Sustainable Reverse Logistics for Distribution of Industrial Waste/By-Products: A Joint Optimization of Operation and Environmental Costs

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Abstract:

By-products and waste materials are potentially valuable inputs into a variety of industrial processes. Markets are being aimed at capitalizing on the use and reuse of these materials as inputs. The literature on reverse logistics analysis mostly concentrates on the end-of-life products recovery systems and mainly does not address the recovery process for waste/by-products streams in an exchange network among industries.

We developed a reverse logistic model that minimizes the operational and environmental costs of exchanging waste and by-product materials in a business-to-business network. The network contains firms, value added process centers (e.g. disassembly, recycling, or remanufacturing), disposal centers, and virgin material market. The model takes the form of a mixed integer linear model. The model output contains the locations of the value added process centers and the material movement that minimizes the weighted sum of the operational and environmental costs.

Since the problem is NP-hard, we developed a Genetic Algorithm (GA) to efficiently solve the model for large problem instances. We demonstrated the modeling and solution approach for the aluminum waste/by-product in Los Angeles County. For this demonstration, we used data results from numerous past studies to assess the operational costs of waste/by-product collection, processing, and movement. To estimate the environmental costs and parameters, we utilized published economic input-output results from previous studies. This model can be used as a guide for policies to encourage the development of sustainable supply networks.

Keywords: industrial waste/by-product, reverse logistics, environmental cost, sustainability, exchange network, joint optimization.

1. Introduction

Increasing world population and standards of living have magnified resource consumption and the disposal rate. In a typical day, humans add 15 million tons of carbon to the atmosphere, destroy 115 square miles of tropical rainforest, create 72 square miles of desert, eliminate between 40 and 100 species, erode 71 million tons of topsoil, add 2700 tons of CFCs (Chlorofluorocarbons) to the environment and increase population by 263,000 (Orr, 1992). Growing concerns about climate changes, local and regional impacts of air, ground and water pollution from industrial activities have significantly expanded the interaction between environmental management and operations, leading to the area termed as “reverse logistics” (Corbett and Kleindrofer, 2001b).

There are economical and political justifications that highlight the necessity of investment in this area of research. Public pressure on reducing the environmental impacts of industrial operations has resulted in setting non-flexible standards and penalties for environmentally intensive industrial operations (Corbett and Kleindrofer, 2001a). On the other hand, processing waste materials and end-of-life goods to be substituted for raw resources will save money both in terms of purchasing fewer raw materials and less disposal.

In Europe, EU regulation increases producer responsibility or product stewardship for several branches of industry (Krikke et al., 2001). These rules force the Original Equipment Manufacturers (OEMs) to set-up a take-back and recovery system for discarded products. Producer responsibility is supplemented by measures such as increased disposal tariffs, disposal bans, restrictions on waste transportation, waste prevention, and emission control. Consumers’ demand for clean manufacturing and recycling is also increasing. Consumers expect to be able to trade an old product when they buy a new one. From another perspective, retailers also expect OEMs to establish a proper environmentally responsible reverse logistics and recovery system. A well-managed reverse logistics program should also be able to provide important cost savings in procurement, disposal, inventory carrying and transportation. Emissions during transportation are often recognized as having the greatest environmental impact on all activities in a product’s life cycle (Corbett and Kleindrofer, 2001b).

There has been a significant growing interest in the subject of reverse logistics (Krikke, 1998; Sarkis, 2001; Fleischmann, 2001). Most of the models developed in this field are similar to the traditional location problems, in particular location-allocation models (Kroon and Vrijens, 1995; Ammons et al., 1997; Spengler et al., 1997; Marin and Pelegrin, 1998; Jayaraman et al., 1999; Krikke et al., 1999, 2001; Fleischmann et al., 2001). In most of the models, transportation and processing costs were minimized while the environmental costs associated with the designed network were often neglected.

Current literature on reverse logistics concentrates on the end-of-life product's recovery systems (Business-to-Consumer, B2C, network). Despite end-of-used materials that have been the subject of most reverse logistics related studies, few works (e.g. Mondschein and Schilkrut, 1997) have addressed the recovery process for waste/by-products streams in an exchange networks among industries, which share a considerable amount of waste streams. For example, Los Angeles County, by itself, produces 12.2 million tons of by-product/waste materials in the manufacturing sector. By-products and waste materials are potentially valuable inputs for a variety of industrial processes. Thinking of wastes and by-products as potentially valuable feedstock may allow for the design of a high degree of sustainability into them. This may also create markets specifically aimed at capitalizing on the use and reuse of these materials as inputs. This direct use of high quality 'wastes' as inputs benefits the supplier, the customer, and the environment as well as it significantly extends the lifespan of a given by-product, delaying its ultimate fate at the landfill and reducing the consumption of the virgin source material(s) for which it has been substituted.

In this study, managing the recovery of waste and by-product streams in an industrial exchange network (Business-to-Business, B2B, network) is investigated. Due to the importance of the logistics issues (e.g. inventory level) in a B2B material exchange network, they are integrated to the proposed approach to build up a novel comprehensive reverse logistics model.

In the next section, the literature on reverse logistics is briefly reviewed. In section 3, a reverse logistic network is first defined for the distribution of waste and by-products. Then, a mathematical model is developed to determine the location of the facilities and the flows of material among them. Due to the combinatorial nature of the problem, we develop a heuristic approach based on a Genetic Algorithm (GA) to efficiently solve the problem for large size problem instances. The development of the GA approach is presented in section 4. In section 5, we demonstrate the effectiveness of the solution on randomly generated data sets.

2. Literature Review

During the last decade, reverse logistics has received increasing attention from both academic researchers and industrial practitioners. Serious and persistent environmental concerns and government regulations have created a motivation to pursue further research in this field. During the early nineties, the Council of Logistics Management published two studies on reverse logistics. First, Stock (1992) proposed the application of reverse logistics in business and society in general. One year later, Kopicki et al. (1993) elaborated the opportunities on reusing and recycling. In the late nineties, several other studies on reverse logistics were completed. Kostecki (1998) discussed marketing aspects of reuse and issues involving the extension of product life cycle. Stock (1998) investigated how to start and carry out reverse logistics programs. Rogers and Tibben-Lembke (1999) demonstrated a collection of reverse logistics business practices using a comprehensive questionnaire among US industries.

Reverse logistics studies can be divided into several categories. Dowlatshahi (2000) identified five categories as follows: global concepts of reverse logistics, quantitative models, logistics (distribution, warehousing, and transportation), company profiles, and applications. Recently, many researchers have concentrated on the optimization and quantitative models in reverse logistics. Most of the proposed models are similar to traditional facility location models, and are in the shape of a mixed integer linear program for a single period of time (Kroon and Vrijens, 1995; Ammons et al., 1997; Spengler et al., 1997; Barros et al., 1998; Marin and Pelegrin, 1998; Jayaraman et al., 1999; Krikke et al., 1999; Fleischmann et al., 2001). Other researchers studied problems with a single inbound commodity except for Spengler et al. (1997) and Jayaraman et al. (1999). Louwers et al. (1999) proposed the design of a recycling network for carpet waste. The goal of their study was to determine the locations and capacities of the regional recovery centers to minimize investment, processing, and transportation costs. They developed a nonlinear model and solved it optimally with standard software. A comprehensive review on various cases can be found in Brito et al. (2002).

We found little work addressing the environmental costs of material exchange networks. Locklear (2001) elaborated several techniques that can be applied to determine the value of environmental costs. One approach is Contingent Valuation, where external costs are based on how much the public is willing to pay for protection of the environment. Shadow Pricing is another technique, which uses existing regulations to estimate the costs that the society is willing to accept for the reduction of pollution. In 1990, Tellus Institute conducted an analysis to estimate the external costs for seven different components of air emissions including CO_2 and NO_x (Locklear, 2001). Their estimations are based on the Contingent Valuation method and have been frequently cited in the literature. According to their results, in US dollars per pound, values for CO_2 and NO_x are 0.012 and 3.4 respectively.

Saleem (2001) reported cost estimates for three manufacturing scenarios in the Heating Ventilation and Air Conditioning (HVAC) industry. In the first scenario, costs were calculated for HVAC production using virgin materials. In the second one, costs for production using materials from secondary mining (recycling) processes were estimated, which reflected an 82% cost reduction compared to the first alternative. In the third approach, materials acquired from disassembly of value extracted HVAC units were used, which resulted in 88% cost savings as compared to the use of material from primary extraction.

Mathews (1999) used a Leontief input-output (IO) model to evaluate the environmental impact on the entire economy resulting from the production processes. In addition, his model considers environmental impacts. He generated a substantial data set linking releases of criteria pollutants and greenhouse gases with manufacturing activities in each industrial sector. The total air pollution releases found for each commodity were combined with a range of environmental damage valuation studies to estimate the external costs of these activities.

3. Problem Formulation

In this section, a mathematical model for the problem is presented. First, elements of the model are defined. A diagram outlining different elements of the proposed sustainable network and their interconnectivity is depicted in Fig. 1. This diagram demonstrates a general regional recovery network within a system boundary (e.g. LA County regional recovery network). We note that the issues of social concerns (e.g., social justice, employment) are outside the scope of this research.

In this model the locations of plants, collection centers, and value-added process centers (e.g., remanufacturing and recycling) are inside the system boundaries, while the locations of virgin material markets and disposal centers could be both inside and/or outside the boundaries. Also, the locations of virgin material markets, plants, and disposal centers are fixed. The other facilities' locations are determined through implementation of the model. As Fig. 1 illustrates, the waste and by-products generated by a firm are transferred to the collection centers. If their qualities are acceptable, they will be consumed directly by another firm as an input into the firm's production process. In the collection centers, the materials are collected, inspected and passed to other facilities such as the VAP centers or the disposal centers. Based on the quality of the materials, they may be sent to plants to be used as a substitute for raw materials. After performing these value-added processes, the materials are sent to the downstream firms. A portion of the material flow deemed “unusable” is sent to a disposal center.

The primary goal of the network is to provide sufficient raw materials for the plants from the ‘material exchange network’, but if more materials are required (due to low quality material generated in the network) the virgin material market is available as well.

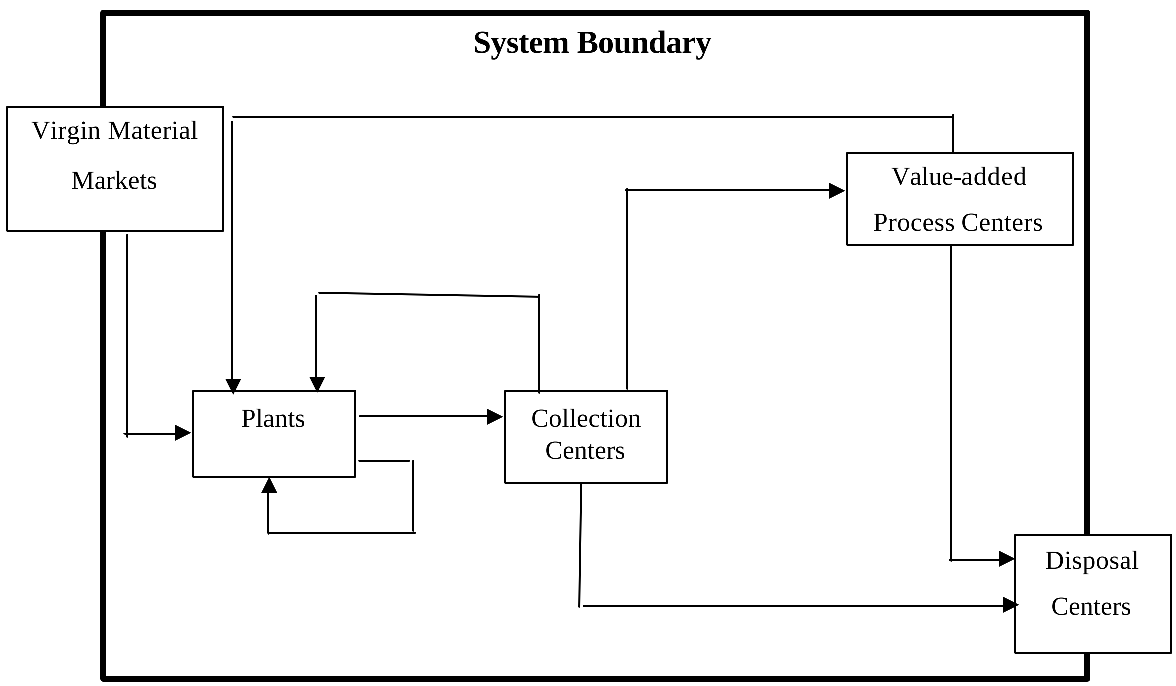

Fig. 1: A model diagram illustrating the distribution of the waste/by-products.

The mathematical model developed here minimizes two categories of costs: the operation costs and the environmental costs. The operation costs include facility opening, transportation, processing, and inventory costs. The environmental costs include energy, water, and air pollution costs, virgin material opportunity or replacement costs, disposal costs including tipping fees and effects on local communities or social costs. The minimization of the objective function is subject to a set of constraints, namely, material balance at facilities, demand constraints, shipping from open facilities, capacity constraints, domain constraints, and non-negativity constraints.

The following sets and indexes are used to define the parameters and variables of the model.

Sets:

V: Set of virgin material markets

P: Set of plants

I: Set of collection centers

J: Set of value added process centers

D: Set of disposal centers

K: Set of material types

TP: Set of time periods

Indexes:

v: Index for virgin material markets

p, r: Index for plants

i: Index for collection centers

j: Index for value added process centers

d: Index for disposal centers

k: Index for material types

t: Index for time periods

Model Parameters:

CT_{vpk}: Transportation cost per mile per unit of material k from virgin material market v to plant p.

CT_{pik} : Transportation cost per mile per unit of material k from plant p to collection center i.

CT_{ipk} : Transportation cost per mile per unit of material k from collection center i to plant p.

CT_{prk}: Transportation cost per mile per unit of material k from plant p to plant r.

CT_{ijk} : Transportation cost per mile per unit of material k from collection center i to value-added process center j.

CT_{idk} : Transportation cost per mile per unit of material k from collection center i to disposal center d.

CT_{jpk} : Transportation cost per mile per unit of material k from value-added process center j to plant p.

CT_{jdk} : Transportation cost per mile per unit of material k from value-added process center j to disposal center d.

CN_{vpk}: Environmental cost of transportation per mile per unit of material k from virgin material market v to plant p.

CN_{pik} : Environmental cost of transportation per mile per unit of material k from plant p to collection center i.

CN_{ipk} : Environmental cost of transportation per mile per unit of material k from collection center i to plant p.

CN_{prk}: Environmental cost of transportation per mile per unit of material k from plant p to plant r.

CN_{ijk} : Environmental cost of transportation per mile per unit of material k from collection center i to VAP center j.

CN_{idk} : Environmental cost of transportation per mile per unit of material k from collection center i to disp. center d.

CN_{jpk} : Environmental cost of transportation per mile per unit of material k from VAP center j to plant p.

CN_{jdk} : Environmental cost of transportation per mile per unit of material k from VAP center j to disposal center d.

CP_{ik} : Unit processing cost of material type k at collection center i.

CP_{jk} : Unit processing cost of material type k at value-added process center j.

CP_{dk} : Unit processing cost of material type k at disposal center d.

h_{pk} : Inventory cost per unit per period for material type k at plant p.

h_{ik} : Inventory cost per unit per period for material type k at collection center i.

h_{jk} : Inventory cost per unit per period for material type k at value-added process center j.

p_{pk} : Backorder cost per unit per period for material type k at plant p.

p_{ik} : Backorder cost per unit per period for material type k at collection center i.

p_{jk} : Backorder cost per unit per period for material type k at value-added process center j.

F_i : Cost of opening collection center i.

F_j : Cost of opening VAP center j.

CD_{dk} : Unit disposal cost (tipping fee) at disposal center d for material type k.

CV_{vk} : Virgin material opportunity cost of producing a unit of material type k by virgin material market v.

CE_{jk} : Energy consumption cost at value-added process center j for a unit of material type k.

CW_{jk}: Environmental cost of disposing a unit of material k into water at VAP center j.

CW_{dk}: Environmental cost of disposing a unit of material k into water at disposal center d.

CA_{jk}: Environmental cost of disposing a unit of material k in air at value-added process center j.

CA_{dk}: Environmental cost of disposing a unit of material k into air at disposal center d.

T_{vp}: The distance between virgin material market v and plant p.

T_{pi} : The distance between plant p and collection center i.

T_{pr}: The distance between plant p and plant r.

T_{ij} : The distance between collection center i and value-added process center j.

T_{id} : The distance between collection center i and disposal center d.

T_{jp} : The distance between value-added process center j and plant p.

T_{jd} : The distance between value-added process center j and disposal center d.

CAP_{pk} : The capacity of plant p for material type k.

CAP_{ik} : The capacity of collection center i for material type k.

CAP_{jk} : The capacity of value-added process center j for material type k.

CAP_{dk}: The capacity of disposal center d for material type k.

S_{pk}^{t} : Total supply of material type k at plant p in time period t.

R_{pk}^{t} : Demand of plant p for material type k in time period t.

T: Number of planning periods.

B : A large number.

w_{jk} : Fraction of material k disposed to water at value-added process center j.

w_{dk} : Fraction of material k disposed to water at disposal center d.

a_{jk} : Fraction of material k disposed to air at value-added process center j.

a_{dk} : Fraction of material k disposed to air at the disposal center d.

a : A multiplier to adjust material type k balance in the constraints.

b : A multiplier to adjust material type k balance in the constraints.

d : Minimum fraction of input material to the collection centers that can be disposed.

? : Max fraction of material that enters the collection center that can be used by the plants.

? : Minimum fraction of material in VAP centers that can be disposed.

t : Maximum fraction of materials in the plants that can directly be used by the other plants.

Decision Variables:

x_{vpk}^{t} : The flow of material type k from virginal material market v to plant p in period t.

x_{prk}^{t} : The flow of materia l type k from plant p to plant r in period t.

x_{pik}^{t} : The flow of material type k from plant p to collection center i in period t.

x_{ijk}^{t} : The flow of material type k from collection center i to VAP center j in period t.

x_{idk}^{t} : The flow of material type k from collection center i to disposal center j in period t.

$x_{ipk}{}^{t}$: The flow of material type k from collection center i to plant p in period t.

$x_{jpk}{}^{t}$: The flow of material type k from VAP center j to plant p in period t.

$x_{jdk}{}^{t}$: The flow of material type k from VAP center j to disposal center d in period t.

Y_i : The indicator of opening collection center i.

Y_j : The indicator of opening value-added processing center j.

$INV_{pk}{}^{t}$: Inventory level of material type k at plant p at the end of period t.

$INV_{ik}{}^{t}$: Inventory level of material type k at collection center i at the end of period t.

$INV_{jk}{}^{t}$: Inventory level of material type k at value added process center j at the end of period t.

$BOR_{pk}{}^{t}$: Backorder of material type k at plant p at the end of period t.

$BOR_{ik}{}^{t}$: Backorder of material type k at collection center i at the end of period t.

$BOR_{jk}{}^{t}$: Backorder of material type k at value-added process center j at the end of period t.

Objective Function

The objective function minimizes two categories of costs: operation costs (Z_1) and environmental costs (Z_2). A weight, l and 1- l , is assigned to each part of the objective function to differentiate the degree of sensitivity for each cost category. The objective function is as follows:

$$Min\ \ Z = lZ_1 + (1 - l)Z_2$$

In the objective function, the production costs (Z_1) include facility opening (1), transportation (2), processing (3), and inventory/backorder costs (4):

$$Z_1 = \sum_{i\in I} F_i\, Y_i \ + \sum_{j\in J} F_j\, Y_j \qquad (1)$$

$$+ \sum_{t\in T} [\sum_{p\in P}\sum_{i\in I}\sum_{k\in K} CT_{pik} x^{t}_{pik} TD_{pi} + \sum_{p\in P}\sum_{r\in R}\sum_{k\in K} CT_{prk} x^{t}_{prk} TD_{pr} \qquad (2)$$

$$+ \sum_{i\in I}\sum_{p\in P}\sum_{k\in K} CT_{ipk} x^{t}_{ipk} TD_{pi} + \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} CT_{ijk} x^{t}_{ijk} TD_{ij}$$

$$+ \sum_{i\in I}\sum_{d\in D}\sum_{k\in K} CT_{idk} x^{t}_{idk} TD_{id} + \sum_{v\in V}\sum_{p\in P}\sum_{k\in K} CT_{vpk} x^{t}_{vpk} TD_{vp}$$

$$+ \sum_{j\in J}\sum_{p\in P}\sum_{k\in K} CT_{jpk} x^{t}_{jpk} TD_{jp} + \sum_{j\in J}\sum_{d\in D}\sum_{k\in K} CT_{jdk} x^{t}_{jdk} TD_{jd}$$

$$+ \sum_{i\in I}\sum_{k\in K} CP_{ik} (\sum_{p\in P} x^{t}_{pik}) + \sum_{j\in J}\sum_{k\in K} CP_{jk} (\sum_{i\in I} x^{t}_{ijk}) + \sum_{d\in D}\sum_{k\in K} CP_{dk} (\sum_{i\in I} x^{t}_{idk} + \sum_{j\in J} x^{t}_{jdk})$$

$$+ \sum_{k\in K}\sum_{i\in I} (h_{ik} INV^{t}_{ik} + p_{ik} BOR^{t}_{ik}) + \sum_{k\in K}\sum_{p\in P} (h_{pk} INV^{t}_{pk} + p_{pk} BOR^{t}_{pk}) \qquad (3)$$

$$+ \sum_{k\in K}\sum_{j\in J} (h_{jk} INV^{t}_{jk} + p_{jk} BOR^{t}_{jk})] \qquad (4)$$

Environmental costs (Z_2) include environmental impacts of transportation (5), impacts of energy (6), water pollution (7), air pollution (8), virgin material opportunity costs of producing from virgin materials (9), and disposal costs including tipping fees (10). Virgin material opportunity cost is the extra expense that a firm is willing to pay when it refuses to substitute the virgin material market by an acceptable recycled material. The mathematical formulation is as follows:

$$Z_2 = \sum_{t\in T}[\sum_{p\in P}\sum_{i\in I}\sum_{k\in K} CN_{pik} x^t_{pik} TD_{pi} + \sum_{p\in P}\sum_{r\in R}\sum_{k\in K} CN_{prk} x^t_{prk} TD_{pr} \tag{5}$$

$$+ \sum_{i\in I}\sum_{p\in P}\sum_{k\in K} CN_{ipk} x^t_{ipk} TD_{pi} + \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} CN_{ijk} x^t_{ijk} TD_{ij}$$

$$+ \sum_{i\in I}\sum_{d\in D}\sum_{k\in K} CN_{idk} x^t_{idk} TD_{id} + \sum_{v\in V}\sum_{p\in P}\sum_{k\in K} CN_{vpk} x^t_{vpk} TD_{vp}$$

$$+ \sum_{j\in J}\sum_{p\in P}\sum_{k\in K} CN_{jpk} x^t_{jpk} TD_{jp} + \sum_{j\in J}\sum_{d\in D}\sum_{k\in K} CN_{jdk} x^t_{jdk} TD_{jd}$$

$$+ \sum_{j\in J}\sum_{k\in K} CE_{jk} (\sum_{i\in I} x^t_{ijk}) \tag{6}$$

$$+ \sum_{j\in J}\sum_{k\in K} CW_{jk} (w_{jk} \sum_{i\in I} x^t_{ijk}) + \sum_{d\in D}\sum_{k\in K} CW_{dk} w_{dk} (\sum_{i\in I} x^t_{idk} + \sum_{j\in J} x^t_{jdk}) \tag{7}$$

$$+ \sum_{j\in J}\sum_{k\in K} CA_{jk} (a_{jk} \sum_{i\in I} x^t_{ijk}) + \sum_{d\in D}\sum_{k\in K} CA_{dk} a_{dk} (\sum_{i\in I} x^t_{idk} + \sum_{j\in J} x^t_{jdk}) \tag{8}$$

$$+ \sum_{v\in V}\sum_{p\in P}\sum_{k\in K} CV_{vk} x^t_{vpk} \tag{9}$$

$$+ \sum_{d\in D}\sum_{k\in K} CD_{dk} (\sum_{i\in I} x^t_{idk} + \sum_{j\in J} x^t_{jdk})] \tag{10}$$

Constraints

Constraint (1) indicates that the total supply of materials from each plant must be equal to the output flows. Constraints (2) to (4) guarantee the balance of material in collection centers, VAP centers, and plants accordingly. That is the input flows in the current time period plus the available inventory up to this period in one side should be equal to the demand or output flows plus inventory to be kept in the current period from the other side. Maintaining balance of material in VAP centers is more complex than the other facilities due to the possible chemical reactions. Therefore, by introducing multipliers (a, b), equation (3) can be modified based on different scenarios. Constraints (5) and (6) ensure that materials flow through the active facilities. Capacity constraints for plants, collection, VAP, and disposal centers are listed from (7) to (10). The next four sets of constraints are added to the model in order to provide flexibility in real word scenarios. Based on historical data, constraints (11) and (13) assign the least disposal rate for each collection center and VAP center accordingly. Constraints (12) and (15) limit the amount of reused material provided by a collection center and other plants accordingly. Constraints (16) and (17) identify the domain of the decision variables.

$$\sum_{i\in I} x^t_{pik} + \sum_{r\in R} x^t_{prk} = S^t_{pk} \qquad \forall k\in K,\ \forall p\in P, t=1,...,T \quad (1)$$

$$\sum_{p\in P} x^t_{pik} + INV^{t-1}_{ik} - BOR^{t-1}_{ik} = \sum_{p\in P} x^t_{ipk} + \sum_{j\in J} x^t_{ijk} + \sum_{d\in D} x^t_{idk} + INV^t_{ik} - BOR^t_{ik} \qquad \forall k\in K,\ \forall i\in I, t=1,...,T \quad (2)$$

$$\sum_{i\in I} x^t_{ijk} + INV^{t-1}_{jk} - BOR^{t-1}_{jk} = \sum_{k'\in K} a_{k'} \sum_{p\in P} x^t_{jpk'} + \sum_{k'\in K} b_{k'} \sum_{d\in D} x^t_{jdk'} + INV^t_{jk} - BOR^t_{jk} \qquad \forall k\in K,\ \forall j\in J, t=1,...,T \quad (3)$$

$$\sum_{i\in I} x^t_{ipk} + \sum_{j\in J} x^t_{jpk} + \sum_{r\in R} x^t_{rpk} + \sum_{v\in V} x^t_{vpk} + INV^{t-1}_{pk} - BOR^{t-1}_{pk} = R_{pk} + INV^t_{pk} - BOR^t_{pk} \qquad \forall k\in K, \forall p\in P, t=1,...,T \quad (4)$$

$$\sum_{p\in P} x^t_{ipk} + \sum_{j\in J} x^t_{ijk} + \sum_{d\in D} x^t_{idk} \le Y_i B \qquad \forall k\in K,\ \forall i\in I, t=1,...,T \quad (5)$$

$$\sum_{p\in P} x^t_{jpk} + \sum_{d\in D} x^t_{jdk} \le Y_j B \qquad \forall k\in K,\ \forall j\in J, t=1,...,T \quad (6)$$

$$\sum_{i\in I} x^t_{ipk} + \sum_{j\in J} x^t_{jpk} + \sum_{r\in R} x^t_{rpk} + \sum_{v\in V} x^t_{vpk} + INV^{t-1}_{pk} - BOR^{t-1}_{pk} \le CAP_{pk} \qquad \forall k\in K, \forall p\in P, t=1,...,T \quad (7)$$

$$\sum_{p\in P} x^t_{pik} + INV^{t-1}_{ik} - BOR^{t-1}_{ik} \le CAP_{ik} \qquad \forall k\in K,\ \forall i\in I, t=1,...,T \quad (8)$$

$$\sum_{i\in I} x^t_{ijk} + INV^{t-1}_{jk} - BOR^{t-1}_{jk} \le CAP_{jk} \qquad \forall k\in K,\ \forall j\in J, t=1,...,T \quad (9)$$

$$\sum_{i\in I} x^t_{idk} + \sum_{j\in J} x^t_{jdk} \le CAP_{dk} \qquad \forall k\in K,\ \forall d\in D, t=1,...,T \quad (10)$$

$$\sum_{d\in D} x^t_{idk} \ge d * \sum_{p} x^t_{pik} \qquad \forall i\in I, \forall k\in K, \forall t\in T \quad (11)$$

$$\sum_{p\in P} x^t_{ipk} \le g * \sum_{p\in P} x^t_{pik} \qquad \forall i\in I, \forall k\in K, \forall t\in T \quad (12)$$

$$\sum_{d\in D} x^t_{jdk} \ge h * \sum_{i\in I} x^t_{ijk} \qquad \forall j\in J, \forall k\in K, \forall t\in T \quad (13)$$

$$\sum_{r\in P} x^t_{prk} \le t * \left(\sum_{r\in P} x^t_{prk} + \sum_{i\in I} x^t_{ipk} + \sum_{j\in J} x^t_{jpk}\right) \qquad \forall p\in P, \forall k\in K, \forall t\in T \quad (14)$$

$$Y_i, Y_j \in \{0,1\} \qquad \forall i\in I, \quad \forall j\in J \quad (15)$$

$$x^t_{pik}, x^t_{ipk}, x^t_{ijk}, x^t_{idk}, x^t_{jpk}, x^t_{prk}, x^t_{jdk}, x^t_{vpk} \ge 0 \qquad \forall p\in P, \forall i\in I, \forall j\in J, \forall d\in D, \forall v\in V, \forall k\in K, t=1,...,T \quad (16)$$

4. Solution Approaches

The developed mathematical model is a mixed integer linear program (MILP), which belongs to the Facility Layout and Location category of optimization problems. Similar problems in the literature are addressed as Discrete Facility Location or Fixed Charged Location problems. Due to the combinatorial nature of these problems, they are identified as NP-Complete problems.

Goldberg (1989) proposed Genetic Algorithm (GA) as an efficient meta-heuristic approach to solve combinatorial problems. We applied GA to solve the MILP model presented in the previous section. In the developed algorithm, GA is first applied to generate a set of zero-one values. Then, CPLEX 8.1 is used to solve the corresponding Linear Programming (LP). Fig. 2 demonstrates the steps of this approach.

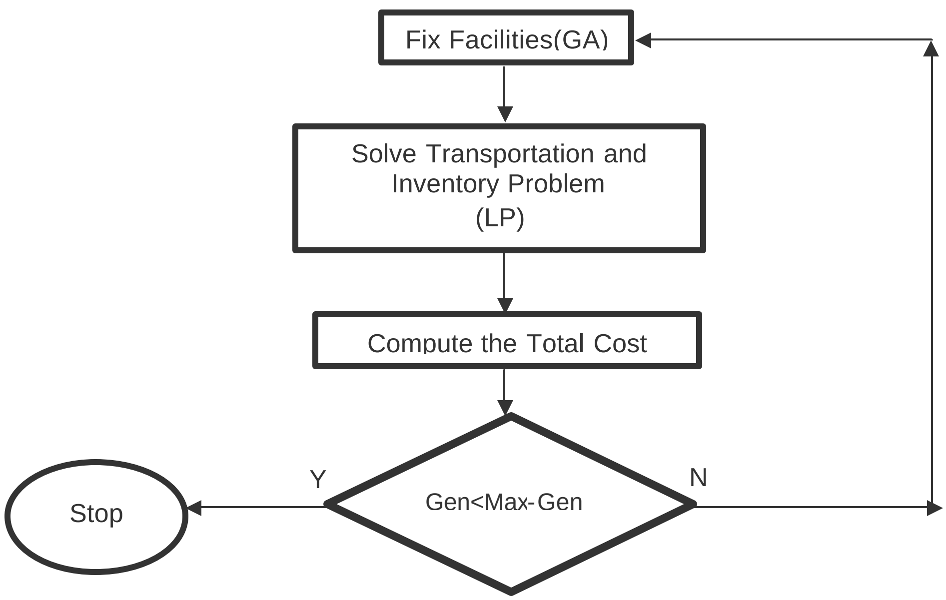

Fig. 2: Steps of the algorithm, developed to solve the MILP model with GA

Fig. 3 shows the steps of the GA procedure in detail. The initial set of zero-one values (solution to binary variables) is randomly generated. The size of this set depends on the number of binary variables (collection centers and VAP centers) and termed as the population size. To obtain the material flow variables for each set of binary variables an LP is solved using a commercial optimization software (CPLEX 8.1). After solving the LP sub-problems for the whole population, the solved sub-problems are sorted based on the objective function in order to determine which stream of binary values has the better objective value. In the next consecutive generations, the current set of sorted solutions (we refer to them as a parent stream) is used to generate a new population set (offspring set). There are several methods to form an offspring set, such as crossover, reproduction, and mutation (Goldberg , 1989). Based on an assigned probability (0.8 for crossover, 0.1 for reproduction, and 0.1 for mutation) one of these techniques is selected.

In the crossover procedure, two members of the parents' set are chosen and mixed to generate two new zero-one modules in the offspring set. Three different techniques with equal chance of occurring are employed to mix the original binary solutions. They are random, semi-random, and tournament. In random selection, two members of the parents' set are randomly chosen and crossover or pair-wise exchange is made on a randomly selected digit. The probability of choosing from better solutions is higher in semi-random selection. In tournament, two members of the parents' set are compared. The one with the better objective function value is kept and the other one is returned to the set. Using the same process, the other parent string is determined. In reproduction, the best "*n*" answers from the parents set are moved to the offspring set. For example, *n* can be determined randomly from a portion of the population size. In our procedure, we retain the best 10% of the population for reproduction. This technique gives more weight for good solutions to be involved in the next generations. To perform the mutation, one of the digits of the binary set is randomly changed. This technique prevents trapping in a local minimum solution (Goldberg, 1989). The termination criterion in GA is defined as the number of repetitions or generations. The maximum number of generations is subjective and is based on the size and structure of the problem.

Modified Genetic Algorithm

In order to improve the quality of the GA solutions, we modify the initial seed solution. Instead of randomly generating the initial binary set, the zero-one constraints are relaxed and the model is solved. Then, based on predefined rules, zero-one values are assigned to the binary variables. Different rounding boundaries are applied to define the rules. For example, 0.90 can be considered as one of the rounding boundaries. This means that if the outcome of the model for a binary variable is equal or greater than 0.90 the corresponding variable is set to one. Otherwise, it is assigned to a value of zero.

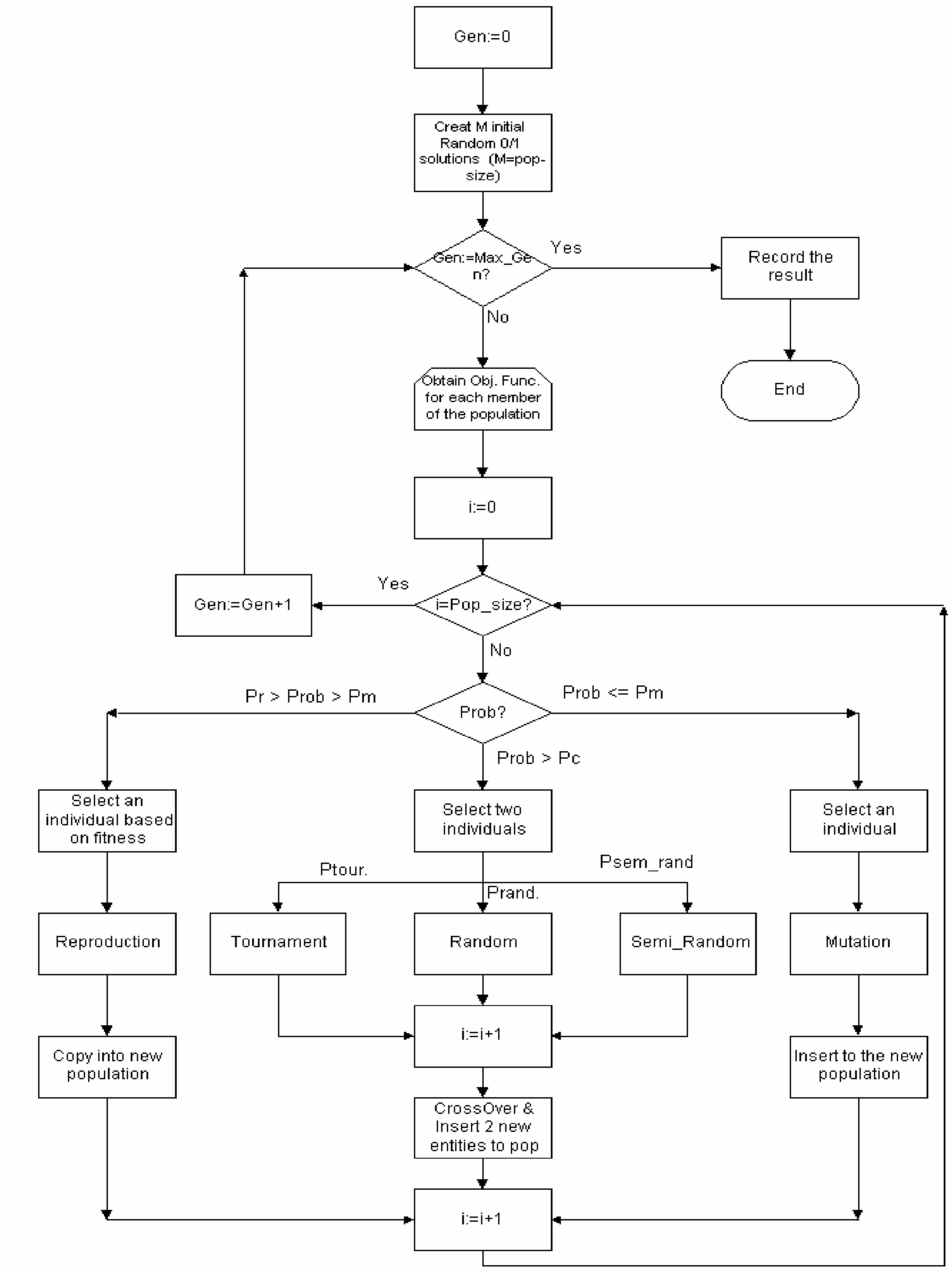

Fig. 3: The Genetic Algorithm. Parameters used in the sample problem are as follows: M=20, Max-Gen=10, Pm=.10, Pc=0.20, and Ptour=Prand=Psem_ram=0.33

5. Case Study

This section illustrates the model and the effectiveness of the solution approach on the aluminum industry in Los Angeles County. Los Angeles County with over $850 billion economic output each year and around 1.2 million employees is one of the largest industrial regions in the United States. Moreover, generation of 12.2 million tons of waste and by-product materials in LA County provides a significant economic opportunity for reverse logistics material exchange networks.

Aluminum is produced either in the primary industry or the recycling (secondary) industry. The primary aluminum industry consists of mining to produce bauxite, refining to produce alumina, and smelting to produce aluminum. Aluminum can be efficiently recycled with far less energy compared to the extraction of aluminum from bauxite ore (Aluminum Association, Inc., 2000). Therefore aluminum scrap recycling is an attractive alternative both from an economical and an environmental perspective. The aluminum recycling industry consists of the scrap industry and secondary smelters and fabricators (Lagioia et al., 2001). Secondary scrap is a major portion of the domestic aluminum supply. It has two components, new and old. New scrap refers to the material that is left over after fabrication of aluminum products. Old scrap is the term applied for aluminum products that have reached to the end of their life and are discarded. In 2000, almost 3.5 million tons of aluminum were recovered from new and old scrap (Plunkert, 2002). Secondary old scrap aluminum production has expanded rapidly and in 2000, represented over 30 percent of total aluminum production in the United States. Before presenting the experimental results, we first discuss how the parameters of the model were estimated.

5.1 Parameter Estimation

In this section, a methodology to estimate environmental costs of the model is elaborated. Operational costs including transportation costs have been frequently presented in the literature (Litman, 1999). To estimate environmental parameters, we have used the literature and used those provided by economic input-output analysis shown in the recent EIO studies. We also realize that the estimation of environmental parameters is case dependent. For instance, estimated values for environmental parameters of a case with a specific type of material and in a specific location (city/state) vary from another case with different material and/or locations (Small and Kazimi, 1995). As mentioned before, we have developed our model parameters to focus on the aluminum industry values currently used in LA County.

The environmental parameters of the model are as follows: virgin material opportunity cost, cost of energy at VAP, transportation environmental cost, disposal cost (tipping fee), water disposal cost, and air disposal cost. Virgin material opportunity cost is determined by comparing the price of virgin raw material with the recycled counterpart. If the virgin material was more expensive than the recycled material (in the majority of cases), the difference was the extra cost that buyers are willing to pay to purchase virgin material. In some cases, due to the costly process of recycling, the recycled material ends up to be more expensive than the raw material. In these situations, decision makers could apply incentives or penalties to change the market parameters in favor of the recycled material to protect the environment. The cost of energy, which is mainly electricity in our aluminum example, was calculated based on the electricity price of LA County ($0.11 per KWH in 2005 based on the Southern California Edison reports at http://www.sce.com or http://www.icced.com/news_pdf/Energy_Rates.pdf).

The environmental transportation costs have been addressed in a number of studies (see Litman 1999, for a comprehensive list of related studies). There are different opinions among researchers regarding the estimation of environmental transportation costs. Varieties of interpretation for emissions effects on environment and various methods to obtain these impacts are the major sources of controversy. A frequently used approach to estimate the environmental cost is contingent valuation or the direct estimation of damages. In this approach, the adverse consequences of emissions are traced and economic values of these impacts are evaluated. For example, Small and Kazimi (1995) concentrated on measuring the cost of regional air pollution from motor vehicles. They applied contingent valuation to provide estimation for motor vehicle air pollution in the Los Angeles region under a variety of alternative assumptions. They claimed that due to the topography of the State of California and Los Angeles, climate tends to concentrate emitted pollutants and produce chemical reactions (e.g., smog). In their effort to estimate air pollution, they focused on the various causal links that lead to the deterioration of human health. They assumed a value of life in their analysis and used an inflation rate based on US gross domestic product per capita, under the presumption that people's valuations grow with income (Small and Kazimi, 1995). They estimated three main categories of costs: mortality from particulates, morbidity from particulates, and morbidity from ozone. Their estimations are also distinguished based on different types of vehicle: Gasoline Car, Light-duty Diesel Truck, and Heavy-duty Diesel Truck. Volatile organic compounds (VOC), nitrogen oxides (NO_x), sulphur oxides (SO_x), and particular matter of less than 10 microns diameter (PM10) are emissions that were included in this estimation. We used Small and Kazimi (1995) and Matthews (1999) results to estimate the related environmental costs. The estimated costs are listed in table 1 and 2.

TABLE 1: COST OF VEHICLES EMISSION IN THE LOS ANGELES REGION (CENTS PER VEHICLE-MILE)

Vehicle Type	CO	VOC	NO_x	SO_x	PM10	Total
Light-duty diesel truck	0.21	0.13	1.81	1.35	1.36	4.86
Heavy-duty diesel truck	1.02	0.64	14.48	6.30	13.27	35.71

TABLE 2: COST OF EMISSION IN THE LOS ANGELES REGION (CENTS/GRAM)

Emission Type	CO	VOC	NO_x	SO_x	PM10	Total
Cost	0.12	0.32	1.18	12.16	11.24	25.02

In order to identify the emissions volumes, Economic Input-Output (EIO) analysis was applied. EIO analysis is a framework developed to examine the inter-industry flows of commodities throughout an economy (Leontieff, 1930; Yan 1969; Miller and Blair 1985). The EIO method divides an economy into a series of industrial sectors to measure the flow of goods. The EIO techniques include a variety of inputs (e.g., raw materials, semi-finished goods, capital equipment and labor) in the analysis of the production demands. The input materials must be purchased within the regional economy or imported from outside. EIO analysis provides a structured accounting system that records the purchases and sales of inputs within each industry in an economy.

The Green Design Institute (GDI) research group at Carnegie Mellon University has provided an Internet based tool that incorporates economic input-output equations with a set of energy, resource, and environmental metrics (see: www.eiolca.net). This site allows the user to estimate the overall environmental impacts from producing a million dollar of commodities or services in the United States. Table 3 shows a sample table that was generated from the GDI database. This table estimates the volume (metric ton) of emissions from each sector needed in the supply network of producing one million dollars of primary aluminum (only the top 10 sectors are listed for brevity). A similar table can be obtained to estimate the energy consumption. Although, water pollution is negligible in recycling scrap aluminums, the procedure to obtain the volume of generated water pollutants is identical to the air pollution.

Table 3 and table 2 (costs of emission), are used to estimate air pollutant costs of $612 per ton (see table 4). It should be noted that since the EIO tables are calculated based on 1992 data, current prices should be converted to the dollar value of 1992 using "Statistical Abstract of the United States, 2000" (http://www.census.gov/prod/www/ statistical-abstract-us.html).

TABLE 3: THE ESTIMATED RELEASES OF CONVENTIONAL POLLUTANTS INTO THE AIR FROM THE PRODUCTION OF 1 MILLION DOLLAR OF ALUMINUM FROM EACH SECTOR NEEDED IN SUPPLY NETWORK.
(mt: Metric Ton)

Sector	SO2 Mt	CO mt	NO2 mt	VOC Mt	Lead mt	PM10 mt
Total for all sectors	**37.1481**	**82.0706**	**14.3330**	**1.8768**	**0.0071**	**3.5705**
Primary aluminum	21.7857	77.1515	4.3621	0.8272	0.0001	2.5730
Electric services (utilities)	12.4644	0.3995	6.1003	0.0499	0.0003	0.3150
Products of petroleum and coal, n.e.c.	1.4222	0.0374	0.1375	0.0873	0.0000	0.1047
Primary nonferrous metals, n.e.c.	0.4564	0.2536	0.0183	0.0025	0.0064	0.0109
Industrial inorganic and organic chemicals	0.1662	0.1461	0.1371	0.0907	0.0001	0.0164
Crude petroleum and natural gas	0.0965	0.0672	0.1622	0.0481	0.0000	0.0019
Blast furnaces and steel mills	0.0937	0.3010	0.0287	0.0110	0.0000	0.0172
Railroads and related services	0.0920	0.1944	0.6962	0.0398	0.0000	0.0397
Petroleum refining	0.0735	0.0663	0.0461	0.0364	0.0000	0.0052
Primary smelting and refining of copper	0.0713	0.0018	0.0017	0.0005	0.0000	0.0032

In order to gain a first hand knowledge about aluminum use in LA County, a survey was administered to about 200 firms. The survey revealed that end of life aluminum products (e.g. aluminum cans, foils, etc.) are collected by a number of small collectors and send to recycling centers. However, recycling centers (VAP centers) collect and recycle the industrial aluminum scraps. In another words, collection centers seems to be embedded in VAP centers. Moreover, it was discovered that none of the aluminum scraps are disposed in the region and almost all are recycled. Based on these facts about aluminum flow in the region, the model presented in section 3 was modified as follows. All variables and related costs parameters of collection centers and disposal centers (e.g. x_{ijk}^{t} , x_{idk}^{t} , x_{jdk}^{t}) were eliminated. In addition, constraints 8, 10, 11, and 13 were dropped from the math model.

Table 4 provides estimation of the model parameters. In order to compare different solution approaches (see section 4.2), we developed a data set based on table 4 and some assumptions, which are listed as follows.

TABLE 4: PARAMETERS ESTIMATION

Parameter definition	Value
Transportation (operational, environmental) from virgin material market and plants to other plants ($/mile/ton)	(2.06[1], 0.36)
Transportation (operational, environmental) between facilities (plants & VAP centers) ($/mile/ton).	(0.48 ,0.05)
Fixed annual cost of a VAP center ($)	150000[2]
Inventory holding cost per period for each ton in a VAP center (K1, K2) ($/ton)	(10, 8)
Inventory holding cost per period for each ton in plants (K1, K2) ($/ton)	(10,8)
Backorder cost for each ton in each period in a facility ($/ton)	1000
Cost of air pollution for each ton at a VAP center ($/ton)	612[3]
Cost of Energy consumption for each ton at a VAP center ($/ton)	21[4]
Processing cost at the facilities for each ton ($/ton)	76[5]
External cost of purchasing from Virgin Material Market per ton ($/ton)	$686[6]
Fraction of material (K1,K2) disposed to air/water at value-added process center j	(0.08, 0)
Large number (B)	100000
VAP centers capacity (ton)	10000
Plants supply, demand, and capacity (ton)	50000

[1] Considering the ratio of consumer price index of Los Angeles to the US in 1996 (157.8/156.9, source: Statistical Abstract of US, http://www.census.gov/prod/3/97pubs/97statab/prices.pdf) the transportation cost for LA was obtained and also converted to its equivalence in 2000.

[2] Based on an interview with real estate agencies (Khaneasan.com and http://www.loopnet.com). For the equipment price, Ernie Baker from Bakery Furnace (http://www.bakerfurnace.com/cfurn.htm) was interviewed. Based on the interview, a Reverbatory furnace with a hydraulic system that is usually used to melt the scrap aluminum, with dimensions of 36”x60”x30” (inside), and capacity of 2000 pd costs about $140,000. The total cost of a facility, which collects scarp aluminum and performs value added processes was estimated $3,000,000. This cost is depreciated over 20 years.

[3] Using www.eiolca.com for SIC code 3365 the volume of emissions generated by processing $1 million of scrap aluminum was obtained. Considering the cost of aluminum production in 1996 ($72 per ton for primary aluminum: http://www.cfoasia.com/archives/200403-05.htm, and based on the survey for recycled one the production cost is about $40 per ton) the equivalent production volume was calculated and the emissions quantity generated from production of a ton aluminum obtained. The result converted to the 2000-dollar value and multiplied by table 2 (after converting the unit to $/ton). Lead excluded from the group of emissions.

[4] See footnote 3, the following conversion factor was used: 1 KWH=3.6 MJ

[5] See Berck and Goldman 2003. The value adjusted to 2000$, using Customer Price Index.

[6] The primary aluminum value ($1640/ton) obtained from Buckingham and Plunkert (2002) and aluminum scrap value ($986/ton) derived (converted to the 2000$) from Berck and Goldman (2003).

In the data set, one virgin material market, twenty plants, ten time periods and two material types (primary and secondary aluminum) were considered. We tested different combinations of VAP centers. The smallest run problem size had 5 VAP centers while the largest had 50 VAP centers. In this model, we set l to 0.50. Therefore, both parts of the objective function were equally weighted and also no chemical conversion was assumed in the value added process centers ($a = b = 0$). In order to have a disincentive for backorders, a prohibitive high cost was assigned for the related parameters. Also we assumed that the annual fixed cost of having a VAP center is $150000 and the capacity of each VAP centers is 10000 tons. Supply, demand, and the capacity of plants were set to 5000 units. The distances between the facilities were uniform random values between 5 and 90. It should be noted that since there was no disposal center and collection center in the aluminum case, parameters *d*, *?*, and *?*, were set to zero. Moreover, none of the scrap aluminum were directly used by other plants, therefore *t* was set to zero as well. As mentioned before, disposal and water pollution costs in the aluminum case were negligible.

5.2 Results

We tested the proposed solution approach on data that is demonstrated on table 4. We compared the performance of the GA against optimal solutions found by solving the mixed integer linear model using a commercially available optimization software package, CPLEX 81. The experiments were run on a Pentium IV, 3.2 G system with 512 MB RAM.

To implement the GA, the population size and the total number of generations were set to 20 and 10 accordingly. The crossover, reproduction, and mutation probabilities were set to .80, .10, and .10, respectively. In crossover, three techniques of random generation, semi-random generation, and tournament were employed with an equal chance of occurrence. In the semi-random technique, one of the binary values was selected randomly and the best solution in the previous generation was chosen as the second binary string to participate in the crossover.

The number of binary solutions that transfer to the new generation in reproduction was randomly chosen from the best 10% of the population size. For the modified GA, the rounding boundaries that were used to generate the initial solution set were 0.90, 0.80, 0.70, 0.60, 0.55, 0.50, 0.40, 0.30, 0.20, and 0.10.

The results are shown in Table 5. The first column shows the number of VAP centers. The next three columns list the number of constraints, the number of zero-one variables, and the number of continuous variables. For the

CPLEX results, we list the optimal solution OP and the CPU time in seconds to obtain the optimal solution (T). For the two GA results, we list the objective value at the time of termination (OBJ), the CPU time in seconds to obtain the solution (T), and the percentage gap from the optimal solution (GAP).

The results show that the GA algorithm and especially the modified GA algorithm are effective procedures in identifying near-optimal solutions. The modified GA was able to find the optimal solution in four of the problem sets and in all problem sets, the solution given by the modified GA were within 2% of the optimal solution. Fig. 4 shows a plot of the gap as a function of the number of binary variables. As Fig. 4 shows, the modified GA performs better than the GA. As the number of binary variables increases the gap between the GA solution and the optimum outcome also amplifies; however, the gap stays at the same level for the modified GA.

Table 5: Comparison of Different Solution Approaches

# VAP	# of Constraints	# zero-one variables	# of Continues Variables	CPLEX		GA			Modified GA		
				OP	T(sec)	Obj	T	Gap%	Obj	T	Gap%
5	2080	5	12820	3.0577e+7	6	3.0577e+7	339	0	3.0577e+7	350	0
10	2520	10	16300	3.1082e+7	134	3.1082e+7	610	0	3.1082e+7	650	0
15	2980	15	20420	2.9920e+7	199	3.0126e+7	865	0.68	2.9920e+7	660	0
20	3420	20	24400	2.9438e+7	438	2.9802e+7	895	1.22	2.9538e+7	749	0.34
25	3880	25	29020	2.7220e+7	918	2.7466e+7	938	0.90	2.7247e+7	750	0.20
30	4320	30	33500	2.723e+7	1530	2.8026e+7	1513	2.84	2.7389e+7	964	0.58
35	4780	35	38620	2.6953e+7	1867	2.7920e+7	1670	3.46	2.7390e+7	1130	1.90
36	4860	36	39440	2.6887e+7	5672	2.7868e+7	1795	3.5	2.6887e+7	914	0
37	4960	37	40660	2.6746e+7	75537	2.7648e+7	1730	3.26	2.691e+7	1176	0.61
40	5220	40	43600	2.6402e+7	95560	2.711e+7	1887	2.61	2.6458e+7	1013	0.21
45	5680	45	49220	2.6387e+7	232560	2.7365e+7	1949	3.57	2.6767e+7	1431	1.42
50	6120	50	54700	2.5959e+7	104340	2.7317e+7	2279	4.97	2.6252e+7	1186	1.12

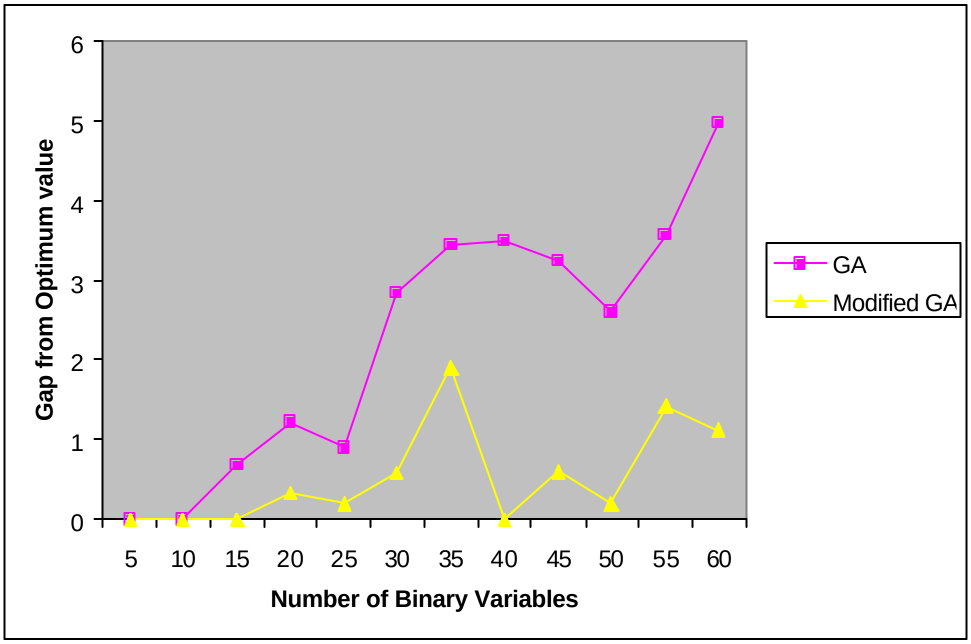

Fig. 4: Comparison of performance of GA and Modified GA approaches.

Fig. 5 illustrates the execution time as a function of the number of binary variables. For the smaller problem sizes, the CPLEX execution time is smaller than the GA approaches. However, an increase in the number of binary variables will exponentially increase the execution time when CPLEX is used to solve the model optimally. As for the other two methods, the execution time changes slowly and within a small range.

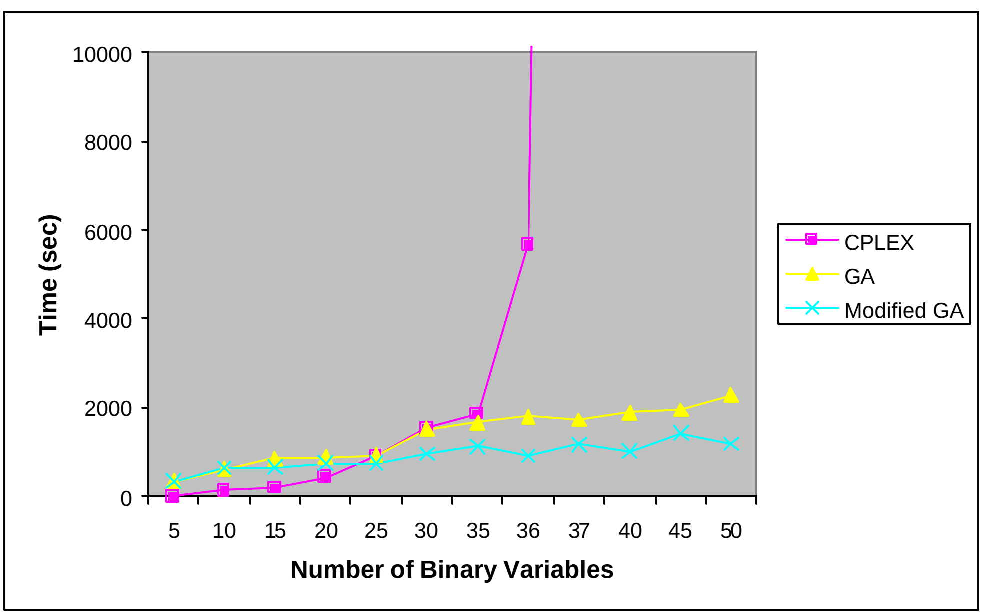

Fig 5. : Comparison of execution time for different methods.

6. Interpretation of the Result

In order to provide a better insight for decision makers regarding the consumption of virgin material in the region, sensitivity analysis was employed. A sample problem similar to those presented in table 5, with 11 VAPs, 38 plants, and 3 virgin material markets is selected to illustrate and develop a sensitivity analysis on virgin material opportunity cost (CV). The other parameters of the model were based on the data set shown in Table 4. The output of the implemented model identified the consumption of %3 primary aluminum from virgin material market. Fig. 6 demonstrates the relationship between virgin material consumption and the cost of obtaining raw material from the virgin material market (CV) instead of recycled materials. As mentioned before, this cost is basically the difference between price of primary and secondary aluminum. Decreasing the cost of producing secondary aluminum and/or increasing the price of primary aluminum elevates the cost of CV. In order to motivate manufacturers to use secondary aluminum, thus moving toward green manufacturing, policy makers may take a variety of actions (new tax regulations, penalties, incentives, etc.) in favor of recycling alternative. As Fig. 6 demonstrates, if the variation of primary and secondary aluminum cost draws near $700 per ton, the consumption of virgin aluminum will not be profitable and from an economical point of view manufacturers prefer to use secondary aluminum. It should be also noted that throughout this analysis, we assumed equal quality for primary versus secondary aluminum.

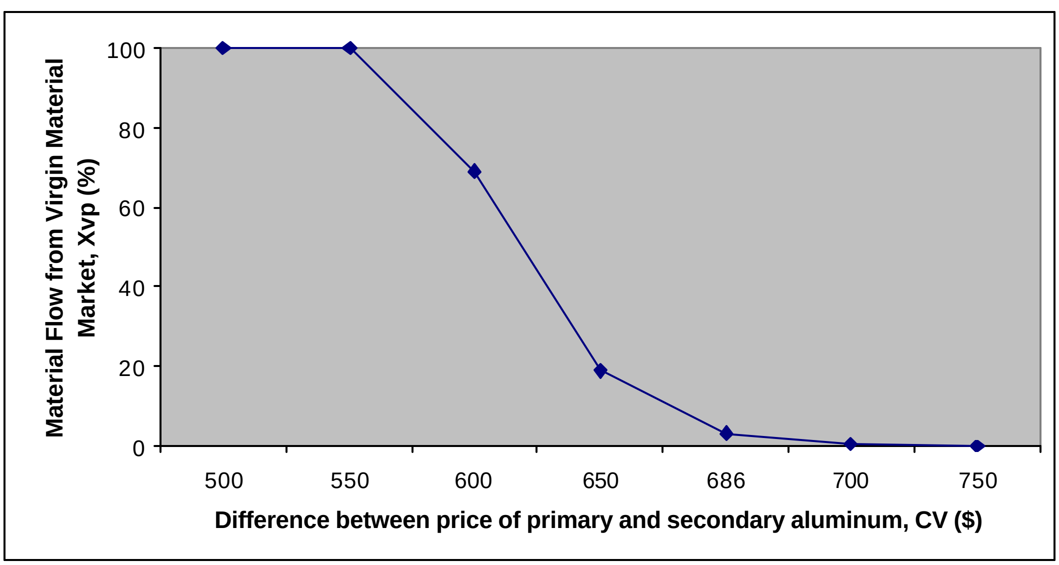

Fig. 6: The relationship between the primary aluminum consumption and the difference between price of primary and secondary aluminum in LA County

7. Summary and Conclusion

In this study, we developed a joint optimization framework for a sustainable reverse logistics system with a concentration on a B2B material exchange network. The modeling effort carefully integrated ecological costs as well as operational costs toward a more sustainable closed loop supply network. A survey study and data from the literature were employed to estimate the model parameters. The implementation procedure was demonstrated on an example based on the aluminum industry in Los Angeles County. Due to the combinatorial nature of the model, Genetic Algorithm was employed to solve the model more efficiently for large size problems. In order to generate more accurate solutions faster, a traditional GA algorithm was modified and then applied to the problem. The results showed that the modified GA approach found solutions within 2% of the optimal solution, on the majority of tested problems. An analysis was also provided to demonstrate the role of regulators in promoting a sustainable material treatment. It was described that available low price virgin materials can sometimes lead to abolition of a recycling practice, which in these cases, regulators should utilize creative policies (appropriate penalties and incentives) to promote environmental friendly programs. As an extension to this study, we suggest to remove regional boundary constrains and develop a global model, which incorporates international transition of waste materials and recycling activities. In this model waste materials can be collected from one country and recycled in another one. Similar to the regional model, the roll of regulators seems to be essential in order to promote sustainable treatment in cases where the trade-off between transportation cost and environmental cost is not in favor of sustainable treatment. We also recommend future research to include probability aspect of the model parameters into a stochastic modeling effort. We also suggest testing this model with the environmental costing approaches other than contingent valuation and EIO. For example a life cycle costing to include both internalities and externalities would be a next best way to estimate the environmental parameters for this model (McLaughlin and Elwood, 1996).

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References:

[1] Ammons JC, Realff MJ and Newton D Decision models for reverse production system design. In: Madu CN (eds) Handbook of Environmentally Conscious Manufacturing. Kluwer: Boston, 2000: pp 341–362.

[2] Barros A.I., Dekker R., Scholten V. A Two-Level Network for Recycling Sand: A Case Study. European Journal of Operational Research 1998; 110: 199-214.

[3] Berck P., Goldman G. California Beverage Container Recycling and Litter Reduction Study. Report to the Department of Conservation, CA 2003.

[4] Blackburn J. D., Guide Jr. D. R., Souza, G. C., Van Wassenhove L. N. Reverse Supply Networks for Commercial Returns. Harvard Business Review 2004; 46(2): 6-22.

[5] Brito M.P., Flapper S.D.P., Dekker, R. Reverse Logistics: A Review of Case Studies. Econometric Institute Report EI 2002-21 2002.

[6] Caro F., Andalaft R., Silva X., Weintraub A., Sapunar P., Cabello M. Evaluating the Economic Cost of Environmental Measures in Plantation Harvesting through the Use of Mathematical Models. Journal of Production and Operations Management 2003; 12(3):290-306.

[7] Corbett C. and Kleindrofer P.R.. Introduction to the Special Issue to the Environmental Management and Operation (Part 1: Manufacturing and Eco-logistics). Journal of Production and Operations Management 2001a; 10(2):107-112.

[8] Corbett C. and Kleindrofer P.R. Introduction to the Special Issue to the Environmental Management and Operation (Part 2: Integrating Management and Environmental Management Systems). Journal of Production and Operations Management 2001b; 10(3): 225-228.

[9] Daugherty P J., Richey R G., Genchev S E., and Chen H. Reverse Logistics: Superior Performance through Focused Resource Commitments to Information Tech. Transportation Research Part E 2005; 41(2):77-92.

[10] Dowlatshahi S. Developing a Theory of Reverse Logistics. Interfaces; 2000.30(3): 143-155.

[11] Fleischmann M., Bloemhof-Ruwaard J. M., Dekker R., Van der Laan E., Van Nunen J.A.E.E., Wassenhove L.V. Quantitative Models for Reverse Logistics: A Review. European J. of Operational Research 1997;103:1-17

[12] Fleischmann M., Beullens P., Bloemhof-Ruwaard J.M., Wassenhove L.V. The Impact of Product Recovery on Logistics Network Design. Journal of Production and Operations Management 2001; 10 (2): 156-173.

[13] Guide, V. D. R., Van Wassenhove, L. N. Closed-Loop Supply Networks: Practice and Potential. Interfaces 2003; 33(6): 1-2.

[14] Goldberg D. A. Genetic Algorithms in Search, Optimization, and Machine Learning. Addison-Wesley Publishing Company, Inc. 1989.

[15] Hall D. K., Williams J. R. S., Bayr K. J. Glacier Recession in Iceland and Austria, EOS, 1992; 73(12): 129, 135, and 141.

[16] Jayaraman V., Patterson R.P., Rolland E. The Design of Reverse Distribution Networks: Models and Solution Procedures. 1999, Cited at: http://www.bus.ualberta.ca/rayp/Refurb65.PDF

[17] Kopicki R.J., Berg M.J., Legg L., Dasappa V., and Maggioni C.: Reuse and Recycling: Reverse Logistics Opportunities, Council of Logistics Management, Oak Brook, IL. 1993.

[18] Kostecki M. The Durable Use of Consumer Products: New Options for Business and Consumption, Kluwer Academic Publishers 1998.

[19] Krikke H., Bloemhof-Ruwaard J., Van Wassenhove L. Design of Closed Loop Supply Networks: A Production and Return Network for Refrigerators. Erim Report Series Research in Management, ERS-2001-45-LIS 2001.

[20] Krikke H. R., Koo E.J., Schuur P.C. Network Design in Reverse Logistics: A Quantitative Model, Lecture notes in Economics and Math Sys. Springer Verlag Berlin 1999.

[21] Kroon L., Vrijens G. Returnable Containers: an Example of Reverse Logistics. International Journal of Physical Distribution & Logistics Management 1995; 25(2): 56-68.

[22] Krupnick A, Portney P Controlling Urban Air Pollution: A Benefit-cost Assessment. Science 91; 252: 522-528.

[23] Kummer N., Turk V. Sustainable supply network management. Triple innova. June 2006. Cited at: http://de.triple-innova.com/custom/user/resources/ti_SCMBrochure.pdf.

[24] Lagioia G., de Marco O., Pizzoli Mazzacane E., Materials flow analysis of the Italian economy, Industrial Ecology 2001; 4(2): 55-70.

[25] Litman T., Transportation Cost Analysis, Victoria Transportation Policy Institute 1999.

[26] Locklear E. C. A Decision Support System for the Reverse Logistics of Product Take-Back Using Geographic Information Systems and the Concepts of Sustainability, M.S. Thesis, School of the Environment, Univ. of South Carolina, SC 2001.

[27] Louwers D., Kip B.J., Peters E., Souren F., Flapper S.D.P. A Facility Location-Allocation Model for Reusing Carpet Materials. Computer and Industrial Engineering 1999; 36(4): 1-15.

[28] Marin A., Pelegrin B. The Return Plant Location Problem: Modeling and Resolution. European Journal of Operations Research, 1998; 104: 375-392.

[29] McLaughlin, S., Elwood H. Environmental accounting and EMS. Pollution Prevention Review, Publisher: Spring 1996; 13-24.

[30] Mondschein S.V., Schilkrut A. Optimal Investment Policies for Pollution Control in the Copper Industry. Interfaces 1997; 27(6): 69-87.

[31] Nagurney A., Toyasaki F. Reverse Supply Network Management and Electronic Waste Recycling: a Multi-tiered Network Equilibrium Framework for E-cycling. Transportation Research Part E: Logistics and Transportation Review 2005; 41(1):1-28.

[32] NASA website Jan. 2006: http://www.nasa.gov/vision/earth/environment/2005_warmest.html

[33] Plunkert P.A. Aluminum in April 2002: U.S. Geological Survey. Mineral Industry Surveys, June 2002a.

[34] Rogers D.S., Tibben-Lembke R.S. Going Backwards: Reverse Logistics Trends and Practices, Reverse Logistics Executive Council, Pittsburgh, PA 1999.

[35] Saleem S. A Sustainable Decision Support System for the Demanufacturing Process of Product Take-back based on Concepts of Industrial Ecology. M.S. dissertation, Columbia: University of South Carolina Pres 2001.

[36] Schultmann F, Engels B, Rents O. Closed-Loop Supply Network for Spent Batteries. Interfaces 03;33(6):57-71.

[37] Simms A. Free trade's free ride on the global climate. Publisher: New Economics Foundation 2000.

[38] Small K.A. Estimating the Air Pollution Costs of Transport Modes. Journal of Transport Economics and Policy 1977; 11: 109-132.

[39] Small K., Kazimi C. On the Costs of Emissions from Motor Vehicles. Journal of Transport Economics and Policy 1995; 29(1): 7-32.

[40] Sonnemann W. Environmental Damage Estimations in Industrial Process Networks. Ph.D. Thesis, Dept. of Chemical Engineering, Universitat Rovira I Virgili, Tarragona, Spain. 2002.

[41] Spengler T., Puchert H., Penkuhn T., Rentz O. Environmental Integrated Production and Recycling Management. European Journal of Operations Research 1997; 97: 308-326.

[42] Stock J.R. Reverse Logistics, Council of Logistics Management, Oak Brook, IL. 1992.

[43] Stock J.R. Development and Implementation of Reverse Logistics Program. Council of Logistics Management, IL, 1998.

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