Selection of Remanufacturing Facility Locations to Minimize Cost and Environmental Impact

Abigail R. Clarke[1], Qiong Zhang[2], John K. Gershenson[1], and John W. Sutherland[1]

[1] Department of Mechanical Engineering-Engineering Mechanics, Sustainable Futures Institute, Michigan Technological University, Houghton, Michigan, USA

[2] Department of Civil and Environmental Engineering, Sustainable Futures Institute, Michigan Technological University, Houghton, Michigan, USA

Abstract

Remanufacturing is gaining prominence as revenue streams develop partially due to environmentally motivated product take-back legislation. The economic and environmental factors driving remanufacturing influence the design and scale of distribution/collection systems. The minimum efficient scale for environmental and economic performance is addressed in this paper via a p-median formulation, i.e., calculating the minimum weighted distance from p manufacturing/remanufacturing facilities to n demand locations. A shoe manufacturing and resoling example investigates siting strategies employed by the footwear industry, namely i) centralization, where a few core facilities reach the entire market and ii) decentralization, which distributes smaller-scale facilities to service market regions.

Keywords:
Environmental Impact; Facility Siting; Network Optimization

1 INTRODUCTION

Since product take-back is mandated in Europe, its effects have spread to producers worldwide and to the design of distribution systems along with products. Manufacturers are beginning to recognize that creating environmentally responsible products and processes decreases spending on operation and overhead, as well as prospective financial liability for environmental and human health damages [1]. Certain industries have experimented with remanufacturing and have met both success and failure [2]. Office furniture remanufacturing led by Herman Miller, Steelcase, and Haworth had been financially successful in the past. However, moving from independently owned decentralized remanufacturing facilities with low production volumes to centralized high production volume facilities ended the industry's success due to high transportation costs and management troubles with returned products [3]. Transportation costs and logistics have great bearing on the success of remanufacturing operations [4]. Hence restructuring facility locations and distribution routing strategies can ensure or weaken the economics of remanufacturing. More industries may consider remanufacturing as an attractive choice to meeting existing or looming legislative requirements, necessitating concrete strategies for facility location and distribution that maintain financial viability.

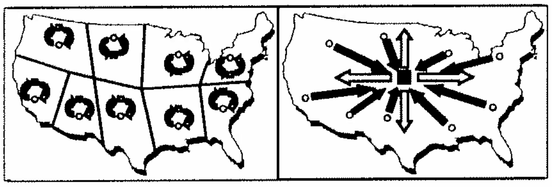
The difficulty in gathering returned products together has significant financial and environmental impacts. Logistics expenses make up a substantial portion of the costs in the reverse supply chain [4]. Because of differences in transportation costs between supply chains, reverse network design is key to economic feasibility of product remanufacturing [5]. Relocating facilities may reduce cost and environmental damages.

Processing of low value products relies on economies of scale, encouraging centralized networks. Higher transportation costs, however, tend to drive networks to decentralize [5]. The environmental impact of many decentralized facilities may be greater than a large centralized facility with the same total capacity. Alternatively, pollutants that are concentrated in one area may cause greater damage. Hence strategies for siting remanufacturing facilities including the scale of operation balance both economic and environmental performance of supply chains.

2 BACKGROUND

Companies need to identify effective strategies for establishing forward and reverse networks simultaneously [11]. Exploring different strategic options such as centralization or decentralization can provide network design solutions (Figure 1). 'In a centrali[zed] network each activity is installed at a few locations only, whereas in a [decentralized] network the same operation is carried out at several different locations in parallel [6].'

The siting of manufacturing, distribution, collection, and remanufacturing facilities depends on the decision about how close such facilities should be to where demand for manufactured and remanufactured products exists [7]. When products can be reused many times with little change to the



(a) (b)

Figure 1: Decentralized (a) and centralized (b) networks

product, transportation becomes a relatively large portion of the total costs, effectively promoting decentralized locations close to customers [6]. On the other hand, '[f]acilities with high fixed costs generally require centralised operations, while other activities may be decentralised to reduce transportation costs [6].' Processing low value products relies on economies of scale that are met through a centralization of the collection network structure [6]. Realff et al. [8,9] note that as the difficulty of manufacturing increases – reuse, remanufacturing, and refurbishing become favored recovery strategies. As centralized and decentralized strategies in addition to other factors encourage product recovery, the environmental impact of such recovery warrants increased consideration.

Environmental impact has been previously addressed in methods for the optimization of product take back networks [10-12]. However, the effect of location, i.e. spatial differences, on environmental damage has rarely been considered in remanufacturing facility siting optimization. In order to apply strategic environmental decision-making this paper presents a method to evaluate re/manufacturing operations for when and where to use many decentralized facilities or a few centralized facilities for a forward and reverse supply chain.

3 METHOD FOR FACILITY SITING

The challenge of this method is where to locate manufacturing/remanufacturing facilities and meet the demands of nearby population centers. Principles of network analysis and environmental impact assessment will be integrated, and incorporated via weighted costs and environmental indices, to obtain a solution that simultaneously addresses both objectives.

This situation can be described by the p-median problem, where the number of facilities to site, p, will be varied from 1 to the number of demand centers, n. The overarching idea is to select the best value for p that minimizes costs and environmental impacts. For each scenario, which sites a specific number of facilities, the total production capacity of the set of facilities will remain the same. This production capacity equals the collective demand, but the production capacity of an individual facility will decrease as the number of facilities sited increases with the production costs scaled accordingly. A simple schematic outlying a potential solution to the problem addressed by this method for siting three re/manufacturing facilities is displayed in Figure 2.

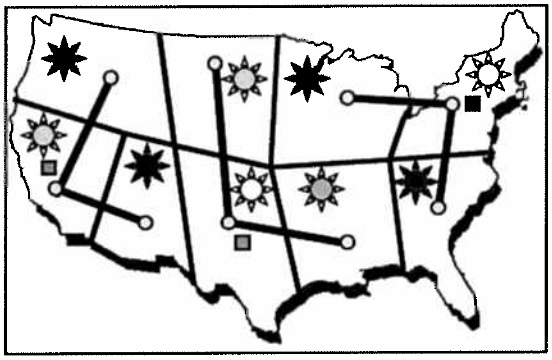


Figure 2: Theoretical minimal solution for siting 3 facilities, p=3, striped lines represent optimized road networks and suns represent regional variation in production environmental impact –where greater shading indicates greater impact

3.1 Model for Network Costs

Facility siting optimization may be characterized as the p-median problem, i.e. siting facilities at the smallest demand-weighted distance from all demand locations. Environmental impact is included as a second decision variable in addition to distance, a common decision variable used in supply chain optimization.

Equation 1 shows the objective function for the p-median problem. Equations 2 through 6 are the associated constraints of the objective function. Subscript i denotes a node and subscript j a facility, h_i is the demand for node i, d_{ij} is the distance between node i and facility j, T_j is the human and ecological toxicity potential at facility j, M_{ij} denotes existence or lack of a connection between node i and facility j, L_j denotes the existence or lack of a facility at j, p is the number of facilities to site, and λ_i is the Lagrange multiplier [13].

$$\text{Minimize } \sum_i \sum_j h_i (T_j + d_{ij}) M_{ij} \tag{1}$$

$$\sum_j M_{ij} = 1 \quad \forall \text{i} \tag{2}$$

$$\sum_j L_j = p \tag{3}$$

$$M_{ij} - L_j \le 0 \quad \forall \text{i, j} \tag{4}$$

$$L_j = 0,1 \quad \forall \text{j} \tag{5}$$

$$M_{ij} = 0,1 \quad \forall \text{i, j} \tag{6}$$

An algorithm for solving the p-median problem (for a known value of p) using the Lagrangian Relaxation technique was programmed into Matlab. Lagrangian Relaxation allows a constraint to be unmet, where the optimal solution occurs when the relaxed constraint is met. In this case, the relaxed constraint is Equation 2. The Lagrange multiplier is varied systematically before an iteration of the heuristic begins to bring the constraint closer to meeting the unmet condition.

Equation 7 is solved prior to each iteration to update the Lagrange multiplier. Equation 8 calculates the step size, t^n. Subscript n denotes the number of the iteration, λ_i^n is the Lagrange multiplier for the iteration, M_{ij}^n denotes existence or lack of a connection between node i and facility j for the iteration, α^n is a factor that is initialized to a value of 2, and is decreased every 20th iteration when the lower bound does not improve, UB is the upper bound, and LB^n is the objective function value or the lower bound for the iteration [13].

$$\lambda_i^{n+1} = \max\,[0, \lambda_i^n - t^n(\sum_j M_{ij}^n - 1)] \tag{7}$$

$$t^n = \frac{\alpha^n(UB - LB^n)}{\sum_i(\sum_j M_{ij}^n - 1)^2} \tag{8}$$

The effect of having an unmet constraint becomes reflected in the objective function via the Lagrange multiplier term. By finding upper and lower bounds through optimizing the new objective function, in subsequent iterations a solution meeting all constraints can be found (if one exists) [13]. Equation 9 shows the revised objective function for the Lagrangian Relaxation formulation.

$$\text{Minimize } \sum_i\sum_j h_i(T_j + d_{ij})M_{ij} + \sum_i \lambda_i(1 - \sum_j M_{ij}) \tag{9}$$

$$= \sum_i\sum_j [h_i(T_j + d_{ij}) - \lambda_i]M_{ij} + \sum_i \lambda_i$$

3.2 Evaluating Environmental Impacts

The environmental impacts of manufacturing and remanufacturing of products are primarily due to transportation and production. The global warming potential and composite human and ecological toxicity potentials were aggregated into one index to represent environmental impacts of transportation and production. The SimaPro 7.1 database was used to provide the transportation environmental impact data [14]. Pollutant releases for manufacturing and remanufacturing operations to the environment were obtained from Toxic Release Inventory reports for footwear manufacturers and shoe sole producers respectively [15]; chemical release amounts were averaged from all of these reports to represent production environmental impact. All indices were calculated for annual production levels on a per unit (pair of shoes) basis for easy updating if production output levels changed.

The global warming potential was calculated in CO_2 equivalents using the International Panel on Climate Change's indicator [16] incorporated into the Eco-Indicator 95 method as the greenhouse effect [17]. The composite toxicity potential is an aggregate of three indicators for inhalation, ingestion, and fish toxicity [18]. These indicators are calculated from chemical toxicity data, the concentration of released chemicals that transport into different compartments of the environment e.g., surface water, and exposure factors. Exposure factors represent the amount of a chemical that an individual encounters through inhalation, ingestion, or dermal contact [18]. The three indicators are normalized by dividing all values by the highest values for that indicator, multiplying by a weighting factor, and summing to form the toxicity potential [19]. Each indicator was weighted equally as one-third of the total impact.

The concentrations of released chemicals in different environmental compartments were estimated using the multimedia fate and transport model, CHEMGL [20]. The U.S. national version of CHEMGL splits the U.S. into 9 distinct ecological regions [21]. A chemical released in a particular region will concentrate at different levels in the specific environmental compartments. The toxicity potential was calculated for every region where a facility might locate and for the number of shoes requested by a demand location.

Normalization and Weighting

Before adding the toxicity potential to the objective function, the toxicity potential, T_{ij}, and distance, d_{ij}, are normalized in the same manner as the three indicators mentioned above – dividing by the highest respective value and weighting each variable equally at one-half of total impact. Both cost and the transportation environmental impact (global warming potential) are explicitly considered in the objective function through the number of facilities sited (p), demand, and distance traveled. Multiplying factors by the three variables begets fixed and transportation costs as well as environmental impact. Adding the normalized toxicity potential, T_{ij}, and normalized distance, d_{ij}, then multiplying the decision variables with demand, h_i, creates the objective function (Equation 1).

4 APPLICATION OF THE METHOD

In order to provide the method's proof of concept a simplified theoretical example is considered. A hypothetical new business, Ecofeet, manufactures and resoles shoes. The Ecofeet's management notes that two successful business strategies exist for re/manufacturing facility location in the shoe industry. For the first strategy, shoes are sent back to one centralized production facility where all shoe remanufacturing (resoling) occurs. For the second strategy, shoes are produced and resoled in each of the demand locations, a more decentralized strategy. Ecofeet wants to select a facility siting strategy that makes the most fiscal and environmental sense for its operations.

4.1 Ecofeet's Operations

The demand locations as well as the potential manufacturing and remanufacturing facility sites for Ecofeet are assumed to be the nine largest U.S. cities by population (Table 1). The distance taken for delivering products within a demand location is neglected. Facility location scenarios are investigated ranging from siting one large facility to having one small facility at each of the 9 demand locations. All transportation is assumed to occur by 16 ton trucks at a cost of \$.95 USD per truck-km, or \$1.53 USD per truck-mile [22]. The average load for a fully loaded truck is assumed to be 9.78 tons (8876.5 kilograms) or 3240 pairs of shoes.

City	Annual Demand	p	Fixed Costs
New York	3449269	1	$72,918,250
Philadelphia	609733	2	$48,048,122
Chicago	1171385	3	$37,644,769
Los Angeles	1617716	4	$31,660,412
Phoenix	597405	5	$27,681,911
San Diego	523856	6	$24,805,317
Dallas	496376	7	$22,607,691
Houston	841682	8	$20,862,037
San Antonio	521208	9	$19,434,487

Table 1: Demand and fixed costs [22-24]

In order to obtain the demand for shoe consumption, national sales data from the American Apparel & Footwear Association [24] was used. Ecofeet's production output is 10% of average U.S. national annual sales for the juvenile's, men's, and women's footwear categories (excluding all work or athletic shoes). The total sales of footwear to juveniles, men, and women for 2002-2005 was divided by the national U.S. population from that same time period and averaged among the three sales categories to obtain the per capita demand for shoes. Fixed costs were assumed to follow economies of scale based on Equation 10 derived from a footwear manufacturer's annual reports [25]. C represents costs and X represents production output in pairs of shoes.

$$C = 4516X^{.6018} \quad (10)$$

4.2 Results

Three cases of product take-back were considered: no take back, 10%, and 100% return. Not surprisingly the no take back case had the lowest overall objective function value. The no return case requires less transportation and processing then both other cases that involve remanufacturing operations (Table 2). The objective function values among the cases differ by a factor near the rate of product return. Similar trends emerged from all three cases. The objective function values for siting one and two facilities are significantly greater than the steady descent from siting three to nine facilities. For each case, the objective function was minimized when the greatest number of facilities (9) was sited.

	Objective Function		
p	no return	10%	100%
1	4111100	4406000	8216700
2	2282100	2396500	4558800
3	1681800	1734500	3358300
4	1435900	1463800	2866400
5	1374500	1396400	2743700
6	1342700	1361500	2680100
7	1315200	1331200	2625100
8	1298400	1312700	2591500
9	1283100	1295900	2560900

Table 2: Objective function of no return, 10%, and 100% return cases

	Cost	Environmental Impact		Objective
p	USD ($)	GWP	Toxicity	
1	$77,245,000	30079	2336500	4406000
2	$101,780,000	11269	6053500	2396500
3	$119,600,000	4217	7649700	1734500
4	$134,120,000	2379	6635700	1463800
5	$146,580,000	1515	6226400	1396400
6	$157,620,000	958	6083000	1361500
7	$167,600,000	497	5949900	1331200
8	$176,750,000	218	5476800	1312700
9	$185,240,000	0	4234900	1295900

Table 3: Objective function, cost, and environmental impact for the 10% product return case

The highest objective function value, when one facility is sited, is more than 3 times the minimal solution of the optimal solution for all cases. This difference can be better explained through a specific case. Table 3 shows the general trends for the 10% product return case. The objective function improves steadily as the number of facilities sites is increased. As the number of facilities increases the costs rise and the environmental impact due to transportation falls. The environmental impact due to production (the toxicity potential) varies greatly when siting different numbers of facilities. This behavior is explained by the different location of facilities and the corresponding sensitivity of the respective surrounding environs.

The equal weighting of environmental impact and costs undoubtedly affected the optimization outcome. For the solution siting the greatest number of facilities, environmental impact due to transportation (global warming potential or GWP) was at its lowest value. When siting the greatest number of facilities in this example, the environmental impact due to production (toxicity potential) for every case was at its second lowest value. The optimal solution for reducing toxicity potential or cost occurs when siting a single facility. Siting a single facility was the scenario with the highest objective function and worst optimality overall when the global warming potential, toxicity potential, and cost are considered with equal weighting. Therefore, the optimal solution was greatly influenced by the environmental impacts due to transportation. The great difference between transportation environmental impact values explains why the objective function is much greater for siting a single facility than the objective function for the scenario siting 9 facilities. This result is not anomalous since transportation environmental impact and costs were both greatly undervalued.

Most of the costs in this example were due to the fixed costs, which includes set-up and equipment expenses on an annualized basis for all cases. The 10% product return case demonstrates that transportation costs are a small fraction of the fixed costs for this example (Table 4). These transportation costs assume delivery by truck at high volumes for both forward and reverse distribution. Likely the transportation costs are conservatively low since resoled shoes are more likely to be returned to individual customers a pair at a time. Shipping to individual customers would significantly increase reverse distribution costs per pair of shoes. Considering distribution within a city would also increase costs.

p	Fixed	Transport	%
1	$77,220,000	$25,000	0.03%
2	$101,770,000	$10,000	0.01%
3	$119,600,000	$0	0.00%
4	$134,120,000	$0	0.00%
5	$146,580,000	$0	0.00%
6	$157,620,000	$0	0.00%
7	$167,600,000	$0	0.00%
8	$176,750,000	$0	0.00%
9	$185,240,000	$0	0.00%

Table 4: Fixed, transportation costs and % transportation cost is of fixed costs for the 10% product return case

All of the cases converged to solutions that sited facilities in the same locations for each scenario (Table 5). This finding makes sense since most of the environmental impact of shoe production and remanufacturing in this example comes from producing the soles. The solutions for siting three and greater facilities seem to follow a pattern of successive selection of the next facility that contributes least to the objective function in terms of cost and toxicity potential. As long as total distance traveled for transport decreases the global warming potential will also reduce. The siting of one or two facilities is not described by this pattern. This distinction shows that highly centralized and more decentralized siting strategies come to unique location solutions. The results for the no product return and 100% return cases are provided in the Appendix.

Demand	Facility Assignments for various p								
(Abbreviations)	1	2	3	4	5	6	7	8	9
New York (NY)	PA	NY	NY	NY	NY	NY	NY	NY	NY
Philadelphia (PA)	PA	NY	NY	NY	NY	NY	NY	NY	PA
Chicago (CH)	PA	NY	NY	CH	CH	CH	CH	CH	CH
Los Angeles (LA)	PA	PH	LA	LA	LA	LA	LA	LA	LA
Phoenix (PH)	PA	PH	LA	LA	PH	PH	PH	PH	PH
San Diego (SD)	PA	PH	LA	LA	LA	LA	LA	SD	SD
Dallas (DA)	PA	PH	HO	HO	HO	DA	DA	DA	DA
Houston (HO)	PA	PH	HO	HO	HO	HO	HO	HO	HO
San Antonio (SA)	PA	PH	HO	HO	HO	HO	SA	SA	SA

Table 5: Facility assignments for siting one facility to nine, from p=1 to 9, for all three scenarios

5 CONCLUSIONS

This shoe production and resoling example demonstrates that this method can be applied to compare cost and environmental impact trade-offs for siting many manufacturing and remanufacturing operations close to customers or at a few centrally located facilities. The method and remanufacturing example explained in this paper simplifies many of the financial and business concerns and ignores geographical or legal constraints. This method is not meant to consider all of the concerns of facility siting.

However, refining several issues in this method warrant adjustment to better reflect the reality of facility siting decision-making. Existing supply chain facilities influence new siting decisions. Also, products are often delivered to metro areas instead of city centers, increasing travel. Scale of environmental impact varies; incorporating the complexity of how pollution scales with production output can more accurately compare costs and environmental impacts.

For this specific example a highly decentralized structure for the manufacturing and remanufacturing facility network produces the minimal objective function value when cost and environmental impact are weighted equally. This finding is reflected by the siting realities of successful decentralized shoe resoling businesses authorized by original footwear manufacturers in the U.S. The environmental impact associated with transportation was critical. However transportation costs were likely undervalued, perhaps biasing the results. Several important conclusions can be drawn.

- Centralization and decentralization strategies determine different optimal facility sites
- Toxicity potential of chemical releases changes significantly between locations
- Decentralized facility siting strategies have the potential to balance production costs and environmental impacts for particular industrial situations

These conclusions reiterate that each particular industry and every new location for facilities will come to different optimal solutions between centralized and decentralized siting strategies.

Despite the limitations in the scope of this method, it fills an emerging need for representing future environmental impacts of industrial and business decisions balanced with costs. Concern for the environment, especially consequences for human and environmental health, grows. Therefore tools for choosing where to locate which types of production like this method will become increasingly useful aiding decision-makers in the future.

6 ACKNOWLEDGMENTS

The authors gratefully acknowledge the support from the National Science Foundation through the Sustainable Futures IGERT project (DGE 0333401)

7 REFERENCES

[1] Clarke, A. and Gershenson, J. K., 2006, Design for the Life-Cycle, Handbook of Environmentally Conscious Mechanical Design, Kutz, M., ed., John Wiley & Sons, Inc., Hoboken, New Jersey, 67-125.

[2] Thierry, M., Salomon, M., van Nunen, J. and van Wassenhove, L. N., 1995, Strategic issues in product recovery management, California Management Review, **37**/2:114-135.

[3] Gunter, K. L., 2004,Inventory and value management in demanufacturing facilites, Mechanical Engineering-Engineering Mechanics, Michigan Technological University, Houghton, Michigan.

[4] Krikke, H., van Harten, A. and Schuur, P. C., 1999, Business case Océ: reverse logistic network re-design of copiers, OR Spektrum, **21**/3:381-409.

[5] Fleischmann, M., Beullens, P., Bloemhof-Ruwaard, J. M. and van Wassenhove, L. N., 2001, The impact of product recovery on logistics network design, Production and Operations Management, **10**/2:156-173.

[6] Fleischmann, M., Krikke, H. R., Dekker, R. and Flapper, S. D. P., 2000, A characterisation of logistics networks for product recovery, Omega, **28**/6:653-666.

[7] Jayaraman, V., Guide, V. D. R., Jr. and Srivastava, R., 1999, A Closed-loop logistics model for remanufacturing, Journal of the Operational Research Society, **50**/5:497-508.

[8] Realff, M. J., Ammons, J. C. and Newton, D., 1999, Carpet recycling: determining the reverse production system design, Polymer-Plastics Technology and Engineering, **38**/3:547-567.

[9] Realff, M. J., Ammons, J. C. and Newton, D., 2000, Strategic design of reverse production systems, Computers and Chemical Engineering, **24**/2:991-996.

[10] Spengler, T., Puchert, H., Penkuhn, T. and Rentz, O., 1997, Environmental integrated production and recycling management, European Journal of Operational Research, **97**/2:308-326.

[11] Krikke, H., Bloemhof-Ruwaard, J. and Van Wassenhove, L. N., 2003, Concurrent product and closed-loop supply chain design with an application to refrigerators, International Journal of Production Research, **41**/16:3689-3719.

[12] Bloemhof-Ruwaard, J. M., Van Wassenhove, L. N., Gabel, H. L. and Weaver, P. M., 1996, An environmental life cycle optimization model for the European pulp and paper industry, Omega, **24**/6:615-629.

[13] Daskin, M. S., 1995, Network and Discrete Location: Models Algorithms and Applications, John Wiley and Sons, Inc., New York.

[14] Pré Consultants, 2006, SimaPro 7.1 Multi User, Pré Consultants, http://www.pre.nl/simapro/simapro_lca_software.htm

[15] U.S. Environmental Protection Agency, 2007, TRI Explorer, http://www.epa.gov/triexplorer/

[16] Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., Johnson, C. A. and Trenberth, K., ed., 2001, *Climate Change 2001: The Scientific Basis,* IPCC Third Assessment Report, International Panel on Climate Change, Geneva, Switzerland.

[17] Goedkoop, M., 1996, The Eco-Indicator 95: Final Report, *90-72130-80-4,* PRé Consultants, Amersfoort, the Netherlands.

[18] Zhang, Q., Crittenden, J. C. and Mihelcic, J. R., 2001, Does simplifying transport and exposure yield reliable results? An analysis of four risk assessment methods, Environmental Science and Technology, **35**/6:1282-1288.

[19] Shonnard, D. R. and Hiew, D. S., 2000, Comparative Environmental Assessments of VOC Recovery and Recycle Design Alternatives for a Gaseous Waste Stream, Environmental Science & Technology, **34**/24:5222-5228.

[20] Zhang, Q., Crittenden, J. C., Shonnard, D. and Mihelcic, J. R., 2003, Development and evaluation of an environmental multimedia fate model CHEMGL for the Great Lakes region, Chemosphere, **50**/10:1377-1397.

[21] Wright, H. E., 2007,Integrating Life Cycle Assessment and Relative Risk for an Emerging Chemical of Concern: The Flame Retardant, Decabromodiphenyl ether or oxide (DecaBDE), *M.S.,* Civil and Environmental Engineering Michigan Technological University, Houghton, Michigan.

[22] Barnes, G. and Langworthy, P., 2003, The Per-mile Costs of Operating Automobiles and Trucks, Minnesota Department of Transportation, St. Paul, Minnesota.

[23] U.S. Census Bureau, 2006, Table 1: Annual Estimates of the Population for the United States, Regions, States, and for Puerto Rico: April 1, 2000 to July 1, 2006 Population Division.

[24] American Apparel & Footwear Association, 2006, ShoeStats 2006, American Apparel & Footwear Association, Arlington, Virginia.

[25] Crocs Inc., 2006, Prospectus, Crocs, Inc., Niwot, Colorado.

8 APPENDIX

	Cost	Environmental Impact		Objective
p	USD ($)	GWP	Toxicity	
1	$72,938,000	24862	2124900	4111100
2	$96,104,000	9311	5505200	2282100
3	$112,940,000	3486	6956800	1681800
4	$126,640,000	1966	6034700	1435900
5	$138,410,000	1251	5662500	1374500
6	$148,830,000	791	5532100	1342700
7	$158,250,000	411	5411000	1315200
8	$166,900,000	231	4980800	1298400
9	$174,910,000	0	3851300	1283100

Table 6: Objective function, cost, and environmental impact for the no product return case

	Cost	Environmental Impact		Objective
p	USD ($)	GWP	Toxicity	
1	$110,700,887	99448	4241100	8216700
2	$145,850,000	37245	10988000	4558800
3	$171,400,000	13943	13885000	3358300
4	$192,200,000	7863	12044000	2866400
5	$210,050,000	5005	11302000	2743700
6	$225,870,000	3164	11041000	2680100
7	$240,170,000	1644	10800000	2625100
8	$253,280,000	722	9941000	2591500
9	$265,450,000	0	7686800	2560900

Table 7: Objective function, cost, and environmental impact for the 100% product return case