO_2-eqv./person	Coal	574 kg/person
Photosmog (Low)	18.7 kg C_2H_4-eqv./person	Aluminum	3.38 kg/person
Photosmog (High)	18.7 kg C_2H_4-eqv./person	Iron	103 kg/person
Eutrophication	254 kg NO_3-eqv./person	Zinc	1.38 kg/person

Table 3: Relevant Weighting Factor for this Report

Effect	**Weighting Factor**	**Effect**	**Weighting Factor**
Slag and ash	1.1000	Lignite (brown coal)	0.002584
Volume waste	1.1000	Natural gas	0.016393
Global warming	1.3000	Crude oil	0.023256
Acidification	1.5000	Coal	0.005814
Photosmog (Low)	1.4000	Aluminum	0.0051282
Photosmog (High)	1.4000	Iron	0.0084746
Eutrophication	1.4000	Zinc	0.0500

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3. MULTI-OBJECTIVE DECISION MAKING ENGINE

Multi-objective decision making engine is the core part of the proposed PMM model. As discussed before, to facilitate decision making of recycling plan for dismantled components, three major factors are considered: cost, environmental impacts, and recoverable materials. Environmental impact analysis is performed by utilizing a consistent environmental assessment method – EDIP (Environmental Development of Industrial Products). Cost analysis and recoverable materials will be discussed later in this part. The input of the decision-making engine includes various Recycling Bins, recycling facilities with different recycling methods. The output of the engine is optimal recycling plan for each Recycling Bin. Figure 4 shows the hierarchy of the decision-making problem. To solve the problem, Utility function and Analytic Hierarchy Process (AHP) are applied and will be discussed later.

3.1 Cost Factor and Recoverable Material Factor

The overall cost for waste management may include the sum total of all on site and off site expenses associated with the generation and management of solid and hazardous waste. These costs can be categorized into:

- Quote Price/Cost for each recycling bin type;
- Transportation fees (related to Distance):
    - Vehicle/Equipment fees;
    - Liability in Transportation;
    - Weighing Charges;
    - State Taxes;
    - Demurrage Fees;
    - Trailer Spotting Charges;
    - Rejected Load Fees.

- Pre-transportation cost:
    - Containers, Package Materials, Labels, Safety/Emergency Facility;
    - Labor cost;
    - Special Handling fees.

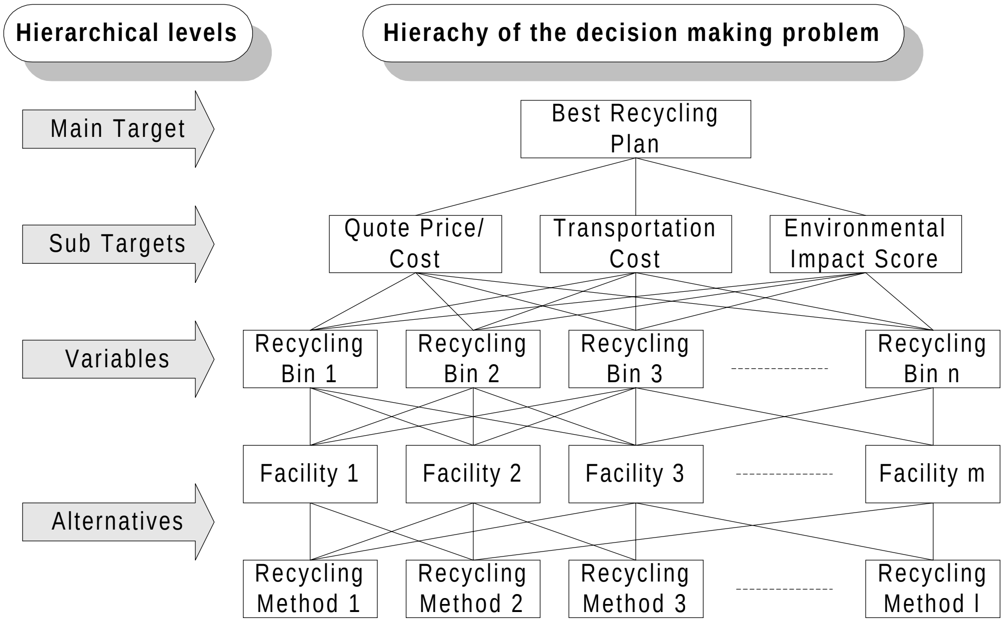

Figure 4: PMM Decision-Making Hierarchy

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Some of the costs are fixed, e.g., on site labor, and do not very significantly by waste type. Other costs, such as off site treatment and disposal costs, however, do vary by waste type and are directly dependent upon the composition and volume of material generated. The detail study on cost analysis is not the focus of this research. However, quote price (which varies in different Recycling Bins) and transportation cost (which is related to the distance between recycling facility and the Pantex Plant.

In the recycling scenarios for some Recycling Bin type, precious metal recovery percentage should be considered in order to generate an optimal recycling plan. Unlike environmental impact factor, recoverable materials contributes positive scores as a decision making factor. An example of recovery percentage for different PCB recycling scenarios is shown in Table 4.

3.2 Decision-Making Steps

After determining three decision-making factors – cost, environmental impact, and recoverable materials, each factor should be normalized into a comparable score via a utility function. An example of the utility function is shown in Figure 5. From the figure, we can see for any input factors (cost, environmental impact scores or recovery percentage), a normalization function can be determined by its average point (x_0) and steeping rate (λ). These two control parameters can be modified based on users' intent. Via the utility function, the normalized value can be obtained ranging [0, 1], with the larger may represent the more satisfactory rate.

3.3 AHP Method

Many decision-making problems involve ranking several alternatives according to their relative weights or choosing top alternative from others with respect to some specific criteria. To deal with this type of problems, the Analytic Hierarchy Process (AHP) is proved as a useful and easy-handling method. In the AHP, the hierarchical pairwise comparison is employed to induce the relative weights of alternatives through pairwise comparison. Decision-makers choose a value from a scale to express the relative significance of one alternative over another based on a Saaty's scale. All of the pairwise comparison values can be summarized in a comparison matrix, from which the relative weights of all the alternatives can be extracted. Based on the comparison matrix, a series of calculations are performed to choose the best alternative.

Table 4: Estimated Recovery Percentages for PCB Recycling Scenarios

Weight % Recovery	**Copper (Electro)**	**Lead (Pyro)**	**Tin (Electro)**	**Tin (Pyro)**
Copper	99	95	90	90
Nickel	85	0	0	90
Lead	85	99	90	90
Tin	80	90	99	99
Zinc	85	0	0	90
Silver	90	90	90	0
Gold	98	95	95	0
Palladium	90	90	90	0
Platinum	90	90	90	0

Antimony	0	90	90	90

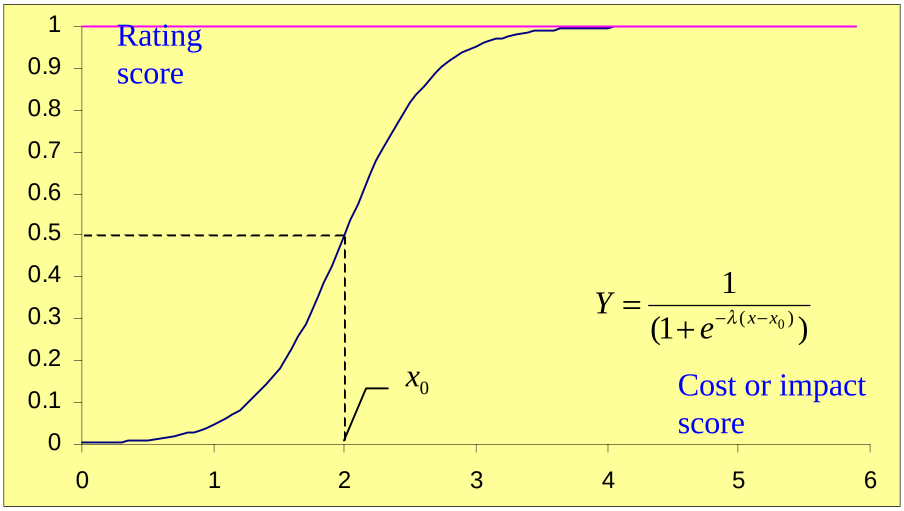

Figure 5: Utility Function for Normalization

Assuming that for n criteria, the pairwise comparison of element i to element j has one of the numerical values called a_{ij}, the pairwise comparison matrix of criteria can be obtained as the following: (note that $a_{ji} = 1/a_{ij}$)

$$CM_n = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}$$

To calculate a vector of priorities from the *Comparison Matrix* (*CM*), the principal eigenvector is computed, and after normalized, it becomes the vector of priorities. Let $PV = (p_1,..., p_n)^T$ form a principle eigenvector for n criteria. Also for m alternatives, we have an $m \times m$ comparison matrix on each criterion. Each matrix can also have geometric means of the rows and relative weights of the priorities. The only difference is that now p_{ij} stands for relative weight of the priorities for the ith alternative with respect to the jth criterion. Then p_{ij} forms a new priority matrix called *PM*. The final weight of alternative is computed as:

$$R = PM \times PV = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1(n-1)} & p_{1n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ p_{m1} & p_{m2} & \cdots & p_{m(n-1)} & p_{mn} \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \\ \cdots \\ p_{n-1} \\ p_n \end{bmatrix} = [r_1, \ldots, r_m]$$

Where m is the number of criteria and n is the number of alternatives. p_{ij} (i=1,…,m; j=1,…,n) represents relative weight of the priority for the ith alternative with respect to the jth criterion. p_j (j=1,…,n) represents the relative weights of priorities for the jth criterion. R is a result vector, and $max(r_i)\ (r = 1,..., m)$ is the best ranking alternative for the overall satisfaction of all criteria.

3.4 Recycling Method Knowledge Base

Recycling Method Knowledge Base (RMKB) is an important part in the model. It contains recycling facility information with cost data, EDIP assessment tables, and specific recycling methods for each collection bin. The research on RMKB is still undergoing. The decision rules for each collection bin are being collected. Currently specific recycling methods for two collection bins – PCB and Plastics – are explored. The environmental impact data for the recycling methods are also collected based on the EDIP method. The detailed discussion is found in Section 2.

The contents of recycling facility data are under constructed. Generally, it include:

- Facility basic information, such as facility ID, name, type, address, contact person;
- Facility treatment information, such as treatment capacity, distance from the Pantex Plant, quote prices for specific collection bins, and EPA certified information.
- Environmental impact information, such as global warming, ozone depletion, acidification, eutrophication data for specific treatment methods in the recycling facility.

The knowledge representation for the above information is a systematic way of codifying what knowledge exists about specific subject area or domain. It deals with the structuring, encoding, and storing of information so that its attributed meaning is clear. In the model, we use the simple knowledge representation method called IF-THEN action. Such rules are used to capture the response to the presence of familiar patterns that characterize much of human thinking. When an expert generates a recycling plan for a specific collection bin with specific material contents, he/she must consider many factors influencing decision-making. The major factors are recycling cost, recycling facility capacity, environmental impact issues, and dispatch time. Like human experts, RMKB should connect each recycling bin with specific recycling methods in specific recycling facilities. The connection is made by an object called "Distribution." Figure 6 shows the conceptual idea of the connection. For each collection bin, there are many possible distribution objects. Also each facility contains many distribution objects. The optimal recycling report will be generated based on this many-one-many relation.

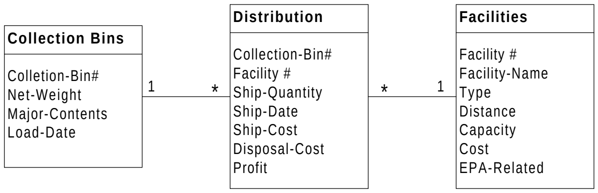

Figure 6: O-O Conceptual Illustration for Recycling Report Generation

In the next section, data collection for the proposed model is conducted. Two examples, PCB and plastics, are studied.

4. PCB SCENARIO

4.1 Material Issues

There are a large number of environmental issues involved in PCB treatment processes due to their complicated mixture of chemical and material substances. The composition of PCB includes three major material classes: organic (24.8%), ceramic (47.6%) and metal (27.6%).

- **Organic:** Organic material is primarily plastic with a content of flame retardant that often causes environmental problems. They include plastic C-H-O polymers, polypropylene, polysters, polychlorinated biphenyls (in some capacitors), brominated flame retardants, and paper.
- **Ceramic:** PCBs contain alumina, silica , barium titanate and cone glass, which cause little environmental problems.
- **Metals:** PCBs include a variety of metal materials including: Pa, Ti, Ag, Pt, Cu, Al, Zn, Fe, Pb, Sn, Hg, Cr, Be, Sb, As, and Ni. Tantalum is found in tantalum capacitors, Gallium is found in gallium-arsenide chips. Mercury is found in mercury chips. Antimony is found in flame retardant materials. Solders and connectors are rich sites for gold, silver, platinum and palladium. Traces of silver are also contained in IGBT power modules, aluminum electrolytic capacitors, microprocessors, key switches and LEDs. Gold is also found in LEDs, key switches, ASICs and microprocessors.

The **major environmentally unfriendly materials** in PCBs include Hg, antimony, cadmium, chromium, arsenic, and beryllium. Hg is used in switches and capacitors. Antimony, used in flame-retardants, is poisonous. SMD chip resistors, ceramics, infrared detectors, semiconductors contain cadmium. Metal frame resistors, bridge rectifiers, relay switches and stainless steel contain varying amounts of chromium. Arsenic is found in relatively large concentrations in optocouplers, power amplifiers, power transistors and LEDs. Beryllium is found as BeO or Be-Bronze in key switches, signal relays, volume controllers, high frequency transistors and UHF-amplifiers.

4.2 PCB Recycling from Metal Recovery Points of View

Metal recovery of PCB scraps is the most important issue to recycle PCB. Iron, Aluminum, Lanthanum, Cerium and cobalt are not very important from recovery point of view. It is economical to concentrate the recovery efforts on recovery of Platinum, Palladium, Gold, Nickel, Silver, Tantalum, Cadmium, Antimony, Copper and Tin. It is not yet economical to recover Tantalum, Cadmium, Antimony and Beryllium. Thus, it is very beneficial to know which parts of a PCB are high in concentration of which elements. Table 5 gives the relative approximate composition of principal metals/materials in PCB scrap.

4.3 PCB Recycling (Metal Recovery) Methods

The recycling of PCB is mostly equivalent to recovery of metals. Three steps are followed through for metal recovery, including pre-treatment, separation/concentration, and refining**.**

4.3.1 Pre-Treatment

This is primarily a weight reduction and homogenization step. By homogenizing the material, it is possible to get a representative sample for assessing the metals content. This serves as basis for calculation of scrap prices. It includes incineration/crushing and mechanical treatment.

Table 5: Relative Approximate Composition of Principal Metals in PCB Scraps

Metal/Material	Kg/Ton of Scrap	Metal/Material	Kg/Ton of Scrap
Ag	0.639	La	0.029
Al	280	Mo	0.1555
Au	0.566	Ni	11
Be	0.089	Pb	22
Cd	0.395	Pd	0.124
Ce	0.051	Pt	0.037
Co	0.083	Sb	4.5
Cu	143	Sn	20
Fe	45	Ta	0.192
Hg	0.009		

- **Crushing/Incineration** is a process combination used for waste reduction and homogenization. The PCB is crushed in size of 1 cm to 2 cm. Shredders are also used to separate ferrous from non-ferrous metals and non-metals. Organic material is removed through incineration. The temperature is about 400 to 800 degree celsius. Calcium carbide, a ‘ sticky ‘ slag may form. The fumes may contain halogens and volatile metals. The metal containing ash is then crushed else it would float at top of the melt.
- **Mechanical treatment** as e.g. shredding is also often used as pre-treatment, which uses shredders in sequences of processes that separate the material into ferrous and non-ferrous metal and a mixed plastics and ceramics fraction.

4.3.2 Separation/Concentration

It is characterized by a certain separation of the metals and the possible concentration of them. The common methods include:

- ***Stripping***: The fingers of contact are leached off. The noble metals are thus brought into the concentrate. Thiorea and cyanides are used as leachants. Gold, platinum and silver are brought into the solution by aqua regia. Niric acid brings palladium and silver in the solution. Cyanide is a good option, but the disadvantage is that it is poisonous. The disadvantage of stripping is that the metal recovery is low since metal reaction occurs only on the surface. About 90% gold is recovered. Use of leachant is economic and the process does not cause any environmental problem.
- ***Dissolution of substrate***: The base metal substrate is etched away to facilitate the recovery of noble metals. First Al is etched away with NaOH, then Ni with dilute sulfuric acid and then Ni and Cu with concentrated sulfuric acid at 150 degree centigrade. Advantages include high recovery rates (up to 100% has been reported). It is a relatively clean and efficient process. Materials like plugs and contacts with relatively high gold content are well suited to this process. Disadvantages include high volumes of base metal solutions have to be treated.
- ***Precipitation***: The desired substance is precipitated from solution as solid precipitate. Gold is precipitated with sodium sulfite, sodium bisulfite or NaCl. Silver is precipitated with a chloride. Palladium and Pt with ammonium chloride. Silver and palladium in Cu rich solutions of nitric acid are selectively precipitated by potassium thiocyanide and potassium cynoferrate. In these precipitates, noble metal rich powder may be obtained for further drying.

- ***Cementation***: It is the simultaneous reduction and oxidation of another metal that goes into the solution. More noble metals are cementated by less noble ones. Cu-Noble metal rich precipitates result from cementation by steel scrap.
- ***Ion-exchange***: Selective separation can be achieved. Selective collection of Ag, Au, Pt and Hg is obtained in a cation exchanger. The exchanger is then incinerated to obtain the metals of high grade.
- ***Salt melt electrolysis***: Used for recovering Al. It is not recoverable by conventional water based electrolysis since it is very reactive. Disadvantages are high electricity consumption, high cost large amounts of chlorides and fluorides are emitted.
- ***Water based electrolysis***: Using cementation, ferri ions are reduced to ferro and copper is bought into the solution. The reverse process of electrolysis will recover copper from the solution and ferri ions are regenerated.

4.3.3 Refining

Refining is the process of obtaining pure marketable metals from the concentration. These are hydrometallurgical or electrochemical processes. Two hydrometallurgical refining processes are precipitation and extraction. Electrolysis method is used for the final refining of copper, aluminum and silver.

Other PCB recycling methods are stated following:

- **Recycling of PCBs by secondary copper smelters**: It recovers Cu, some base metals and Au, Ag, Pt and Pa. Total metal value of computer PCB scrap is about US $9,000 per ton. The secondary copper smelters usually use Knudsen Process to recover noble metals. It is a shaft furnace and converter technique followed by anode casting, electrolytic copper refining and cathode casting. About 10% coke is added to a mixture containing 30% copper. Melting separates the base metals like Ni, Pb, Sn, Fe and Al from Cu. Output contains about 80% copper and has about 90% of all Ag and about 100% of all Au.
- **Valorization of PCB Laminates**: PCB laminates with their content of thermosets, fillers and flame retardant pose a complicated problem to recyclers. The most common treatment is energy recovery from pyrolysis of laminates. The commercially available pyrolysis process is called PYROCOM Process. The temperature is about 700 degree centigrade. Two separate streams of materials result – one of the stream contains volatile HCl, HBR, water, CO, carbon dioxide and higher hydrocarbons such as phenol and carbohydrates; other stream consists of ceramics, glass fibres and metals. The subsequent residue is separated into metal fractions, glass fibres and combustible coke. Gaseous fraction is quenched with water. In a filter, the volatile materials are separated from metal dust. The metal dust is refined and then treated for recovery of individual metals. The gaseous mixture is cooled further and higher order carbon compounds are removed; thus, the emission consists of unpolluted air. The carbon compounds are burned for metal recovery.

4.4 PCB Recycling Scenarios and Their Environmental Impacts

Traditionally, PCB recycling is based on scenarios according to PCB material contents. In this report, three recycling scenarios including copper, lead, and tin scenario are classified and researched based on the contents of PCB scraps. For each scenario, different recycling methods are given and assessed using the EDIP method.

Table 6: Waste Generation, Environmental Impacts and Resource Drawn for the Copper Scenario

Environmental Impact/Resource Draw	in mPE
Slag & Ash	1149.718
Global Warming	90.099
Acidification	50.254
Photochemical Ozone Creation, high NOx	39.631
Photochemical Ozone Creation, low NOx	49.277
Eutrophication	19.923
Lignite	109.175
Natural Gas	145.521
Crude Oil	180.791
Coal	152.652
Aluminum	2.271
Iron	1089.209

mPE = milli person equivalent

4.4.1 The Copper Scenario

The traditional copper recycling scenario consists of the Knudsen process with subsequent anode casting, electrolytic refining, and cathode casting. By using EDIP method, Table 6 shows the normalized results for the copper scenario.

In the table, the rather large contribution to the waste category slag and ash comes mainly from the large amount of slag from the shaft furnace, which in turn is governed by the rather large iron input to the system.

Table 7 shows the percentage contributions to the total waste generation and environmental impacts for all inputs and outputs of the copper scenario.

- **Slag**: Shaft furnace is the major contributor to slag. It occurs because of Al & Fe in PCB and not because of the Fe which is added. Glass and ceramic also contribute to a good deal of slag. Fe is added because it contributes in a big way to heat generated.
- **Global Warming**: The use of direct/indirect fossil fuel results in global warming.
- **Acidification**: Primarily due to use of direct/indirect fossil fuel, which results in SO_2 emission. Also, HBr and other halides result in acidification. They are released during incineration.
- **Photosmog**: If lignite is used in production of electricity, large-scale photosmog may result.
- **Eutrophication**: Lignite combustion and organic material (from PCB) incineration.
- **Converter Operation**: It receives black copper. The alloy scrap has to be melted. Fe is also added as slag. It converts impurities into slag or flue dust oxide. Excess of ambient air is blown into it.
- **Anode Furnace Operation**: First pyrometallurgical refining. 100 kg of fuel oil/ton of material input. Most of the Cu ends up in anode.
- **Electrolytic Refining**: Impure copper (Cu anode) ends up as Cu cathode. The lectrolyte is sulphuric acid. Small amount of sulphuric acid can treat a large amout of copper since it is recyclable with good effect.

Table 7: Percentage Contribution to Waste Generation and Environmental Impact

% share in impact	Slag & Ash	Volume Waste	Global Warming	Acidification	Photosmog low NOx	Photosmog high NOx	Eutrophication
SHAFT FURNACE							
PCB organics	11.84	6.7	35.42	0	0	0	25.97
Coke pre-combustion	0	0.54	0.45	0.37	0	0	0.29
Coke combustion	0.08	0	16.45	0.92	0	0	0
Lime	0.12	21.72	4.47	2.1	0.15	0.11	1.26
Quartz	0	0.19	0.33	0.37	0.42	0.38	0.73
Austrian electricity	0.03	2.09	0.85	1.45	2.73	2.74	1.27
Slag	86.82	0	0	0	0	0	0
CONVERTER							
Fuel oil precombustion	0.01	0.18	0.51	0,89	0.03	0.03	1.21
Fuel oil combustion	0	0.1	5.39	0.34	0.07	0.04	2.53
Iron	0	0	0	0	0	0	0
Austrian electricity	0.17	11.93	4.82	8.26	15.59	15.64	7.22
ANODE CASTING							
Fuel oil precombustion	0.04	0.91	2.58	4.44	0.15	0.13	6.07
Fuel oil combustion	0	5.2	26.96	1.67	0.34	0.21	12.67
Austrian electricity	0	0.24	0.1	0.17	0.32	0.32	0.15
ELECTROLYSIS							
Fuel oil precombustion	0.01	0.17	0.49	0.84	0.03	0.02	1.15
Fuel oil combustion	0	0.1	5.11	0.32	0.07	0.04	2.4
Austrian electricity	0.46	32.27	13.05	22.34	42.16	42.19	19.52
CATHODE CASTING							
Austrian electricity	0.41	29.05	11.75	20.1	37.94	38.06	17.57

- **Anode Rest Remelt**: 16% of the anode is left untreated it is recycled again into electrolytic refining; thus, about 19% of copper is remelted in the anode furnace in steady-state operations.

4.4.2 The Lead Scenario

A smelter refining galena is the best for treating a complex mixture of PCB and Pb alloy scrap. Kaldo furnace is in major use. A copper-rich dross, antimony, tin-salt mixture and a noble metal concentrate are the resulting streams. The Cu ich dross is treated by Cu smelter. Only the treatment of tin rich stream and Sb stream is important from the environmental viewpoint. The main draw on energy resource is on crude oil and coal. Because on the type of draw on electricity, photosmog impact is low. Table 8 shows the normalized results for the lead scenario.

Table 9 shows the percentage contributions to the total waste generation and environmental impacts for all inputs and outputs of the lead scenario.

- **Slag & Ash**: PCB glass, ceramics; minor contribution of NaOH and German electricity. Swedish electricity is primarily based on water power and nuclear energy therefore it does not contribute to it.
- **Volume Waste**: Comes from extraction of NaOH from rock salt. Minor contribution from generation of German electricity from lignite.

Table 8: Waste Generation, Environmental Impacts and Resource Drawn for the Lead Scenario

Environmental Impact/Resource Draw	in mPE
Slag & Ash	243.359
Global Warming	102.434
Acidification	53.592
Photochemical Ozone Creation, high NOx	3.505
Photochemical Ozone Creation, low NOx	3.353
Eutrophication	18.664
Lignite	58.182
Natural Gas	49.3
Crude Oil	319.132
Coal	125.79
Aluminum	4.522
Iron	0.599

Table 9: Percentage Contribution to Waste Generation & Environmental Impact

% share in impact	**Slag & Ash**	**Volume Waste**	**Global Warming**	**Acidifi-cation**	**Photosmog low Nox**	**Photosmog high Nox**	**Eutroph-ication**
KALDO FURNACE							
PCB organics combustion	55.94	0	5.9	33.21	0	0	22.72
Swedish electricity	0.08	2.48	0.29	0.55	1.95	1.4	0.36
Coke pre-combustion	0.02	0.69	0.19	0.35	0.06	0.05	0.31
Coke combustion	0.38	0	14.6	0.87	0	0	0
Fuel oil pre-combustion	0.03	0.17	0.32	0.59	0.25	0.25	0.91
Fuel oil combustion	0	0.09	3.34	0.22	0.57	0.42	1.9
SiO2 (Quartz)	0	0.01	0.01	0.01	0.14	0.15	0.02
CaO (lime)	0.06	2.89	0.4	0.2	0.18	0.15	0.14
Slag	38.66	0	0	0	0	0	0
PYROMETALLURGICAL REFINING							
Sulphur	0	0.02	0.03	0.01	0.03	0.03	0.01
NaNO3	0.03	0.18	3.75	4.51	74.21	78.87	11.14
NaOH	3.02	66.31	8.68	11.18	5.07	4.6	8.84
Primary Zn	0.08	9.26	0.5	0.63	0.33	0.29	0.47
Fuel oil pre-combustion	0.11	0.64	1.23	2.27	0.95	0.98	3.53
Fuel oil	0	0.36	12.93	8.55	2.22	1.61	7.37
German electricity	1.12	10.33	1.68	1.12	1.1	0.94	1.53
IGNOT CASTING							
Fuel oil pre-combustion	0.01	0.04	0.08	0.13	0.06	0.06	0.02
Fuel oil combustion	0	0.02	0.73	0.49	0.13	0.09	0.42
ANTIMONY & TIN REFINING							
Fuel oil pre-combustion	0.34	2.03	3.92	7.21	3.09	3.1	11.22
Fuel oil combustion	0	1.15	41.03	27.14	7.04	5.12	23.4

- **Global Warming**: Burning of fossil fuel and incineration of organics. Also, NaOH and fuel oil contribute to global warming in a major way.
- **Acidification**: Since Kaldo furnace has an SO2 cleaning facility, the flue gas is almost unpolluted air. HBr is the main cause of acidification in Sn scenario.
- **Photosmog**: only in minor quantities. It comes in a major way from combustion of oil gas in heavy machinery.
- **Eutrophication**: No_x emissions from incineration and burning of fossil fuel.
- **Al & Fe**: The draw on Al & Fe is negligible in mPE.
- **Zn**: The draw on Zn is 100%.

4.4.3 The Tin Scenario

The methods discussed are not suitable for the recovery of tin from complex mixtures. There is no draw on zinc and only minor draw on the aluminum and iron resources. Photosmog contributions are relatively very low. This is because there is no gas oil burning mineral extraction. Also, the slag is less than what is generated in copper scenario. Table 10 shows the normalized results for the tin scenario.

Table 11 shows the percentage contributions to the total waste generation and environmental impacts for all inputs and outputs of the tin scenario.

- **Slag and Ash**: A major contributor is smelting operation; the amount of non-recoverable metals (Fe, Al, etc.) in the mix is a major contributor.
- **Volume waste**: The generation of electricity is major contributor. Due to extraction of coal.
- **Global Warming**: Due to fossil fuel burning and combustion of PCB organics.
- **Acidification**: Due to burning of fossil fuel and organics combustion. It can be greatly reduced if the exhaust is treated for SO2.
- **Photosmog**: Total contribution is very low.
- **Eutrophication**: The major contribution is due to emission of Nox and combustion of PCB inorganics.
- **Lignite**: Total draw is very low and is only linked with extraction of lime and quartz.
- **Natural Gas**: Due to gas waste in crude oil extraction and generation of electricity.
- **Coal**: For coke production and energy generation.

Table 10: Waste Generation, Environmental Impacts and Resource Drawn for the Tin Scenario

Environmental Impact/Resource Draw	**in mPE**
Slag and Ash	262.382
Volume Waste	18.224
Global Warming	98.543
Acidification	58.91
Photochemical Ozone Creation, Low Nox	0.694
Photochemical Ozone Creation, High Nox	0.63
Eutrophication , air	13.81
Lignite	0.07
Natural Gas	52.467
Crude Oil	158
Coal	308.77
Aluminum	2.683
Iron	0.061
Zinc	0

Table 11: Percentage Contribution to Waste Generation and Environmental Impact

% share in impact	**Slag and Ash**	**Volume Waste**	**Global Warming**	**Acidifi-cation**	**Photosmog low Nox**	**Photosmog high Nox**	**Eutrophication**
FLAME FURNACE SMELTING							
PCB organics combustion	51.88	0	6.13	30.21	0	0	37.46
Coke pre-combustion	0.03	0.82	0.79	0.61	0.52	0.54	0.8
Coke combustion	0.66	0	28.73	15	0	0	0
Fuel oil pre-combustion	0.2	0.8	2.57	4.12	9.4	10.84	9.54
Fuel oil combustion	0	0.45	26.84	15.53	21.41	17.94	19.9
SiO2 (Quartz)	0	0.03	0.05	0.05	3.95	4.86	0.18
CaO (lime)	0.19	6.08	1.42	0.62	2.88	2.84	0.18
Electricity world average	1.26	33.29	6.89	9.37	21.35	21.84	10.32
SLAG SMELTING							
Coke pre-combustion	0.01	0.32	0.31	0.24	0.2	0.22	0.32
Coke combustion	0.26	0	11.38	5.94	0	0	0
Electricity world average	0.26	6.7	1.39	1.88	4.32	4.4	2.05
Slag	42.72	0	0	0	0	0	0
ANODE CASTING							
Fuel oil pre-combustion	0.01	0.04	0.12	0.23	0.42	0.52	0.47
Fuel oil combustion	0	0.02	1.31	0.76	1.05	0.87	0.98
ELCTROLYSIS							
Electricity world average	1.94	51.38	10.63	14.47	32.94	33.72	15.93
CATHODE CASTING							
Fuel oil pre-combustion	0.01	0.04	0.12	0.2	0.46	0.52	0.47
Fuel oil combustion	0	0.02	1.31	0.76	1.05	0.87	0.98
TOTAL (~)	100	100	100	100	100	100	100

5. PLASTICS SCENARIO

The major problem to recycle plastics is plastic separation. While most thermoplastic materials are recyclable, mixtures are unacceptable. Because of the incompatibility of various plastics with flame-retardant materials, the plastic parts dismantled from nuclear warhead should be identified and separated firstly in order to recycle them. Plastic recycling processes can be divided into the following areas according to the output from the process:

- Material recycling of sorted plastic;
- Material recycling of commingled plastic;
- Chemical or resource recycling of plastics.

Plastic recycling can also be described by the size of plastic used in the recycling process. Processes can be divided into macro, micro and molecular level. Macro level recycling is reuse where the plastic is reused in its original shape. Plastic recycling at micro level is where the size of plastic waste is reduced to very small pieces, called "chips". Then chips are recycled either as pure plastic segments or commingled plastic.

5.1 Recycling of Sorted Plastic

The procedures of recycling of sorted include: marking of plastics, sorting, size reduction, separation, washing, drying, pellet production and energy consumption by material recycling. Among them, separation process is the most important step.

Different separation processes are identified based on physical and chemical properties of the plastic chips. The separated plastics can be classified into PP (Polypropylene), LDPE (Low Density Polyethylene), HDPE (High Density Polyethylene), PET (Polyethylene Teraphtalate), PS (Polystyrene) and PVC (Polyvinyl Chloride). The chips are classified by their physical properties. The following physical or chemical properties can be used in separation of plastic chips:

- Density
- Surface properties
- Magnetic properties
- Electrostatic properties
- Dissolution properties
- Heat properties
- Infrared spectroscopy

- **Sink Float Separator**: Plastic chips float at 0.1-0.4m/s. 98% pure polyolefins fraction is obtained from mixture of Polyolefins (lighter) and Polypropylene in water. Low Density Polyethylene (LDPE) and High Density Polyethylene (HDPE) can be separated in a water-alcohol solution. Polystyrene (PS) and PVC by a salt-water solution. The problem occurs when the densities are very close or are overlapping.
- **Hydrocyclone Separator**: Uses centrifugal force that is much higher than gravity. Higher purity is obtained. The low-density fraction stays in the middle. Resin purity as high as 99.9% is obtainable.
- **Super-Critical Fluids as Variable Density Separators**: One of the problem with conventional systems is the high viscosity of fluids. Supercritical fluid has low viscosity and temperature and pressure above the critical limit and exhibit physical properties intermediate to those of liquid & gases. Near critical fluids (temperature below critical temperature but pressure above the critical pressure) have fluid like densities and gas-like-viscosity. Near-critical CO_2, SF_6, $CO_2 - SF_6$ mixtures can attain densities which span the range for many plastics at ambient temperature and 0.077-0.73 Pa. It is possible to separate a mixture of PP-

LDPE, PP-HDPE, LDPE-HDPE and PVC-PET to 100% purity. Pressure regulation results in the right density. The system is not in use on commercial scales.

- **Separation by Surface Properties**: Differential ability of various plastics to attract water. Specific plastics are made hydrophobic and some are made hydrophilic by addition of chemicals. Gas is vent into the floating chamber. Hydrophobic get separated into gas bubbles that float on the liquid. PE, PVC-hard, PVC-soft plastics have thus been separated with purity of 92-99%.
- **Separation by Magnetic Properties**: Mixture of plastics and ferro-magnetic materials is passed through a magnetic built. Paramagnetic materials can be separated using an AC current separator. Paramagnetic materials thus become temporarily magnetized and are then separated from plastics.
- **Separation by Electrostatic Properties**: Plastic chips are charged. It disappears soon or remains for longer time depending on the type of plastic. Addition of certain chemicals can enhance the difference in electrostatic conductance between particular plastics.
- **Separation by Dissolution Properties**: Different plastics dissolute at various temperatures in particular solution. If xylene is the solution then PS dissolves at 25 degree Celsius. LDPE dissolves at 75 degree Celsius, HDPE dissolves at 105 degree Celsius and PP at 120 degree Celsius. Even PET and PVC can be separated.
- **Separation by Heat Properties**: The surface of plastics is heated by a carbon dioxide laser for about 0.001 seconds. Different plastics have different heat distribution. A thermo-camera takes the pictures & heat distribution is compared with a 'master plan.' The system can be well adapted to sorting plastic pieces of 25sq. cm. or more. The disadvantage is that the pieces must be minimum of 5x5sq. cm. The system is not in use on commercial scales.

Washing of Plastics dissolves and separates dirt, fluid, etc. It follows the following steps:

1. Soaking or dissolution: done in a big stir tank.
2. Loosening dirt from plastic by kneading or by using a device called friction or turbo washer.
3. Separating dirt from plastic: in a hydrocyclone.

Mechanical drying is inexpensive but may be ineffective. Strain screw centrifuge continuously dries the moist plastic. Water leaves in the horizontal direction. Thermal drying is done using pneumatic conveyors with heated air. It reduces the moisture to <1% by wt. (not sufficient for **PA** and **PET** which require moisture <0.1%; they are dried in dry air silos for 2-6 Hr.)

5.2 Recyling of Commingled Plastics

The recycling of commingled plastics may include following methods:

- **Klobbie-Based Intrusion Process**: An extruder is used to soften the plastic mixture. Then the plastics are forced into the mould. The mould may be passed through a cooled water tank.
- **Continuous Extrusion**: for plastic sheeets/laminates.
- **Reverzer Process**: Plastic is softened in a hopper and mixed in a screw. It may be fed into thin mould under low pressure and thus thin, inexpensive sheets can be obtained. Or, it may be extruded into long linear moulds at low pressures. Or it may be compression moulded. 50-70% plastic is melted by friction. It is then pressed

through a heated extruder die. Then, it is passed through moulds of desired shape.

5.3 Chemical or Resource Recyling of Plastics

Chemical or resource recycling is recycling where the polymer chains are degraded to smaller chains. The recycling processes are divided in processes where the output is the basis material for the polymer and processes where the output is a mix of hydrocarbons different from the basis material.

- **Hydrolysis**: Polymers containing carbonyl groups [PET, PUR (polyeurethane) and PA (polyamide)] All polymers produced by polycondensation or polyaddition can be recycled by hydrolysis. Hydrolysis of PET is done at 150-250 degree Celsius. Sodium acetate - catalyst. Output products - terepthalic acid and ethylene glycol (they are used for production of virgin PET)
- **Alcoholysis**: According to J. Scheimann, alcoholysis is the only practical method of recycling PUR, PA and PET. It is carried with methanol at 160-240 degree Celsius. And pressure of 20-70Pa. Outputs are dimethyl terepthalate and ethylene glycol that are used for production of virgin PET.
- **Glycolysis**: Transesterification reaction occurs and PET is broken into low molecular wt. segments. Glycolysis of PUR can yield a mixture of polyols, which can be reused in production of virgin PUR.
- **Plastic Recycling by Pyrolysis**: Waste is treated to about 700 degree celsius in absence of oxygen. Output – pyrolysis oil and gas. This can be used for heating or petrochemical refining. Fluidized Bed Pyrolysis: A sand bed through which gas (pyrolysis gas) is blown . Plastic waste is fed from top. Pyrolysis gas rises up and is distilled out. Solid waste is removed from bottom of the bed. Uniform pyrolysis product is achieved by low temperature gradient. It results in low dispersion of the product. The disadvantage is that the waste should be small sized. Rotary Kiln Pyrolysis: Plastic waste is fed into a heated kiln. Output – solid waste and pyrolysis gas. The solid fraction is land-filled. The advantage is the high output – up to 6-ton/Hr. Relatively large pieces may be treated. Disadvantages are the high temperature gradients that result in large dispersions of structures of molecules in the pyrolysis product.

5.4 Ecoprofiles for Various Plastic Recycling

According to different material contents of plastic recycling, environmental and resource impacts are calculated based on EDIP method. Table 12 depicts the environmental and resource impacts for disposal of low-density polyethylene film.

Table 12: Environmental and Resource Impacts for Disposal of LDPE Film

Normalization	**Material recycling**	**Pyrolysis**	**Pyrolysis with heat recovery**	**Incineration with heat recovery**	**Landfill**
Environmental impacts	PE*year per kg recycled plastics	PE*year per kg recycled plastics	PE*year per kg recycled plastics	PE*year per kg recycled plastics	PE*year per kg recycled plastics
Global warming	$-53*10^{-6}$	$120*10^{-6}$	$29*10^{-6}$	$-10.6*10^{-6}$	0
Stratospheric ozone depletion	0	0	0	0	0
Acidification	$-105*10^{-6}$	$-1.69*10^{-6}$	$-30*10^{-6}$	$-105*10^{-6}$	0
Nutrient enrichment (N)	$-14.8*10^{-6}$	$38*10^{-6}$	$25*10^{-6}$	$0.97*10^{-6}$	$45*10^{-6}$
Nutrient enrichment (P)	$80*10^{-6}$	$82*10^{-6}$	$82*10^{-6}$	$82*10^{-6}$	$82*10^{-6}$
Photochemical ozone formation	$-319*10^{-6}$	$46*10^{-6}$	$19*10^{-6}$	$-145*10^{-6}$	0
Solid waste	$322*10^{-6}$	$368*10^{-6}$	$280*10^{-6}$	$-281*10^{-6}$	$2174*10^{-6}$
Resource impacts					
Crude oil	$-1540*10^{-6}$	$-971*10^{-6}$	$-1010*10^{-6}$	$-154*10^{-6}$	0
Natural gas	$-2962*10^{-6}$	$-1149*10^{-6}$	$-1770*10^{-6}$	$-2438*10^{-6}$	0
Pit coal	$261*10^{-6}$	$363*10^{-6}$	$240*10^{-6}$	$-452*10^{-6}$	0

From the above table, we can conclude the processes listed in decreasing order of their ability to conserve resources:

> Material recycling > pyrolysis + heat recovery > incineration + heat recovery > pyrolysis > landfilling

In addition, the processes are listed in decreasing order of their being environmentally friendly:

> Material recycling > incineration + heat recovery > pyrolysis + heat recovery > pyrolysis > landfilling

Material Recycling is the most environmentally sound method for disposal of LDPE film since it has the lowest of per person equivalent of all environmental impact except for acidification and solid waste impact. Solid waste impact is local since plastics do not decompose. It is least for incineration. Also it thereby saves fuel. Material Recycling and incineration with heat recovery are on the same level for acidification. Landfilling has the highest impact except for global warming and photochemical ozone formation.

Table 13 shows the environmental and resource impacts for disposal of high-density polyethylene film.

According to the above table, material recycling is the most resource saving process, the second is incineration, the third is pyrolysis and the least resource saving process is landfilling.

Table 14 shows the environmental and resource impacts for disposal of polypropylene. From the table, the material recycling process is the most environmentally sound way to disposal of PP, as this process has the lowest person equivalents for all environmental impacts except for the less important solid waste impact.

Table 15 shows the environmental and resource impacts for disposal of polypropylene terephthalate.

Table 13: Environmental and Resource Impacts for Disposal of HDPE Film

Normalization	**Material recycling**	**Pyrolysis**	**Incineration with heat recovery**	**Landfill**
Environmental impacts	PE*year per kg recycled plastics	PE*year per kg recycled plastics	PE*year per kg recycled plastics	PE*year per kg recycled plastics
Global warming	$-18.1*10^{-6}$	$120*10^{-6}$	$-10.6*10^{-6}$	0
Stratospheric ozone depletion	0	0	0	0
Acidification	$-82*10^{-6}$	$-1.69*10^{-6}$	$-105*10^{-6}$	0
Nutrient enrichment (N)	$-49*10^{-6}$	$-7.5*10^{-6}$	$-44*10^{-6}$	0
Nutrient enrichment (P)	$0.45*10^{-6}$	0	0	0
Photochemical ozone formation	$-319*10^{-6}$	$46*10^{-6}$	$-145*10^{-6}$	0
Solid waste	$338*10^{-6}$	$368*10^{-6}$	$-281*10^{-6}$	$2174*10^{-6}$
Resource impacts				
Crude oil	$-1333*10^{-6}$	$-971*10^{-6}$	$-154*10^{-6}$	0
Natural gas	$-2377*10^{-6}$	$-1149*10^{-6}$	$-2438*10^{-6}$	0
Pit coal	$325*10^{-6}$	$363*10^{-6}$	$-452*10^{-6}$	0

Table 14: Environmental and Resource Impacts for Disposal of PP

Normalization	Material recycling	Pyrolysis	Incineration with heat recovery	Landfill
Environmental impacts	PE*year per kg recycled plastics	PE*year per kg recycled plastics	PE*year per kg recycled plastics	PE*year per kg recycled plastics
Global warming	$-33*10^{-6}$	$120*10^{-6}$	$-16.4*10^{-6}$	0
Stratospheric ozone depletion	0	0	0	0
Acidification	$-116*10^{-6}$	$-1.23*10^{-6}$	$-107*10^{-6}$	0
Nutrient enrichment (N)	$-49*10^{-6}$	$-7.3*10^{-6}$	$-45*10^{-6}$	0
Nutrient enrichment (P)	$-9.1*10^{-6}$	0	0	0
Photochemical ozone formation	$-150*10^{-6}$	$47*10^{-6}$	$-148*10^{-6}$	0
Solid waste	$340*10^{-6}$	$368*10^{-6}$	$-287*10^{-6}$	$2174*10^{-6}$
Resource impacts				
Crude oil	$-2034*10^{-6}$	$-1115*10^{-6}$	$-157*10^{-6}$	0
Natural gas	$-1223*10^{-6}$	$-890*10^{-6}$	$-2478*10^{-6}$	0
Pit coal	$356*10^{-6}$	$363*10^{-6}$	$-460*10^{-6}$	0

From the table, it is seen that the material recycling process is the most environmentally sound way to disposal of PET, as this process has the lowest person equivalents for all environmental impacts except for the less important solid waste impact. The environmental impacts also indicate that incineration is a more environmental sound way to dispose PET than pyrolysis. Also from consumption of resource, material recycling is the most resource saving process, the second is pyrolysis, the third is incineration, and the least is landfilling. It has to be added that the difference between pyrolysis and incineration is so small that the uncertainty of the calculations will make it impossible to determine which of the processes save most resources. Table 16 shows the environmental and resource impacts for disposal of polystyrene.

From Table 16, it is seen that the material recycling process is the most environmentally sound way to disposal of PET, as this process has the lowest person equivalents for all environmental impacts except for the less important solid waste impact. The environmental impacts also indicate that pyrolysis is a more environmentally sound way to dispose PS than incineration with heat recovery. From the evaluated consumption of resource, material recycling is the most resource saving process, the second is pyrolysis, the third is incineration, and the least is landfilling.

Table 15: Environmental and Resource Impacts for Disposal of PET

Normalization	**Material recycling**	**Pyrolysis**	**Incineration with heat recovery**	**Landfill**
Environmental impacts	PE*year per kg recycled plastics	PE*year per kg recycled plastics	PE*year per kg recycled plastics	PE*year per kg recycled plastics
Global warming	$-183*10^{-6}$	$122*10^{-6}$	$-5.0*10^{-6}$	0
Stratospheric ozone depletion	0	0	0	0
Acidification	$-214*10^{-6}$	$-1.17*10^{-6}$	$-74*10^{-6}$	0
Nutrient enrichment (N)	$-106*10^{-6}$	$-6.2*10^{-6}$	$-30*10^{-6}$	0
Nutrient enrichment (P)	$-6.9*10^{-6}$	0	0	0
Photochemical ozone formation	$-755*10^{-6}$	$52*10^{-6}$	$-104*10^{-6}$	0
Solid waste	$310*10^{-6}$	$368*10^{-6}$	$-186*10^{-6}$	$2174*10^{-6}$
Resource impacts				
Crude oil	$-1823*10^{-6}$	$-952*10^{-6}$	$-111*10^{-6}$	0
Natural gas	$-1676*10^{-6}$	$-906*10^{-6}$	$-1768*10^{-6}$	0
Pit coal	$225*10^{-6}$	$364*10^{-6}$	$-321*10^{-6}$	0

Table 16: Environmental and Resource Impacts for Disposal of PS

Normalization	**Material recycling**	**Pyrolysis**	**Incineration with heat recovery**	**Landfill**
Environmental impacts	PE*year per kg recycled plastics	PE*year per kg recycled plastics	PE*year per kg recycled plastics	PE*year per kg recycled plastics
Global warming	$-93*10^{-6}$	$29*10^{-6}$	$44*10^{-6}$	0
Stratospheric ozone depletion	0	0	0	0
Acidification	$-379*10^{-6}$	$-269*10^{-6}$	$-96*10^{-6}$	0
Nutrient enrichment (N)	$-127*10^{-6}$	$-82*10^{-6}$	$-40*10^{-6}$	0
Nutrient enrichment (P)	0	0	0	0
Photochemical ozone formation	$-425*10^{-6}$	$206*10^{-6}$	$-130*10^{-6}$	0
Solid waste	$262*10^{-6}$	$321*10^{-6}$	$-254*10^{-6}$	$2174*10^{-6}$
Resource impacts				
Crude oil	$-1509*10^{-6}$	$-1488*10^{-6}$	$-142*10^{-6}$	0
Natural gas	$-3398*10^{-6}$	$-1700*10^{-6}$	$-2247*10^{-6}$	0
Pit coal	$377*10^{-6}$	$344*10^{-6}$	$-415*10^{-6}$	0

Table 17 shows the environmental and resource impacts for disposal of polyvinyl chloride (PVC).

From Table 17, it is seen that the material recycling process is the most environmentally sound way to disposal of PET, as this process has the lowest person equivalents for all environmental impacts. The environmental impacts also indicate that incineration is a more environmentally sound way to dispose PS than pyrolysis. From the evaluated consumption of resource, material recycling is the most resource saving process, the second is incineration, the third is pyrolysis, and the least is landfilling.

Generally speaking, on the basis of their ability to conserve resources, the disposal methods are ranked in the following order:

1. Material recycling with vision/chemical analysis based separation
2. Material recycling with selective dissolution based separation
3. Incineration with heat recovery
4. Pyrolysis
5. Landfill
6. Material recycling without separation.

Table 17: Environmental and Resource Impacts for Disposal of PVC

Normalization	**Material recycling**	**Pyrolysis**	**Incineration with heat recovery**	**Landfill**
Environmental impacts	PE*year per kg recycled plastics	PE*year per kg recycled plastics	PE*year per kg recycled plastics	PE*year per kg recycled plastics
Global warming	$-130*10^{-6}$	$94*10^{-6}$	$9.6*10^{-6}$	0
Stratospheric ozone depletion	0	0	0	0
Acidification	$-167*10^{-6}$	$-14.0*10^{-6}$	$-37*10^{-6}$	0
Nutrient enrichment (N)	$-82*10^{-6}$	$-10.6*10^{-6}$	$-14.4*10^{-6}$	0
Nutrient enrichment (P)	0	$0.4*10^{-6}$	0	0
Photochemical ozone formation	$-302*10^{-6}$	$17.7*10^{-6}$	$-56*10^{-6}$	0
Solid waste	$254*10^{-6}$	$301*10^{-6}$	$427*10^{-6}$	$2174*10^{-6}$
Resource impacts				
Crude oil	$-837*10^{-6}$	$-558*10^{-6}$	$-63*10^{-6}$	0
Natural gas	$-1606*10^{-6}$	$338*10^{-6}$	$-1013*10^{-6}$	0
Pit coal	$44*10^{-6}$	$265*10^{-6}$	$-172*10^{-6}$	0

6. CONCLUSION

- A refined system architecture for PMM model is developed based on previous research work.
- The model will be implemented in three phases with input of Pantex DIS data and output of recommended recycling plans.
- The core technique - Fuzzy Analytic Hierarchy Process method - is used to solve this multi-objective decision making problem.
- The prototype model will be developed soon afterwards.

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