SOLVING REVERSE LOGISTICS:
OPTIMIZING MULTI-ECHELON REVERSE NETWORK

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ABSTRACT

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As part of sustainable development initiative, product take-back strategy encourages manufacturers to transform definition of sustainability into business practices that would reduce environmental wastes, while reducing increasingly growing waste management cost from municipal governments. This thesis evaluates the complexity of reverse logistics with regards to product take-back strategy development and presents a programmatic approach of determining appropriate number and location of initial collection points that would reduce variable cost, while promoting more frequent product return. The application of this thesis would grant 'green' opportunities for organizations to strategize and execute cost-efficient reverse logistics to advance sustainability. A single-objective, mixed-integer, binary programming was utilized to optimize the variable cost of handling, transshipping, facilities, and carrying of reverse logistics. Apple Inc.'s current product take-back strategy was carefully evaluated and analyzed to suggest potential improvements to its system. Network optimization design methodology along with case study results would provide useful managerial insights and suggest avenues for further research and applications.

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CHAPTER 1

INTRODUCTION

Sustainability initiatives brought increasingly growing number of countries across EU and Eastern Asia to enact legislations that would demand manufacturers to assume higher responsibilities on their end-of-life products (Toffel, 2003). In many Western European countries, “Green” parties have been initiated to deliver environmental concerns due to industrial and operational wastes into public, social and political action. Accordingly, nearly half of 50 U.S. state legislatures introduced similar rules. In response to globally growing concerns for sustainability, many durable product manufacturers began to launch programs that would both reduce operational wastes and advocate environmental safety. The intent of the ‘product take-back’ laws is to pressurize durable product manufacturers to pursue sustainable development and to transform it into business practices that would promote environmental welfare, while avoiding increasingly growing waste management cost charged by municipal governments. In addition, higher customer expectations on manufacturers’ environmental responsibility have also compelled manufacturers to assume increased responsibility with regards to placing their products on the market.

‘Product take-back’ targets a wide variety of manufacturers of batteries, automobiles, waste packaging, and electrical or electronic products. Instead of filling landfills, more manufacturers are urged to take back their products for reassembling, repackaging, remanufacturing, or component recycling before redistributing to the market. Value recovery process of returned products consists of several sequential activities: collection, evaluation, disassembly, capture of recyclable components, and

disposal of residuals as hazardous wastes (White et al., 2001). Despite growing participation within industries, most value recovery processes still remain small, independent and highly fragmented (Thierry et al., 1995).

To strategize cost efficient product take-back plan, there has been growing interest in the development of reverse logistics that drives reverse flow of returned products from the end customers back to the original equipment manufacturers. Efficient planning and execution of reverse logistics would provide firms a competitive edge in the development of sustainable, yet profit-generating, business strategies. Sound strategy and execution of reverse logistics would promote not only economic, but also environmental benefits as value of returned products should be counted towards savings of raw material and labor. While reverse logistics do not promise guaranteed savings, many have reported noticeable benefits: 40% less overall cost, 33% less inventory usage, and 44% higher customer satisfaction (Poirier, 2004). From environmental viewpoint, reverse logistics make significant contribution towards reduction of hazardous waste (Ginter and Starling, 1978), alleviation of landfill saturation (Kroon and Vrijens, 1995) and preservation of scarce raw materials (Ginter and Starling, 1978).

Reverse logistics take fundamentally different approach from forward logistics having characteristics of highly fragmented return quantities, multiple return channels, complex transportation routing, higher level of expected serviceability for multiple clients and variety of disposition options. Due to such characteristics, realization or execution of reverse logistics often entail many new challenges. Two major challenges of reverse logistics would include cost of value recovery process and low return rates from customers. Recent research reported the cost of reverse logistics accounts for nearly 44%

of entire product take-back process (White et al., 2001). Additionally, Greenpeace's survey in 2007 revealed that many manufacturers struggle to achieve beyond 20 percent of product return rate. Challenges in product take-back processes entail careful evaluation of aforementioned two key issues of reverse logistics in order to minimize the variable cost, while promoting higher customer product return frequency.

The thesis begins with defining the objective of the study, discusses challenges and limitations in current practices of reverse logistics and proposes a methodology of establishing initial collection points as part of reverse supply chain in order to minimize the variable cost of logistics activities and to increase the product return rate by providing convenient return locations to customers. The paper presents a mathematical framework to optimize the variable cost associated with reverse logistics and utilizes a single-objective, mixed-integer, binary programming for optimization with respect to multiple constraints.

CHAPTER 2

OBJECTIVE

The objective of this paper is to propose a decision-making methodology that would determine optimum number and location of initial collection points that would provide reduction in transshipment and handling cost through consolidated transshipping, while increasing customer accessibility via convenient drop locations. The outcome of the study would benefit organizations to reduce cost of reverse logistics in order to promote more cost efficient product take-back strategy. **FIGURE 1** illustrates product return path to be modeled.

FIGURE 1: Product return path diagram

The following specifies the objectives in detail:

- 1) Develop a program – single-objective, mixed-integer, binary programming for cost optimization, which;
 1. minimizes inventory, facility, handling and transshipping cost associated
 2. maximizes capacity utilization of initial collection sites
 3. encourages higher individual returns via extended accessibility
- 2) Verify the program
- 3) Conduct a case study
- 4) Report results
- 5) Recommend additional research

CHAPTER 3

LITERATURE REVIEW

1. Sustainability

Sustainability is becoming one of the most desired and highly prized goals of modern industrial operations and environmental management as the deterioration of natural environment becomes increasingly more concerned. International Union for the Conservation of Nature and Natural Resources, the Global Tomorrow Coalition, and the World Resources Institute establish sustainability as a desired goal of environmental management, development and international cooperation. The term, “sustainability,” is used in numerous disciplines and is defined in many ways according to the context to which it is applied and whether its use is based on an ecological, social, or economical perspective. IUCN defines sustainability as improving the quality of human life while living within the carrying capacity of supporting eco-systems. Although conceptualization of sustainability may differ among different interest groups, the World Commission on Environment and Development defines sustainable development, as ‘development that meets the needs of the present without compromising the ability of the future generations to meet their own needs’ (Brundtland, 1987). Welford asserts that sustainable development should not only require significant reduction of environmental burdens, but also demand much more systematic thinking and interdisciplinary approaches (Welford, 1998).

The first collective effort towards industry response to sustainability issues was made in 1995 by the formation of the World Business Council for Sustainable

Development (WBCSD). The effort of WBCSD has brought more than 160 companies around the world to provide business leadership towards sustainability (Bidwell and Verfaillie, 2000). The Natural Step, a Swedish environmental education organization, has been promoting organizational transformation towards sustainable development (Bradbury and Clair, 1999). To assist corporations in implementing sustainability initiatives, the SIGMA project has developed a set of tool kits that cover broad range from benchmarking to building a business case, creating a management framework as well as consideration of issues such as stakeholder engagement, sustainability measuring and reporting guidelines. UNESCO's Man and the Biosphere program focuses on the integrated approaches to global natural resources management, particularly in and around designated reserves. Moreover, the Global Environmental Monitoring System of the United Nations Environment Programme (UNEP) has designed multinational and multi-disciplinary research and monitoring programs. The World Commission on Environment and Development of the UN has also designed a set of programs that emphasize on global environmental policy making: the Population, Resources, and Environmental Program of the American Association for the Advancement of Science (AAAS), the Program on Analyzing Bio-spheric change of the International Federation of Institutes for Advanced Study (IFIAS), and the program on Ecologically Sustainable Development of the Biosphere of the International Institute for Applied Systems Analysis (IIASA).

2. Industrial response

In many ways, industries have been focusing on maximizing financial or productive capital gain while consuming natural and social capital as needed. Global environmental awareness, however, have brought environment friendly or green

initiatives in every aspect of product operations. Xerox's accomplishment of 'zero-waste-to-landfill' engineering can be a very good example of 'cleaner production' (Senge and Carstedt, 2001). Increasingly many industries have adopted concepts of cleaner production and developed many strategic approaches and practices that increase re-manufacturability or recyclability of products or eliminate harmful wastes. Waste Electric and Electronic Equipment (WEEE) directive of the European Union, for instance, obliges manufacturers of electric and electronic equipment to assume extended responsibility by taking back equipments reached end-of-life state for re-processing and recovery.

Radical transformation did more than mere improvement of corporate images. The financial impact has been remarkable. 3M's 3P (also known as Pollution Prevention Pays) project has saved the company more than \$1 billion in its first year by aggressively limiting harmful byproducts and wastes (Esty and Winston, 2008). Kathy Reed of 3M noted "Anything not in a product in a product is considered a cost (Esty and Winston, 2008)." Timberland's redesigned shoeboxes saved nearly 15% of virgin packaging material (Esty and Winston, 2008). AMD's modified 'wet processing' technology reduced the water usage from eighteen to less than now six gallons per minute.

Besides many notable individual achievements, the sustainability issues must be dealt at supply chain managements' level as today's industries become more and more interdependent on one another in every aspect of product and service delivery. Efforts of environmental management and operations should no longer be limited to issues of localized product operations. Rather, it needs to be assessed in a higher level of operations, which encompass production, transportation, consumption and post-disposal disposition.

Given such a significant and increasing level of attention toward issues related sustainable development, or sustainability, it is imperative to define sustainability on supply chain managements' level to discuss environmental as well as economic benefits as a whole. This article discusses benefits of reverse logistics, namely RL, in terms of promoting sustainability and provides mathematical model to provide economic justification.

3. Reverse Logistics

One of the collective solutions that industries have come up with is the development of the reverse logistics that focus on the value recovery of returned products for recycling or remanufacturing. Reverse logistics refers to the logistic management skills and activities involved in reducing, managing and disposing packages or products (Kroon et al., 1995). Srivastava defines reverse logistics as “Integrating environmental thinking into supply chain management including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers as well as end-of-life management of the product after its useful life”. A growing responsibility towards the environment and governmental regulations, and increasing awareness of valuable commercial opportunities in collecting, recycling, and reusing products and materials stimulate the development. One of the obvious challenges of reverse logistics is reverse distribution of goods and information; which fundamentally differs from that of forward logistics in terms of direction of material and information flow and their respective volume. Due to its difficulties in handling, reverse logistics cost exceeds \$35 billion dollars per year for US companies. For above reasons, many companies treat reverse-logistics as a non-revenue-generating process which would often result in a very

few resources allocated to this part of the supply chain. However, more and more firms now realize that reverse logistics is a business process by itself with growing attention towards sustainability and environmental responsibility. Hawken et al. envision economic benefits of as much as 90% through reduction of energy and materials consumption (Hawken et al., 1999).

Practice of reverse logistics entails a series of tasks to capture value of products returned for recycling (V. Daniel et al., 2003).

Product acquisition to obtain the products from end-users

- i. Transshipment from point of acquisition to a point of disposition
- ii. Testing, sorting, and disposition to determine products' economic attractiveness
- iii. Refurbish to facilitate the most attractive economic options: reuse, repair, remanufacture, recycle, or disposal
- iv. Remarketing to create and exploit secondary markets

As reverse logistics fundamentally differ in many aspects of operations from forward logistics, strategic development of competitive reverse logistics entails careful evaluation, design, planning and control. Product acquisition would initiate at initial collection centers (ICPs) and consolidation would continue before reaching centralized return center (CRC) or manufacturer who would process remanufacturing. **FIGURE 2**, on the next page, depicts previous statement. Product acquisition and consolidation diagram is widely used in reverse logistics modeling and strategy formulating. Srivastava adopted similar model in reverse logistics network design model (Srivastava, 2007).

FIGURE 2: Product acquisition and consolidation

Kroon and Vrijens studied efficiency issues with regards to collection and distribution in reverse logistics in context of recycling of industrial packaging wastes (Kroons and Vrijens, 1995). Jayaraman et al. studied capacity issues with regards to storage limitations of collection facilities in designing a reverse supply chain model and applied operations research techniques to solve for an optimal solution (Jayaramna, 2003). This paper tried to take the work further integrating ideas of establishing initial collection centers (ICPs) to design and solve a reverse logistics model that promotes both customer accessibility and efficiency in processes. Proposed model would employee operations research (OR) techniques to solve optimization problems with regards to various cost analyses. Establishment of initial collection centers are aimed to increase customer accessibility as well as to promote efficiency in consolidation as displayed in **FIGURE 2** below.

FIGURE 3: Consolidation process

4. Strategic modeling

Development of strategic modeling entails a number of critical dimensions including: product acquisition, returns volume, return timing and quality, test, sort and grade, reconditioning, and distribution and selling (Guide Jr. et al., 2000). Due to challenges of identifying and defining these critical dimensions, many aspects of reverse logistics remain with limited knowledge and theory base. For such, many developed strategic models heavily rely on hypothetical scenario or specific product type (Guide Jr. et al., 2002). Guide Jr. et al. took a contingency approach to explore those critical factors for closed-loop supply chains that enable product value recovery (Guide Jr. et al., 2002). Van der Laan (1997) studied independent demand inventory models as they relate to periodic and continuous models (Van der Laan, 1997). Krikke et al. proposed alternative reverse logistics network models specifically for photocopiers in Western Europe (Krikke et al., 1999). Toktay et al. modeled predicting return flows for instant cameras (Toktay et al., 2000). Stuart et al. developed a new mathematical framework to estimate product take-back levels by defining various levels of product life and by incorporating those terms into a life estimation framework (Stuart et al., 1998).

Various optimization methodologies and computational techniques have been studied to provide an optimum solution to complex network problems with aforementioned critical dimensions. Srivastava developed an integrated holistic conceptual framework that combines descriptive modeling with optimization techniques at the methodological level (Srivastava, 2008). Srivastava formulated a multi-product, multi-echelon, profit maximizing reverse logistics and value recovery model covering from collection to first stage of remanufacturing. Min et al. proposed a nonlinear mixed

programming model and a genetic algorithm that solve the reverse logistics problem to determine the number and location of centralized return centers (i.e., reverse consolidation points) (Min et al., 2006).

The thesis proposes a single-objective, mixed-integer programming that would optimize the reverse logistics network in order to determine appropriate number and location of initial collection centers, while Min et al. focused on the determination of centralized return centers in reverse logistics network. Such intended to include consideration of low customer return rate across United States and limited degree of current remanufacturing capabilities across many facilities. In determination of variable cost analysis, quantitative modeling of forward logistics were utilized and manipulated with regards to those in reverse logistics practices. Various constraints were introduced to the model to restrict critical parameters including budget and target number of returns; by which few literatures attempted to restrict or constrained their study results. Single-objective, mixed-integer programming was coded and executed via MatLab to generate optimum cost, target number of return, location matrix and multi-echelon cost grid. The thesis focused on the determination of initial collection points for pre-established centralized return centers as the thesis aims to take more pragmatic approach in consideration of return volume, remanufacturing capacity, and current customer return behavior. As opposed to Srivastava's multi-brand model, the thesis proposes single-brand model to mimic realistic logistics practices currently utilized in U.S. firms. Many U.S. firms including Nike, Cisco and Apple adopt single-brand reverse logistics model.

CHAPTER 4

MATHEMATICAL MODEL

To simplify the multi-echelon reverse logistics network, the model considers following assumptions:

- 1) Despite proximity to centralized return centers, customers are only to return products at the initial collection points in order to avoid individual shipping
- 2) Transportation cost of customers to the initial collection centers is neglected as the model assumes initial collection points are conveniently located
- 3) Capacity requirements at the initial collection points are not considered assuming that sufficient space for small volume of returned products and frequent transshipment to the centralized return center
- 4) Returned products at one initial collection point are shipped to only one centralized return center given minimum distance between the two locations
- 5) All facilities and logistics activities assume 365 days of operation within a calendar year, which would allow drop-box applications
- 6) Returned products from all facilities are to be supplied to one manufacturer
- 7) Transshipping cost from centralized return center to manufacturer is neglected as the cost is unavoidable as long as the centralized return center is in service

The following lists indices, parameters and variables used in model formulation. Indices, parameters and variables were borrowed from Chung's semi-closed supply chain model (Chung et al., 2008), Min et al.'s network optimization model (Min et al., 2006),

and Chopra's forward logistics model and manipulated to fit the purpose and scope of the thesis.

1. Indices

i	index for initial collection points; $i \in I$
j	index for centralized return centers; $j \in J$
ICP	initial collection center
CRC	centralized return center

2. Parameters

f_i	annual facility cost of ICP
f_j	annual facility cost for CRC
d_{ij}	distance between ICP and CRC
R_i	quantity returned at each ICP
R_{ij}	quantity returned to CRC
C_i	carrying cost per unit at ICP
T_i	length of consolidation at ICP
H	handling cost per unit returned
I_i	daily inventory cost per unit returned at ICP
fr_{ij}	$fr(b, d, p)$, freight rate between ICP and CRC
b	base freight rate per unit returned
s	discount rate
	$s (= 1 \text{ for } d \leq \delta_1, = s_1 \text{ for } \delta_1 \leq d \leq \delta_2, \text{ or } = s_2 \text{ for } \delta_2 \leq d)$
p	penalty rate
	$p (= 1 \text{ for } p \leq \alpha_1, = p_1 \text{ for } \alpha_1 \leq d \leq \alpha_2, \text{ or } = p_2 \text{ for } \alpha_2 \leq d)$

c_j	capacity at centralized return center
$\min_i$	minimum number of ICP in the region
$\min_j$	minimum number of CRC in the region
TC	total cost
B	total annual budget specified by manufacturer

3. Decision variables

X_i	1 if initial collection point is in service, 0 otherwise
Y_j	1 if centralized return center is in service, 0 otherwise

4. Model formulation

a. Facility cost

i. ICP $f_i * \sum_{\forall i} X_i$

ii. CRC $f_j * \sum_{\forall j} Y_j$

b. Transportation cost (from ICP to CRC)

$$\sum_{\forall j} \{ \sum_{\forall i} (R_i * 365 / T_i) * fr(R_i, d_{ij}, p) * X_i \}$$

c. Carrying cost at ICP

$$\sum_{\forall i} * (\sum_{\forall i} I_i * R_i * X_i * 365)$$

d. Handling cost

$$H * \{ \sum_{\forall j} (\sum_{\forall i} (R_i * X_i)) \}$$

e. Total cost is the sum of handling cost, carrying cost, facility cost, and transportation cost as summarized by **FIGURE 6**, on the next page.

$$\begin{aligned} \text{Total Cost} = & f_i * \sum_{\forall i} X_i + f_j * \sum_{\forall j} Y_j + \sum_{\forall j} \{ \sum_{\forall i} (R_i * 365 / T_i) * fr(\\ & R_i, d_{ij}, p) * X_i \} + \sum_{\forall i} * (\sum_{\forall i} I_i * R_i * X_i * 365) + H * \{ \sum_{\forall j} (\sum_{\forall i} (R_i \\ & * X_i)) \} \end{aligned}$$

FIGURE 4: Simplified cost analysis

A set of constraints was devised to optimize the proposed mathematical model within specific boundaries. The specified constraints encompass budget, routing, minimum number of facilities, and capacity of facilities. Distances between each of ICPs and CRCs were not constrained; however they were utilized in calculation of discount factors that prized shorter distances. Budget constraints, which few literatures discussed, were included in the model to provide useful insights on decision-making processes. As return volume of reverse logistics is assumed small compared to that of forward logistics, capacity issues on truck were not considered. However, freight rate was included in the mathematical model to impose penalties on trucks with volumes larger than specified limits. Capacity of each ICP or CRC location was constrained by specific volume both to maximize capacity utilization and to minimize delays in logistics process. Minimum number of each ICP and CRC location was set to maintain minimum facilities needed to carry out product acquisition and other remanufacturing activities. Case study introduces return quantity constraints that would set specific target value to ensure minimum return product acquisition. The following explains each constraint in further detail.

1. $TC \leq B$

Total cost of reverse logistics must be less than specified budget constraint

2. For $\forall_i \in I$ and $\forall_j \in J, \sum Y_{ij} = 1$

This ensures that each ICP is assigned to only one CRC

3. For $\forall_i \in I$ and $\forall_j \in J, \sum R_i * X_{ij} * T_i = \sum X_{jk}$

This confirms that the quantity of initial product return from customer to ICP equals that of outgoing flow from ICP to CRC

4. $\min_i \leq \sum X_i$

This maintains minimum number of ICP in the region

5. $\min_j \leq \sum Y_j$

This maintains minimum number of CRC in the region

6. For $\forall_i \in I$ and $\forall_j \in J, \sum R_{ij} \leq c_j * Y_j$

This ensures incoming return flow from ICP does not exceed capacity of each CRC

For the purpose of model verification, hypothetical scenario was developed to test the conceptual validity as well as mathematical functionality. The primary objective of such modeling was to verify if the proposed model would efficiently identify the number and location of the ICPs and corresponding return channel that would minimize the total cost of reverse logistics. Optimum number and location of ICPs would be determined with respect to multiple constraints as specified above. Outcome of the optimization

would assure a manufacturer where to establish ICPs and which routing each would take to transship returned products to CRCs. **TABLE 1** lists all 20 potential ICP locations and 5 pre-established CRC locations in accords with Cartesian coordinate system. All 25 locations were selected random for the purpose of model verification. In any practical application, all locations should consider relative population density as well as customers' buying pattern in terms of sales history per area. Cartesian coordinate system was chosen to ease the calculation of distance between each facility. Unlike Mine et al.'s model, customers' residential locations were not considered; however, ICP locations were chosen as they reflect the center of population density. Moreover, inclusion of customer locations in optimization modeling would less benefit areas where population densities are relatively lower, like many areas across the United States.

potential ICP locations			established CRC locations		
site	x-coordinate	y-coordinate	site	x-coordinate	y-coordinate
1	15.13	21.22	1	8.21	20.21
2	15.64	31.21	2	31.11	28.21
3	2.31	5.67	3	12.24	5.32
4	14.85	5.89	4	47.21	18.92
5	27.34	19.98	5	25.21	45.30
6	23.25	37.30			
7	48.21	17.21			
8	38.45	17.98			
9	24.39	35.87			
10	19.56	41.23			
11	5.98	43.78			
12	43.34	23.87			
13	7.12	36.88			
14	22.27	5.64			
15	12.36	19.87			
16	31.21	5.42			
17	28.43	33.37			
18	39.54	22.69			
19	15.99	7.23			
20	0.21	39.87			

TABLE 1: Potential ICP locations for established CRC locations

TABLE 2 then summarizes anticipated daily return volume from each of the 20 potential ICPs. Stuart et al.'s study developed an estimation framework that would improve estimation of electronic product take-back levels (Stuart et al., 1998). For the purpose of model verification, product return quantities from all 20 locations were

randomized. In construction of practical application, daily return volume should consider customers' buying patterns in terms of annual or quarterly sales data along with product turn over rate. As **TABLE 2** indicates, total daily return by customers reaches 623 from all 20 potential locations. However, established CRCs are not to handle all 623 returned products as optimization would generate only selected ICP locations that meet all specified constraints.

At each potential ICP locations	
ICP site	Daily return (qty)
1	12
2	72
3	54
4	43
5	27
6	31
7	18
8	19
9	20
10	54
11	34
12	41
13	43
14	31
15	33
16	30
17	30
18	29
19	21
20	20

TABLE 2: Daily return volume at each potential ICP locations

TABLE 3 lists parameters that were used in calculation of handling, transshipment, facility, and carrying cost. Each parameter is entitled with a brief description, a symbol used in the model, an assigned value, and an appropriate unit. s_1 , s_2 , p_1 , and p_2 were used as unit-less percentage values in the model. Parameters, such as distance discount, allowed unit penalty, base freight rate, and etc, were referenced from existing literatures (Min et al., 2006 and Srivastava, 2008), compared to various U.S. logistics firms and manipulated to arrive at some good approximation for average values. Srivastava suggested informal interviews with various stakeholders as secondary sources

to decide on many parameters (Srivastava, 2008); however, for the scope and purpose of the thesis, exhaustive research via interviews with stakeholders was not conducted. Various per unit costs were approximated with regards to average total cost per service and number of products handled per service. Target budget of \$50,000 was set to verify if the model would function within specified budget constraint.

Parameters used			
Description	Symbols	Value	unit
Distance discount	δ_1	25	mi
	δ_2	50	mi
	s1	0.9	
	s1	0.95	
Allowed unit before penalty	α_1	30	unit
	α_2	40	unit
	p1	1.1	
	p2	1.15	
Base freight rate	b	0.4	\$/USD
Days of consolidation	Ti	5	day(s)
Carrying cost per unit	Ci	0.05	\$/USD
Annual facility cost	fi	500	\$/USD
	fj	4000	\$/USD
Handling cost per unit	H	0.1	\$/USD
Number of regional CRC	CRC	5	
Number of minimum ICP	min_ICP	3	
Annual budget	B	50000	\$/USD

TABLE 3: Parameters used for mathematical modeling

In order to increase the precision of appointing potential locations for ICPs, decimal values were assigned to represent each of x and y coordinate. With x and y coordinate of each locations, distance between each ICP and CRC was calculated via Euclidean distance formula to promote mathematical simplicity. This would make the model more applicable to large-scale modeling, such as within a county or a region, as higher precision in terms of calculating distances would be desired for small-scale modeling, such as within a city or a village. **FIGURE 5** displays geographical plotting of

all facilities included by **TABLE 1**. Again, Cartesian coordinate system was utilized to ease location-mapping processes. Red star indicates established CRC locations, while blue star indicates proposed potential locations for ICPs.

FIGURE 5: Geographical plotting for all facilities

Cost grid was then created to illustrate cost of reverse logistic activities through all possible, 20 x 5, return channels as **FIGURE 6** shows below. As the figure describes, different amount of cost is associated with each potential return channel. Cartesian coordinate system was also used to represent: x-axis for ICPs, y-axis for CRCs, and z-axis for associated cost of reverse logistics. The difference in cost is largely due to the difference in distance between each ICP and CRC and the difference in daily return volume that is listed in **TABLE 2**.

FIGURE 6: Cost grid per return channel

Optimization of the proposed model utilized a single-objective, mixed-integer, binary programming that uses a linear programming (LP) based, branch-and-bound algorithm. More specifically, the algorithm searched for optimal total cost in regards to the proposed mathematical model by solving specified constraints, in which the binary integer requirement on the variable was represented by the potential ICP locations. As **FIGURE 7** briefly demonstrates the process, the algorithm first searches for a feasible ICP location and then updates the best ICP found as the search tree grows. Lastly, it verifies that no better feasible solution is possible by solving remaining constraints.

FIGURE 7: An example of branching

FIGURE 8 then is the outcome of the above method. A single-objective, mixed-integer, binary programming generates the total cost of reverse logistics along with a location matrix that specifies ideal locations for ICP as well as the optimum return channel it should take. Total cost is calculated based on the mathematical model proposed earlier in respect to specified constraints. 20 x 5 location matrix was created to indicate which return channel should be selected in order to achieve minimum total cost. Rows represent 20 different ICP locations, while columns represent 5 different CRC locations. Again, binary variable was used to represent each return channel, from ICP to CRC, with 0 being closed and 1 being open.

```

TOTAL_COST =
    5.8534e+04
Optimization terminated.
LOC_MTRX =
    0    1    0    0    0
    0    0    0    0    0
    0    0    0    0    0
    0    0    0    0    0
    0    0    0    0    1
    0    0    1    0    0
    0    0    1    0    0
    1    0    0    0    0
    0    0    0    1    0
    0    0    0    1    0
    0    1    0    0    0
    0    0    0    0    0
    0    0    0    0    0
    0    0    0    0    1
    0    0    0    0    1
    1    0    0    0    0
    0    0    1    0    0
    1    0    0    0    0
    0    1    0    0    0
    0    0    0    1    0

```

FIGURE 8: Total cost and location matrix

TABLE 4 summarizes the location matrix shown by **FIGURE 8**. The table lists 15 different ICPs by 5 different return channels. For examples, returned product collected at ICP 8, 16, and 18 must be transshipped to CRC 1 in order to minimize the total cost associated with reverse logistic activities. Listed ICPs are to be established in order to increase accessibility to customers, while consolidating individual shipments.

ICP to open	Transfer to CRC
8, 16, 18	1
1, 11, 19	2
6, 7, 17	3
9, 10, 20	4
5, 14, 15	5

TABLE 4: Locations for ICPs with specified return channel

As so far discussed, a single-objective, mixed-integer, binary programming efficiently developed a location matrix of ICPs and optimized the total cost of reverse logistics. The results met minimum requirement specified by the pre-defined constraints in regards to budget, routing, minimum number of facilities, and capacity of facilities. Application of this hypothetical modeling will be further discussed in the next chapter.

CHAPTER 5

CASE STUDY ON APPLE INC.

Reverse logistics bridge sound environmental management tasks with the decision making process for the conversion of waste into usable resources. Reverse logistics gained its popularity as producing environmental friendly products has become an important marketing strategy. As more manufacturers began to explore product take-back strategies, reverse supply chain has come to encompass a wide range of products such as televisions, personal computers, cellular handsets, and so on. One of the most important outcomes of reverse logistics is increased customer retention through improved brand image with advanced sustainable development strategies.

Despite agreed benefits, the practice and management of reverse logistics are yet to receive the desired attention and are generally carried out by the unorganized sector for some recyclable materials such as plastics and metals due to high cost associated with collection and distribution. Regardless of sources of cost, many manufacturers absorb the cost of return and ultimately pass on to consumers.

FIGURE 9: Cost driver of product take-back

FIGURE 9, on the previous page, breaks down the cost associated with product take-back procedure within electronics industry. It should be noted that cost of reverse logistics comprises nearly 45% of the total cost of the process.

Another fundamental challenge is low product take-back rate. **FIGURE 10** summarizes an investigation conducted by Greenpeace USA in regards to average product take-back rate among electronics manufacturers. According to their investigation, many manufacturers reported 10% or lower product return-rate, despite the new state legislations that requires product take-back in many states. Reasons may vary depending on the industry or type of products; however, include low accessibility, limited advertisement, inconvenient method, and sub-par serviceability. One must also note that statistics provided by the Greenpeace is limited to only United States. Manufacturers from European countries or Eastern Asia countries perform far superior to those from United States. Sony, for instance, reports nearly 85% of product take-back rate (of televisions) in Japan.

FIGURE 10: Take-back rate researched by Greenpeace

Case study was conducted to see if the proposed model could be effectively applied to an existing reverse logistics system for Apple Inc.'s popular iPod in order to produce an optimized solution. Mathematical model was applied to Apple Inc. that sold nearly 45 million units of iPod, according to Apple Inc.'s annual sales in 2007. In particular, the study focused on Apple Inc.'s product take-back operation within Central California.

Apple Inc.'s product take-back program largely comprises of two methods; customer drop-off at Apple retail stores or direct shipment to their centralized return center located in Central California, as shown by **FIGURE 11** and **FIGURE 12**.

Figure 11: Apple Inc.'s return method 1

FIGURE 12: Apple Inc.'s return method 2

When customers drop off products for recycling at one of their retail stores, returned products are consolidated before being directly transshipped to the centralized

return center. Customers, however, are only allowed drop off during open store hours. In addition, Apple Inc. operates only three retail stores, one in each of: San Luis Obispo, Fresno, and Modesto in Central California where nearly 10 million people reside. By allowing drop-offs only at operating retail stores, more customers are pushed to individually ship products directly to the centralized return facility for recycling. Although customers are not required to pay for shipping and handling in most cases, they have to go through a hassle of pre-ordering packaging materials, packaging, and sending at post offices. Each direct shipment costs nearly \$30 to cover packaging materials, shipping and handling. Moreover, direct shipping raises another environmental concern for increased spending of packaging materials.

Proposed model was applied to Apple Inc.'s reverse logistic system with the following additional constraints.

1. $TC \leq B$ ($= \$100,000.00$)

Total cost of reverse logistics must be less than specified budget constraint

2. $G \leq \text{Total_return}$

This ensures number of returned product exceeds stated goal ($G = 60,000, 70,000$ or $80,000$ units)

FIGURE 13, on the next page, presents proposed mapping of potential initial collection centers along with Apple Inc.'s centralized return center, and currently operating retail stores in the Central California. Downward arrow indicates where Apple Inc. currently operates their centralized return center. This is the only centralized return center Apple Inc. operates in the United States. Flags were drawn to indicate cities where

Apple Inc. currently has operating retail stores. Potential locations for ICPs were indicated exclamation marks. Total of twenty potential locations were selected in consideration of regional populations and marked with exclamation marks. Despite their centralized return center handles all return products across all states in the U.S.; however, the case study particularly focused on the central region of California. For such, remanufacturing capacity of the CRC facility was not restricted by constraints.

FIGURE 13: Proposed mapping

For consistency, Cartesian coordinate system was used to represent each location by its x and y coordinate. **TABLE 5** lists 3 of operating retail stores and 17 suggested ICP locations for one established centralized return center in Cartesian coordinate system. Coordinates for the locations were calculated with 100 mile per inch scale as obtained from Goggle map.

Operating retail stores			established CRC locations		
site	x-coordinate	y-coordinate	site	x-coordinate	y-coordinate
1	4.2	4.1	1	2.4	3.9
2	4.2	0.6			
3	5.9	2.7			
Suggested ICP locations					
1	5.3	0.0			
2	7.7	0.2			
3	6.2	0.5			
4	7.1	3.9			
5	5.3	1.3			
6	7.8	1.6			
7	9.1	1.9			
8	8.4	3.2			
9	7.1	2.9			
10	4.1	1.5			
11	3.4	2.2			
12	4.7	3.4			
13	4.9	2.1			
14	6.9	1.9			
15	5.4	3.4			
16	7.1	0.9			
17	4.1	2.3			

TABLE 5: Locations in Cartesian coordinate

FIGURE 14 then presents graphical mapping of each location. Apple Inc.'s centralized return center was marked with a red star as shown below. Three operating retail stores along with 17 suggested ICPs were marked with blue stars and indicated with arrows to help understanding.

FIGURE 14: Location mapping with Cartesian coordinate system

Anticipated annual return volume from each location was generated with regards to Apple Inc's sales in 2007 along in considerations with demographics of each of the twenty locations as reported by U.S. census bureau. As study only focused on the recycling of iPods, it did not consider all other electronic products manufactured by Apple Inc. The model also targeted 10% of return volume to be consistent with statistics obtained by Greenpeace as previously shown by **FIGURE 10. TABLE 6** displays actual numbers used as anticipated return volume for recycling in units. One must note that iPods purchased from online stores or stores in other region could be returned to one of the locations listed in the table.

Anticipated annual return units per location (units)	
Operating retail stores	
1	4656
2	8213
3	9369
Suggested ICP locations	
1	4847
2	3240
3	6506
4	1404
5	6713
6	2506
7	7634
8	9155
9	8355
10	5375
11	8401
12	9308
13	6213
14	7974
15	7731
16	8746
17	8123

TABLE 6: Annual return volume from 20 locations

Single-objective, mixed-integer, binary programming was used in order to produce an optimal solution to Apple Inc.'s reverse logistic network. Cost grid among all 20 locations were first generated in order to graphically show the differences in terms of the total cost required to deliver returned goods from each collection locations to the

centralized return center. 3D bar chart was used to graphically present the cost grid as shown by **FIGURE 15**. Y-axis and Z-axis represent potential location for ICPS and total cost of logistics required, respectively. As it can be easily identified from the figure, the total cost of logistics varied widely depending on the distance between each location and the centralized return center and anticipated volume of returned products per location.

FIGURE 15: Cost grid per return channel

Optimization of proposed mathematical model for Apple Inc's reverse logistics produced total cost of logistics, number of units returned, and cost per unit returned. Three case were tested to target different minimum return volume with 60,000, 70,000 and 80,000 units. Case 1, targeted minimum return volume of 60,000 units, resulted total cost of \$76,330 returning 67,559 units. Case 2, targeted minimum return volume of

70,000 units, resulted total cost of \$79,367 returning 70,825 units. Lastly, Case 3, targeted minimum return volume of 80,000 units, resulted total cost of \$88,452 returning 80,056 units. **TABLE 7** summarizes the result of optimization as shown below.

CASE	Cost (USD)	Unit returned	Cost per unit returned (USD)
1	76330	67559	1.13
2	79367	70825	1.12
3	88452	80056	1.10

TABLE 7: Summary of optimization

Cost per unit returned significantly improved as target minimum return unit was increased. Such is solely due to more condensed consolidation of reverse logistics. **FIGURE 16** shows decreasing pattern of cost per unit return as total number of returned unit increases. Consolidation aggregates highly fragmented individual return to a bigger sum that would require lower logistics cost in terms of transshipment to the centralized return center.

FIGURE 16: Cost per unit return

FIGURE 17: Mapping of the ICPs by the return volume (Case1, Case 2, Case 3 from the left)

FIGURE 17 displays three maps per Case 1, Case 2, and Case 3 from the left. Three cases, previously summarized in **TABLE 7**, required different ICPs to operate in order to obtain desired minimum number product returns. Since each ICP location was assigned with different values for anticipated return volume, different set of ICPs were chosen to achieve desired minimum return volume.

CHAPTER 6

CONCLUSION AND FURTHER RESEARCH

Issues of sustainability are emerging regardless of region or nature of business across the globe. Meanwhile, promoting sustainability would require significant efforts to conceptualize ‘green’ processes and devise diverse approaches to their realization for implementation. This task does not belong to a single industry or region. Rather, companies and organizations must work together to jointly reduce environmental burdens. Strategic plans are necessary to integrate environmental practices with daily operations in order to maximize competitive advantages.

This paper accentuates and emphasizes the importance of optimizing reverse logistics by establishing initial collection points (ICPs) as means of consolidation. The major contribution of this research lies in developing a model for analyzing the reverse logistics network and providing useful insights in optimization. Optimization technique introduced in this paper can serve as useful decision aid tool to find an optimal solution for reverse logistics network. The proposed model may be modified by differing constraints, variables, parameters or routing configurations in order to design a specific return strategy.

The model determines the optimum total cost of logistics, location of initial collection centers, and routing to different centralized return centers. Proposed model was developed borrowing pre-existing concepts from literature and industry practices and applied to problems in an operations research (OR) framework. Single-objective,

multiple-constrained, mixed-integer, binary programming was utilized to solve the optimization problem.

As in the existing literature, optimized consolidation significantly improved cost efficiency of the multi-channel reverse logistic network. There was shipping distance and return quantity dependency of various cost analysis, which was in agreement with the basic rationale behind the approach. The number of ICPs and CRCs within reverse logistic network also impacted cost analysis to a considerable extent. Furthermore, the total number of each facility

The model would serve as a decision-aid tool towards reverse logistics network design for product returns and value recovery across many industries. The paper emphasized the close connection between reverse logistics and sustainable development and highlighted potential business opportunities as well.

Although presently underdeveloped remanufacturing technologies along with high capital requirement in many facility establishments may pose bottlenecks in many procedures, improved efficiencies via highly coordinated processes would promote return logistics to an economically attractive option to many. Research and development should also be focused to create a 'critical mass' via reverse logistics

Further research should evaluate time variable of reverse logistics in terms of tracking, routing, and transshipping in order to make disposition decisions for particular period of time. Such would further integrate reverse logistics to time-constrained value recovery processes in order to generate dynamic financial justifications. Toktay et al.

argued that return flow parameters should be updated time in a similar manner with forward logistics (Toktay et al, 2004).

The proposed model had its own limitations. The study only focused on the ‘supplier’ side of the reverse logistics developing a model that follows a traditional push system. The model did not address control issues that may arise between two sides of the network. Initial collection centers did not consider specific locations with difficulty of formatting lengthy location variables. Again, the study dealt with time in calculation of carrying cost; however, did not consider various practical lead-times that may arise due to transportation or handling. In addition, the proposed model did not consider cost of sequential logistics activities that include examination, cleaning, or disposal.

With its own limitations; however, the proposed model bears high flexibility in terms of including specific constraints, controlling variables or modifying routing sequences. The model can be easily applied to existing reverse logistics network model to determine benefit of establishing initial collection centers in order to increase customer accessibility and consolidation efficiency. Existing models may also be configured to find an optimal solution. Research towards best practices would help obtaining solutions for various strategic, tactical and operational problems.

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