Modeling and Assessment of e-waste Management Issues in India: Generation, Flows and Extended Producer Responsibility

THESIS

Submitted in partial fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

MAHESHWAR DWIVEDY

Under the Supervision of

Prof. R.K. MITTAL

BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE
PILANI – 333 031 (RAJASTHAN), INDIA

2013

BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE

PILANI - 333 031 (RAJASTHAN) INDIA

CERTIFICATE

This is to certify that the thesis entitled "**Modeling and Assessment of e-waste Management Issues in India: Generation, Flows and Extended Producer Responsibility**" submitted by Maheshwar Dwivedy, ID.No. 2006PHXF013P for award of Ph.D. Degree of the institute, embodies original work done by him under my supervision.

Date**:** _____________ Signature: ___________________

Prof. R K MITTAL

Senior Professor and Director
BITS - Pilani, Dubai Campus

ACKNOWLEDGEMENT

I wish to acknowledge my heartiest gratitude to our family goddess Maa Durga for her infinite benevolence and blessing. Thanks to my late elder father (Late) Shri Gauri Shanker Dwivedy for constantly encouraging me towards academics and for supporting me every day.

I am grateful to my supervisor Prof. R.K. Mittal, Director, Birla Institute of Technology & Science, Pilani - Dubai Campus, for his constant guidance and active interest towards the completion of my thesis. Your insight was invaluable, and you took my research capabilities to the next level. True to your word, you were always there around to help me and I could not have wished for a better guide.

I am happy to acknowledge special thanks to my Chancellor, Vice Chancellor, Director, Deputy Directors and Deans for giving me the ideal platform and the life-time opportunity to teach in the Department of Mechanical Engineering of BITS-Pilani, Pilani Campus and allowing me to pursue my doctoral thesis by providing substantial assistance through financial support. I would also like to thank Prof. N.N. Sharma, Dean, Academic Registration and Counseling Division, BITS-Pilani and Prof. S.K. Verma Dean, Academic Research Division for their help and support.

My thanks to Prof. K.S. Sangwan, Head of the Department, and the entire faculty and staff of Mechanical Engineering Department for enabling me to pursue this interdisciplinary research, and broaden my knowledgebase through a variety of courses and activities.

Thank you Prof. B.K. Rout, Prof. Srikanta Routroy and Prof. M.S. Dasgupta for your constant enquiry and concern about the status of my thesis. I great fully acknowledge the Doctoral Research Committee (DRC) and Doctoral Advisory Committee (DAC) members, Department of Mechanical engineering, who spared their precious time to provide constructive criticism and valuable suggestions that immensely helped in improving the quality of my Ph.D. thesis.

Thank you, my fellow cube mates (Dr. G. Anand, Dr. Barun Pratihar, Dr. Amit Singh, Dr. Arun Jalan, Mr. Arshad Javed, Mr. Jitendra Singh Rathore). You are some of the funniest/snarkiest, smartest and warmest people I've ever met. Thanks for making this such an awesome experience. I look forward to our many future reunions. Special thanks to Dr. Kalluri Vinayak and Dr. B.K. Rout for being right there where it mattered not only as a friend but also as a critique. To Prof. R.B. Kodali, thank you for the random but often many funny and educational discussion that we had over several cups of tea at Nagarji. Where else can I discuss politics, philosophy and academics all in one breadth? To all my colleagues at BITS-Pilani, I give my deepest thanks for your moral support and encouragement.

Finally, I owe a great debt of thanks to my great guiding parents for making all my dreams come true. Their love, support, motivation and all physical help have been immeasurable. My special loving thanks to my wife Kalpana and son Prithvi who have stood rock solid behind me well beyond their call of duty.

Maheshwar Dwivedy

ABSTRACT

Previous research has highlighted the importance of conceptualizing a sustainable e-waste framework in the developed countries. With limited natural resources juxtaposed with increased human activity, there seems but a greater need to integrate the experiences of the developed nations to develop solutions that are not only robust but also sensitive to the market conditions that exist in developing countries. The integration of best practices of mature systems and practices prevalent in the west, to developing countries like China and India in particular, have been an under-researched subject in the overall e-waste research field. Several key fundamental issues related to e-waste management are not yet properly researched keeping in mind the unique needs of the developing world, more so particularly in the Indian context. Hence, this study aims to address the e-waste management issues in the context of India not only through an economic perspective but also addresses environmental and social challenges associated with them.

In a broader context, the research outlined in the thesis tries to address the over-reaching implications of the exploding growth (as our study shows) of Waste Electrical and Electronic Equipment (WEEE), also called by the acronym "e-waste" on policy making in the context of India. More precisely, the thesis is interdisciplinary in approach, borrowing exclusively on literature and past research, to model and investigate several key issues concerning e-waste in India. Our own investigation gave interesting insight into several important issues into the problems emanating from e-waste generation in India. A time delay multiple lifespan material flow analysis (MFA) model was used to demonstrate the historical e-waste quantities in India. To predict the future e-waste projection in India, a logistic function with bounds on the carrying capacity was proposed to forecast e-waste generation upto 2050. The generation estimates from India were compared with the data from the US and implications discussed. To model the dynamic flow of e-waste across different stake holders in the e-waste trade chain in India, Markov chain based simulation through matrix perturbations using condition numbers were performed to demonstrate

the equilibrium e-waste flow patterns in India. The results of the study were used to propose a hypothetical e-waste management frame work in the context of India.

The proposed framework was tested in the Indian context through scenario based modelling, survey methodology and mathematical models. The thesis investigated the appropriateness of two possible e-waste collection modes: individual and collective collection; comparing and contrasting them through an economic analysis in the Indian context. When focusing on the consumer behaviour and consumer awareness on e-waste and their management, the thesis attempted to model the consumer behaviour and attitudes towards e-waste. Consumer willingness to pay for recycling of e-waste was modelled using logistic regression of multivariate data captured from an online survey. The thesis attempted to explore and buttress the possibility of Extended Producer Responsibility (EPR) in the Indian context, by analyzing different manufacturer take-back schemes. EPR through reuse and remanufacturing was modelled and analyzed using game theory to ascertain the impact of competition between the sales of new and remanufactured products on the overall manufacturer's profit function.

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Abbreviations

ARF	Advanced Recycling Fee
BAN	Basel Action Network
BFR	Brominated Flame Retardant
B&W	Black and White
CIA	Central Intelligence Agency
CPR	Collective Producer Responsibility
CRT	Cathode Ray Tube
DfE	Design for Environment
EEE	Electrical and Electronic Equipment
ELCINA	Electronic Industries Association of India
EPA	Environmental Protection Agency
e-products	Electronics in Products
EOL	End-of-Life
EPR	Extended Producer Responsibility
EU	European Union
GTZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
IBM	International Business Machines
IP	Intellectual Property
IPR	Individual Producer Responsibility
IT	Information Technology
JEITA	Japanese Electronics and Information Technology Association
MAIT	Manufacturers' Association for Information Technology
MoEF	Ministry of Environment and Forests
MT	Metric Tonne
NGO	Non-governmental Organization

OEM	Original Equipment Manufacturer
PC	Personal Computers
PCB	Polychlorinated Biphenyls
PRO	Producer Responsibility Organization
PVC	Polyvinyl Chloride
ROC	Receiver Operating Characteristic
RoHS	Restriction of the Use of Certain Hazardous Substances in Electrical and Electronic Equipment
SPSS	Statistical Product and Service Solutions
StEP	Solving the e-waste Problem
SVTC	Silicon Valley Toxics Coalition
TV	Television
UN	United Nation
UNEP	United Nation Environmental Programme
UK	United Kingdom
USA	United States of America
WEEE	Waste Electrical and Electronic Equipment

List of symbols

A_m	Measure of manufacturer's relative competitive advantage
b	Unit buy-back price
c	Unit production cost
c_{m1}	Unit production cost in period-1
c_{m2}	Unit production cost in period-2
c_d	Unit cost of disposal of returned goods
c_r	Unit cost of remanufacturing
C	Cost incurred per unit returned
d	Demand
d_j	Demand of manufacturer j
D_{m1}	Demand for new products in period-1
D_{m2}	Demand for new products in period-2
D_r	Demand for remanufactured product in period-2
D_R	Demand for remanufactured product in retail channel
D_S	Demand for goods in the second hand channel
D_L	Demand for returned goods in the market
$D(Y,K)$	Sales for various electronic devices for the year (Y) and item (K)
f	Penalty cost for not meeting collection targets
K	Maximum carrying capacity
$L_{A(Y,K)}$	Landfilled items of type K in year Y
L_i	Transformation of the logit
M	Mean first passage time matrix
m_j	Cost per unit the recycler pays to obtain the collected items from the manufacturer j

m	Subsidy given to the manufacturer
N	Number of computers owned per capita (penetration rate)
N_i	Penetration rate in year i
N_0	Initial penetration rate at $t = 0$
$O_{(Y,K)}$	Obsolete items of type K in year Y
O_i	Obsolete quantities generated in year $'i'$
p_j^s	Selling price of new product for manufacturer j in the scheme s
P	Transition matrix of Markov chain
p_{m1}	Price of new products in period-1
p_{m2}	Price of new products in period-2
p_r	Price of remanufactured product in period-2
P_R	Price of remanufactured product in the retail channel
P_S	Price of second hand product in the second hand channel
Q_i	Population in year $'i'$
r	Rate of adoption or growth rate
r_i	Mean recurrence time
$R_{C(Y,K)}$	Recycled items of type K in year Y
$R_{U(Y,K)}$	Reused items of type K in year Y
$S_{T(Y,K)}$	Stored items of type K in year Y
St_i	Stocks in use in year $'i'$
S_i	Sales in year $'i'$
t	Unit take-back collection fee paid by the manufacturer to the third party collecting agency (Chapter-6); Fraction of the unit product price (Chapter-7)

w_1	Unit selling price of refurbished goods quoted by the manufacturer to the retailer
w_2	Unit selling price of second hand goods quoted by the manufacturer to the second hand channel
W	Limiting probability
Z	Fundamental matrix
α_j	Market share of manufacturer j
β	Cross elasticity of demand (Chapter-3); Proportion of green consumers in the market (Chapter-6)
τ_j	The fraction of total products of manufacturer j collected
γ	Fraction of collected units purchased by the recycler from the manufacturer (Chapter-4); Proportion of products sold in the first period that are returned for remanufacturing in the end of first period (Chapter-6)
θ	Acceptability of product from the remanufacturer (Chapter-6); Customer preference for second hand goods (Chapter-7)
ν	Customer valuation for new product
ν^{rm}	The valuation of the customer who is indifferent to purchasing from the manufacturer and remanufacturer
ν^{m}	The valuation of the customer who is indifferent to purchasing from the manufacturer and not purchasing
ν^{r}	The valuation of the customer who is indifferent to purchasing from the remanufacturer and not purchasing
λ	Proportion of returned goods flowing to the retail channel

Chapter 1

Introduction

1.1 What is e-waste?

Over the recent past decade, the electronics industry has revolutionized the world so much so that electrical and electronic products have become ubiquitous of today's life around the planet. These products are today all pervasive in areas such as medicine, mobility, education, health, food supply, communication, security, environmental protection, culture, leisure and entertainment. Such appliances include many domestic devices like refrigerators, washing machines, mobile phones, personal computers, printers, toys and TVs. Electronic waste, or e-waste, refers to electronic products that have been retired from use or discarded. Managing e-waste has become a serious problem as new sales and replacement rates of electronic products have increased. The volume of electronic waste is growing at an increasing rate. The extensive adoption of electronic products, advances in technology, the tendency of consumers to purchase multiple electronics, social pressure and the rapid obsolescence of products are some of the major contributing factors. As per the estimates made by United Nations University (Huisman et al., 2007), the current e-waste arising across the twenty seven members of the European Union amount to around 8.3-9.1 million tons per year while the global inventory are estimated to be approximately 40 million tons per year and constitute the fastest-growing waste stream in the EU. In the United States of America (USA), in 2006 alone, more than 34 million TVs and displays have been sold on the market, while more than 24 million PCs and roughly 139 million portable communication devices such as cell phones, pagers or smart-phones have been manufactured (Schluep et al., 2009). Similarly, in the case of China (He et al., 2006), roughly 14 million PCs were sold in 2005, as well as more than 48 million TVs, nearly 20 million refrigerators and 7.5 million air conditioners were sold in the year 2001. Such high sales figures reflect the fact that, for many consumers, computers have become a regular component of everyday life and business. It also reflects the rate of technological obsolescence of IT products. As processor speed continues to improve rapidly, together with other vital features of the computer system, people have felt a necessity to upgrade their computers before they reach the end of their useful life. In the duration of 20 years, computer processor speed has shot from 16 MHz to 3.6 GHz; in the same time span, the average length of ownership has dropped from 8 years to 3 years (Babbitt et al. 2009). Another potential reason for the rapid rate of growth in product ownership is the fact that a significant portion of IT consumers simultaneously own multiple computers.

1.2 The Hazardous Content of e-waste

e-waste is a major global concern because as opposed to other municipal waste, they largely contain thousands of toxic ingredients including heavy metals and harmful chemicals such as lead, cadmium, mercury, arsenic etc., with the potential to pollute the environment and damage the human health if treated inappropriately using primitive recycling methods or when disposed to unsecured landfills. Lead, mercury, cadmium and brominated flame retardants (BFRs) are the principal toxic elements that are found in e-waste. For instance, computers use cadmium in rechargeable computer batteries and switches. Cadmium has been found to bio-accumulate in the environment and can be extremely hazardous to humans with devastating effect on kidneys and bones. On an average, the CRT monitors in a PC contain about 1.82 kg of lead. It is estimated that about 70 per cent of heavy metals found in US landfills come from electronic discards (Toxics Link, 2003). When such components are improperly recycled, lead is released into the environment. Once lead accumulates in the environment, it has acute toxic and chronic effects on plants, animals and humans alike. It can damage the nervous and blood systems, and the kidneys in animals and human beings. It also affects the developmental and learning abilities of children. Fire retardant plastics, including polyvinyl chloride (PVC) make up the printed circuit boards, connectors and cables, which if disposed improperly, e.g. burnt or land-filled, can discharge dioxins damaging the re-productive and immune system. Moreover, the presence of mercury in fluorescent lighting devices, batteries, and printed wiring boards presents severe environmental risk. Although mercury accounts for fewer than 0.002% of the total weight of the PC, even a token 1/70th of a teaspoon of mercury can contaminate the entire ecology of a region. When released into the rivers, it gets transformed into methylated mercury. This accumulates in living organisms and reappears back through the food chain particularly via fish. Methylated mercury also causes chronic damage to the brain damages the nervous system, kidney and brain, and in worse, can be passed on through breast milk (SVTC, 2001). Other toxic substances that exist are lead and barium oxide can be found in CRT glass; polychlorinated biphenyl (PCB) in condensers to name a few. The inappropriate disposal of e-waste can cause severe respiratory problems, produce toxic effects, and initiate allergic reactions even in small concentrations. Table 1.1 shows the effects of PC constituents on human health.

Table 1.1: Impact of PC constituent on human health

Toxic substance	Birth Defects	Brain Damage	Heart/liver/ Spleen & Lung damage	Kidney damage	Nervous/ Reproductive System damage
Barium		☹	☹		
Cadmium	☹	☹		☹	☹
Lead	☹	☹		☹	☹
Lithium	☹	☹	☹	☹	☹
Mercury	☹	☹	☹	☹	
Nickel	☹		☹	☹	☹
Palladium	☹	☹	☹	☹	
Silver	☹	☹	☹	☹	☹

Source: e-waste crisis: Global e-waste crisis caused by improper computer & electronic recycling. http://www.greencitizen.com/ewaste_crisis.php

Besides the above toxic substances, e-waste also contains valuable materials, which can be extracted or recovered through recycling process. Electronic scrap typically comprises metals, plastics and refractory oxides (Sodhi and Reimer, 2001) approximately in the ratio 40:30:30. For instance, a mobile phone has 40 elements, such as copper, tin, ferrous metals, cobalt, iridium, antimony as well as precious metals e.g. gold, silver, platinum and palladium. The presence of hazardous substances in e-waste classifies them into hazardous waste, while many valuable elements can be recovered through refining. Both the hazardous and valuable characterizes e-waste and therefore have to be handled scientifically.

1.3 e-waste Management Initiatives

The exponential growth in the generation of e-waste and its long term ramification to the environment forced the developed world to legislate and implement policies so as to tackle the environmental problems associated with e-waste. In 2003, EU published its

Waste Electrical and Electronic Equipment (WEEE) Directive (2002/96/EU, 2003) and Restriction of Hazardous Substance (RoHS) directive (2002/95/EU, 2003) to initiate e-waste management. The WEEE directive transfers the burden of recycling to manufacturers by requiring them to take back and recycle waste electrical and electronic equipment. The intention of this WEEE directive was to aim for decreasing generation of e-waste and promote their reuse and recycling. Similarly, the RoHs directive restricts the use of hazardous substances in electrical and electronic appliances. In US, till present, 39 states of America have adopted e-waste management laws respectively (EPA U.S., 2009) each with its own goals and implementation strategies. Yet another initiative, the Basel Convention (Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, 1989), legally banned the export of hazardous waste and their disposal from developed countries to developing countries. Though the amendment prevented export to developing countries in the name of disposal, it does not prevent e-waste trade for recycling purpose in the name of providing raw materials to the developing country. A large proportion of exported toxic wastes destined for recycling in developing countries have been found to be non-recyclable. Also the recycling processes employed in the importing nations are less than desirable and have led to detrimental environmental hazard. As an emerging issue, e-waste has been under the scrutiny of several governmental and non-governmental agencies like Greenpeace, and solving the e-waste Problem (StEP), which is the delegation of United Nations for e-waste problem. All these organizations initiatives focus primarily on the promotion of 3-R principle and the principle of Extended Producer Responsibility (EPR).

1.4 The 3-R Principle

The 3-R is the hierarchy principle in e-waste management, which can be termed as Reduce, Reuse and Recycle.

The idea of '**Reduce**' was to push producers and consumers towards adopting the environment friendly behavior having the least environment burden. This strategy enforces the producers to design more environmental friendly products by decreasing the composition of hazardous elements, apply techniques like DfE (Design for environment) to reduce the lifecycle impact of products: lower energy consumption, lower material consumption etc. The principle also appeals consumers to promote the purchase of environmental friendly products.

'Reuse' strategy refers to extending the life of a used e-product. If the used e-products and their accessories are in good condition to work, they could be re-sold to serve after cleaning, repair, refurbishing and in certain cases replacing components. Even in the case of products which are beyond repair, the components can be disassembled and reused.

The **'Recycle'** strategy refers to the proper and scientific end-of-life disposition of obsolete equipment. It's the widely prevalent practice in developed nations, which conventionally remains at the bottom of the hierarchy, in terms of priority. Here, the valuable elements present in e-waste are reverted back to the raw material stage. The parts, which cannot be recycled, are to be disposed into scientifically designed landfills to prevent any harmful impact to the environment. Recycling is the crucial process for sustainability, which contributes to utilize resource efficiently, decrease consumption of natural resources and save energy from the mining of raw materials. For example, if 100 million cell phones were recycled, the energy we save is enough to provide 19,500 households with electricity power for a year (StEP, 2009).

The benefits of 3-R initiatives is to divert e-waste's materials from inappropriate disposal, landfilling or incineration; reduce air and water pollution; and greenhouse gas emission in the manufacture of new products or handling discarded product; save energy and conserve natural sources, which are valuable and limited (StEP, 2009).

1.5 Extended Producer Responsibility (EPR)

EPR is a notion or concepts that make producers take responsible for their activities not only in production and distribution of goods but also towards the safe disposal of such products. The underlying assumption here is that the stakeholders along the product chain are expected to share responsibility for the entire lifecycle impacts of products. EPR releases consumer's responsibilities in collection and the proper treatment of e-waste. The mentioned responsibilities are shifted to the producers. Under the EPR ambit, the manufacturers could be liable to collect back and properly recycle the returned Electrical and Electronic Equipment (EEE) products. The implementation of EPR requires the support from international and regional agencies due to cross-border issues.

According to the StEP (2009) report, a model of e-waste management consists of four components, as shown below in Fig. 1.1, consisting of: collection system, processing system, system management, and financing scheme.

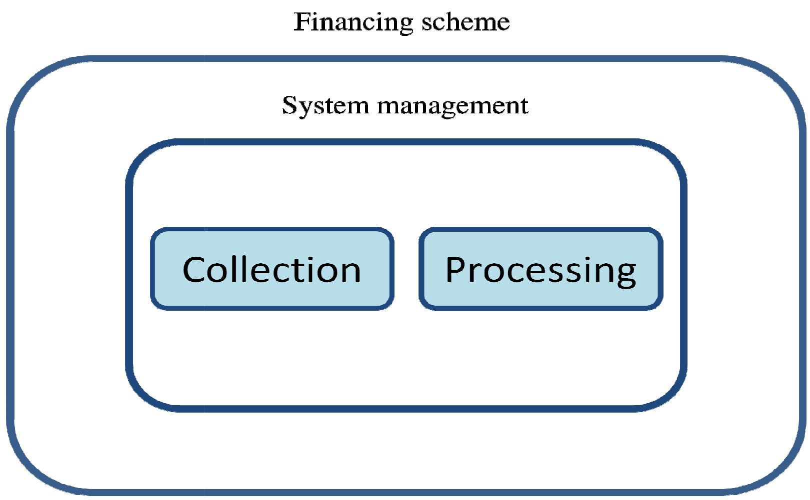

Fig. 1.1: e-waste management model

In this model, collection, processing and financing of e-waste treatment are responsibilities that are assigned to producers instead of municipal authorities. The goal of EPR model is to: motivate producers to design and manufacture products that are easily recyclable; carry less toxic materials; prevent e-waste flow into inappropriate treatment streams and landfills; recover scrap materials for conserving natural resources and energy; promote environmental friendly e-waste collection, transportation, recycling and disposal. The underlying logic behind the EPR policy measure is to correct market failures. Market failures expectedly occur when the price of the goods fails to include all the costs incurred to produce the good. Within the context of EPR, examples of these factors include costs of resource depletion and environmental externalities of resource extraction (Lifset, 1993).

1.5.1 Collection system

The primary objective of e-waste collection system is to develop strategies (either by the manufacturer or government) for collecting e-waste from users. Principal modes for collection are: retailer/dealer collection, drop-off sites, drop-off campaigns, and door-to-door collection. Where retailers are used as collection centers, some jurisdictions require that all electronics retailers collect all e-waste, whereas others only mandate collection of waste from current customers. In Switzerland (SWICO, 2006), all electronics retailers are required to take-back, free-of charge to the customer, all household waste electronic goods brought to them. In Portugal and the Netherlands, retailers are only required to accept waste items from customers who are either buying a new similar item from that store, or can prove that the waste item was originally purchased in that store (NEPSI, 2002). The most significant influence factors affecting collection rates are the cost incurred by consumer in dropping the e-waste to these sites and dissemination of collection information to the consumers. The awareness of consumers about the debilitating effects of e-waste, if disposed unscientifically is vital to the success of any collection program. Disinterested consumers, OEMs, and retailers lead to low collection volumes for recycling and reuse. Appropriate mechanism in deciding the type of collection container, the number of collection sites and the mode of collection are vital for the success of any collection system.

1.5.2 System management

A take-back system necessitates the presence of an entity who will be responsible for coordinating the actions of different stakeholders and enforcing the system rules and regulations. The possible entities could be the government, individual producers or third party organizations. Government entities as in the case of China and several states of the U. S., can be entrusted with the additional responsibility of supervising system operations. To manage the resources, the government levies a recycling fee from the consumers, at the point of sale. These responsibilities include charging collection and treatment fees from consumers, reimbursing collectors and processors, setting and enforcing standards, compliance and monitoring. The second option is the Individual Producer Responsibility (IPR), where producers design their own take back systems for their products. Here, the IPR has the freedom of direct control over its discarded products at the operational level. The closest system to the definition of IPR in our context is the Personal Computer (PC) recycling law in Japan (Atasu and Subramanian, 2012). To comply with this law, the Japanese Electronics and Information Technology Association (JEITA), has implemented a collection system that separates products by brand. The management of take-back schemes may also be carried out by a third party organization, which is responsible for the management and administration of a recycling program for its conglomerate. The membership to such a party may be made entirely of manufacturers of the products being recycled, but it can include government entities and other members such as recyclers or collectors, as well. Such Collective Producer Responsibility (CPR) systems can be found in Sweden, Netherlands, Belgium and Norway. Alternatively, it may be a single entity created by the government to manage a system.

1.5.3 Financing schemes

Financing of downstream e-waste activities and allocation of economic responsibilities along the downstream chain is a complex issue, given that there could be several ways by which different stakeholders can contribute to the process and therefore many models exist. The different approaches are i) compliance cost model, ii) compliance cost with visible fees, iii) reimbursed compliance cost, iv) recycling fee, and v) other hybrid approaches . In a compliance cost model, producers finance the activities of e-waste management in the system. A producer financing its own take-back program is difficult to practice. Therefore, in majority of cases, producers join a compliance scheme floated by different conglomerates and pay their contribution covering their take back and recycling costs. In the compliance cost and visible fee model, producers have to finance not only activities in the system, bearing costs for management of waste they put on the market, but also those historical waste from producers in the past. This they do so, by levying a visible fee from the final users to cover historical waste management costs. In the reimbursed compliance cost model, producers either by joining a compliance scheme or financing their own take back, finance activities in the system by bearing costs for management of e-waste. Such systems also have to bear the costs for management of historical waste. The only difference of this model from the other models is that the visible fee mechanism is directed to generate revenue from final users to pay for all the e-waste management costs. Producers pay compliance schemes in advance when placing appliances on the market but are reimbursed for the costs when selling appliances to final users. The other alternative model is the recycling fee model, sometimes also called as a recovery fee model, which is invariably paid by the consumers whenever they buy new equipment. Here the consumers bear the costs for management of e-waste, which means the producers are absolved from any financial involvement. A recycling fee could be used to generate funds for the future treatment of e-products that are currently being sold. This means that the future recycling costs for each appliance is estimated in advance and paid up-front by the consumer when buying the appliance.

1.6 Destination of e-waste

More challenging than the mounting volume of e-waste is where to put it. There are basically four general destiny for electronic products at the end of their life (U.S. Environmental Protection Agency, 2007): i) Reuse where products are either refurbished for resale, given away for free, or stripped of functioning components that are then remanufactured and sold; ii) Recycling where products are dismantled and shredded for the recovery of raw materials; iii) Disposal where products are either sent to landfills or are incinerated; and iv) Storage wherein products are stored away in a garage or closet.

Amongst these alternatives, reuse and recycling are widely considered to be more environmentally friendly treatment options for end-of-life (EOL) products. However, e-waste is most frequently sent to landfills or stored before being sent to landfills (Huisman and Stevels, 2006). It is estimated that, in 2005, 68% of e-waste in the United States were put in storage after the first use by the original purchaser of the product. In the same time, 24% were diverted to landfills, and 8% to recyclers and reuse. Second or multiple use items were still largely diverted to landfills over recyclers and reuse at 75% to 23% (U.S. Environmental Protection Agency, 2007). Sometimes, products end up being exported to overseas facilities mostly, to poor and developing countries that conduct the above listed EOL treatment (U.S. Environmental Protection Agency, 2007). There are varying estimates to the extent of exportation, but many authors believe it to be substantial (Puckett et al., 2002; Widmer et al., 2005).

There are two rationales for such exportation. The foremost argument in favor of such exportation is to provide second-hand products to people in developing countries who typically cannot afford new products (Puckett et al., 2002). There are both altruistic and economic motivations for such behavior, since the products are not given away for free. The second rationale, being purely economic, is to recycle products in countries where the labor costs are much lower than those in developed countries (Widmer et al., 2005). Concerns exist over such exportation because several reports have shown that, although a limited reuse market exists in the importing countries, some products that arrive are simply of low quality or nonfunctioning (Puckett et al., 2002). Furthermore, the Basel Action Network has shown that the frequency and intensity of environmental and health problems due to exposure to the hazardous chemicals contained in e-waste have increased in those parts of the developing world where e-waste dumping is most prevalent (Puckett et al., 2002).

1.7 e-waste Recovery

In the generic e-waste recovery system (see Fig. 1.2), EOL products are collected and sent to a dismantler (Huisman et al., 2007). The dismantler makes a decision whether a product is more valuable when resold or recycled. If the product has some retained use value, then it is sent to a refurbisher, reseller, or remanufacturer. Refurbishers and resellers prepare the entire product for resale, while remanufacturers remove and resell reusable components.

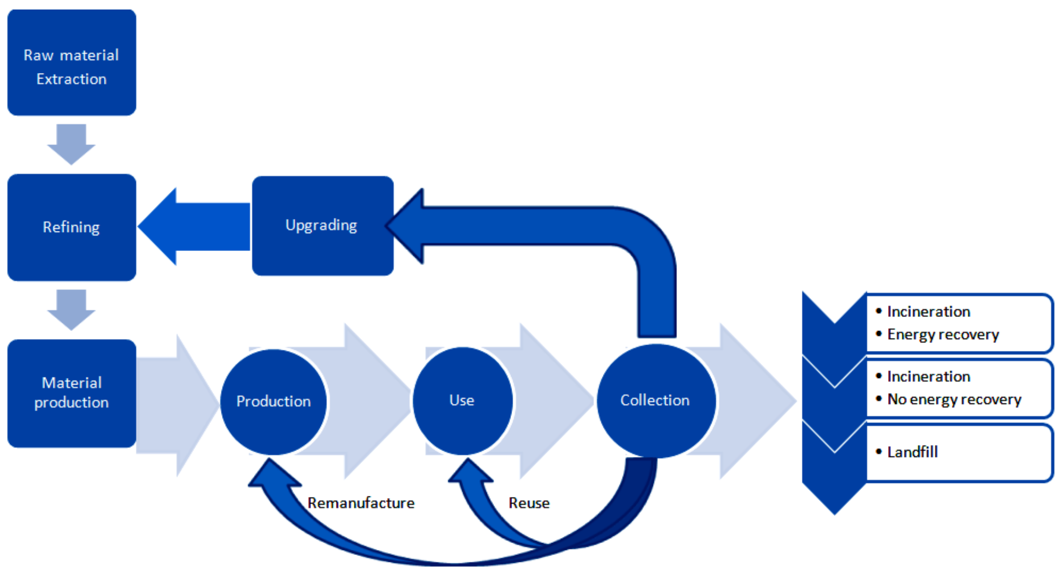

Fig. 1.2: Generic e-waste recovery system

If the product is more valuable when recycled, it is dismantled into its various recoverable commodities. Hazardous components are usually sent away to specific waste-processing facilities. Valuable components are separated into their respective commodity streams by the dismantler or downstream recyclers. The separation process usually involves two or more shredders to create manageable-sized materials for further processing in a magnetic separator and an eddy current separator. Companies that perform precious metals recovery use additional machinery to achieve a high level of material segregation (Sodhi and Reimer, 2001). Companies who receive large products, such as major appliances, take little care to finely separate commodities, as the most available commodities, such as steel, are easy to separate from the rest through the early processing stages (Ferrão and Amaral, 2006). After commodity separation, the metal streams are sent to smelters and plastics to plastic refiners, incinerators, or landfills. The various stages involved in recycling are shown in Fig. 1.3.

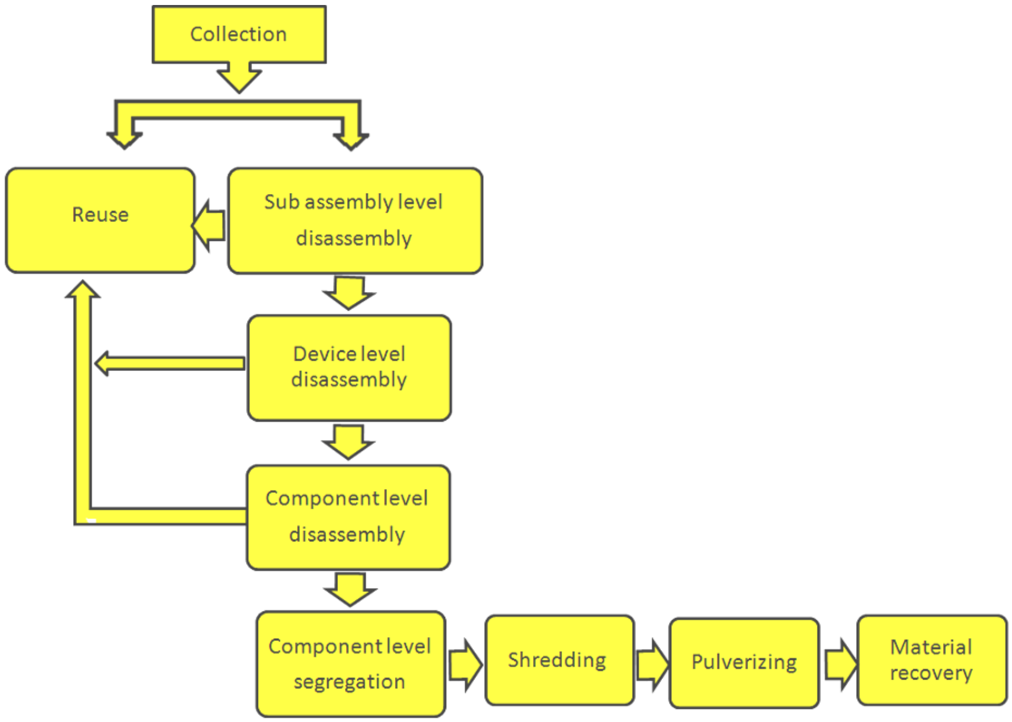

Fig. 1.3: Stages in recovery for recycling (Cui and Forssberg, 2003)

Recycling typically involves segregation and disassembly, followed by shredding or pulverizing, and material recovery. The primary activity of e-waste recycling is disassembling the collected products to the component level. Upon disassembly, the functional components are segregated from the non-functional ones. While the functional components are reused, the non-functional components are further disassembled. While the disassembled functional components are reused, the non functional ones are segregated on the basis of their composition, before being shredded. The last stage in recycling is material recovery (which involves recovering glass, plastics, ferrous and non-ferrous metals) through various refining processes. From Fig. 1.3, both system and component level disassembly and segregation processes are manual operations to a great extent. On the other hand, shredding, pulverizing, and material recovery are best done using automated processes. Even while partial material recovery involving glass, plastics and ferrous metals may be embarked manually, the efficient and safe recovery of non-ferrous metals, especially copper and gold, necessitates mechanized processes. Fig. 1.4 shows the typical composition of e-waste.

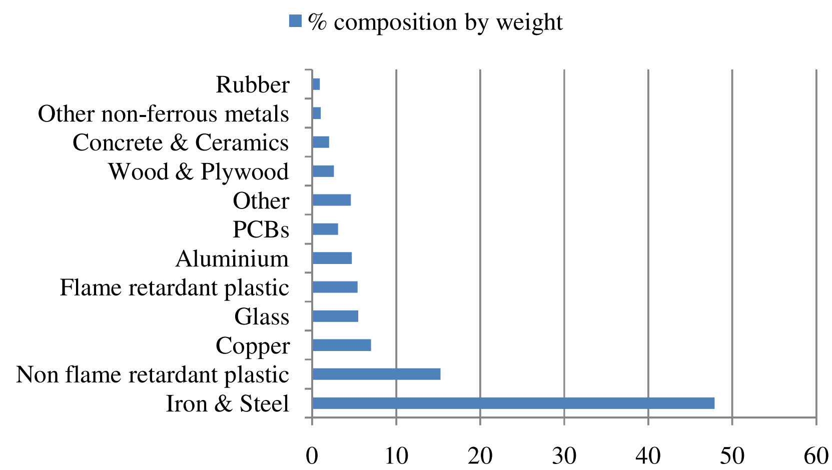

Fig. 1.4: Typical e-waste composition (Widmer et al., 2005)

1.8 The Indian Scenario

In India, e-waste is becoming an important waste stream in terms of both quantity and toxicity, as typical of any developing economy in transit. During the past two decades, the Indian economy has reported significant changes, as typical of an economy in transit. The Indian electronics industry has emerged as a fast growing sector in terms of production, internal consumption and export (Dimitrakakis et al., 2006). The growth of PC ownership per capita between 1993 and 2000 was 604 per cent as against the world average of 181 per cent during the same period (Sinha-Ketriwal et al., 2005). Contrary to the world average of 27 computers per 1000 people and over 500 computers per 1000 people in the US, India in the year 2004 had one of the lowest PC penetration rate at just 9 computers per 1000 people (Moskalyuk, 2004). However, the size of India's market in absolute terms is larger than most of the high income countries (Sinha-Ketriwal et al., 2005).

The increase in consumption rates of electronic products and higher obsolescence rates are leading to growing problems of e-waste. The existing system of e-waste processing in India is mostly handled by a very well networked informal sector (Sinha and Mahesh, 2007; Pavan and Dasgupta, 2009) where the disposal and recycling of computer waste are very rudimentary as far as the recycling techniques employed and safe recycling practices are concerned resulting in low recovery of materials; and pose grave environmental and health hazards. The process followed by these recyclers is product reuse, conventional disposal in landfills, open burning and backyard recycling (Dixit, 2007). Most often, the discarded electronic goods finally end-up in landfills along with other municipal waste or are openly burnt releasing toxic and carcinogenic substances into the air. The major sources of e-waste in India are the government, public and private sectors, retailers, individual households, PC manufacturing units, the secondary markets and illegally imported scrap (Veena, 2004).

According to BAN (2002), India after China is the second largest importer of e-waste from developed countries. Though new computers and peripherals can be imported into the country without any license, the import of used computers can only be made by a licensed dealer, who later can trade them with special permission from the Director General of Foreign Trade (DGFT). However, the import of used computers and other peripherals are free from any kind of duty, under the donation category. The field investigations by Toxics Link, cites large scrap dealers acquiring e-waste not only from the corporate sector and the government but also from illegal imports. These scrap dealers sort the collected units for reuse and recycling markets. Additionally, there are kabaadiwalas, who source functional units from scrap dealers and retailers and sell them to service shops and assemblers. In India, the recycling sector is primarily unorganized and the working conditions are appalling. The mechanism followed in the non-formal recycling sector are shown in Table 1.2. The removal of copper or aluminium is done by open burning of wires, with the least protection. This process is hazardous since burning of PVC results in the emission of carcinogenic dioxins and furans. Dismantling of monitors and hard disks are done with screw drivers and hammers. The recovery of gold from gold coated plug-ins are made through the hazardous process of acid treatment. The leftover toxic laden scrap from broken CRTs and others are dumped illegally.

Table 1.2: Mechanisms for recovery and recovered components

Computer component	Recovered component	Mechanism employed
Monitor	CRT, Circuit board, Copper, Plastic	Screw driver for disassembly (CRTs dumped)
Hard disk	Steel, Al, Actuator, Circuit Board	Broken with hammer
Circuit board	Capacitor, Condenser, Cu, Au, Chipped board	Acid treatment for gold recovery, heating for copper recover, crushing of board by custom made crusher
Printer	Motor, Plastics	Screw driver for disassembly
Cables & wires	Cu, Al	Burning or stripping

Source: Toxics Link (2006)

The current Indian legislation on classification of e-waste remains ambiguous with none of the laws directly referring to e-waste or it's handling (Dutta et al., 2006). Consequential to the lack of appropriate legal instruments, there is an alarming concern over illegal trans-boundary shipment of e-waste. There is a huge potential for organized recycling industry in India given the fact that about 95 per cent of e-waste is processed by the informal sector (MAIT-GTZ, 2007). The first formal recycling unit from the private sector was established in the year 2000 in Chennai, followed by two more in the year 2005 in Bangalore. Presently, around 23 recycling facilities in varying levels of infancy have come up in the organized or the formal sector to address this problem, which when fully operational could recycle 60 per cent of the estimated annual e-waste inventory (Jain, 2010). Though most of the hazardous material found in e-waste are covered under the purview of "The Hazardous and Waste Management Rules, 2008", the current Indian legislation on classification of e-waste as hazardous is ambiguous with none of the laws directly referring to e-waste or it's handling (Dutta et al., 2006). However, the Ministry of Environment and Forests (MoEF) have recently proposed a set of draft rules called the "e-waste (Management and Handling) Rules, 2011" which comes into force from May 1st, 2012. The new rule put the onus of e-waste management on the manufacturers in the lines of the principle of EPR and also restricts the use of hazardous substances in e-products. Through this enactment, companies now have to design their own take-back system. However, the rules remain silent on collection, recycling and reuse targets as well as the role of secondary reuse market.

1.9 Need for Research

The major sources of e-waste in India are the government, private sector, OEMs, retailers and individual households. Of the total e-waste inventory, both the government institutions and the private sector account for about 70 per cent, while the contribution of individuals is about 15 per cent (Sinha and Mahesh, 2007). The treatment of e-waste in India is handled by a very well networked and entrepreneurial informal sector and which replicates a long tradition of waste recycling (Widmer et al., 2005). More recently, several formal e-waste recycling entrepreneurial ventures have also sprung up in parallel with the informal sector in the country. Though e-waste management and disposal continues to be driven by global forces, the specificities will be determined by local conditions. The current e-waste management guidelines issued by the government, though nascent and much belated, will promulgate to all the stakeholders down the e-waste chain and in all likelihood will become the antecedent for a broad based legislation in the near future. Any future legal intervention into this complex issue will necessitate a holistic as well as robust solution in favor of all the stakeholders not only from the economic point of view, but also have to take into account the environmental consideration into the decision making process. Fig. 1.5 shows the major issues in e-waste management in India.

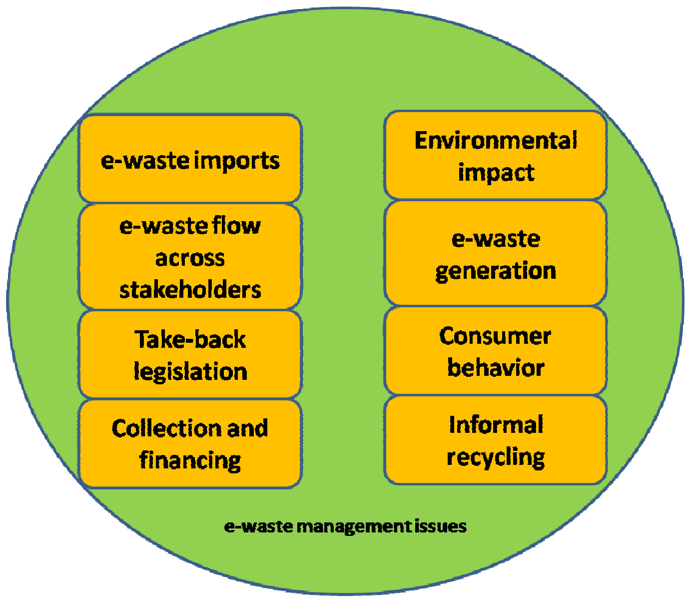

Fig. 1.5: e-waste management issues in India

1.10 Central Research Themes

To make e-waste recovery more profitable today and in the long-term, it is necessary to develop a deeper understanding of the mechanisms at play. Therefore, it becomes necessary to understand and evaluate whether the best practices from the developed world applies in the management of e-waste in India. Regional/country-level differences such as cultural factors complicate developing global strategies for multinationals in the management of e-waste. The overall impact of national characteristics on firms' environmental practices has been insufficiently studied. To comprehend these issues, this thesis will explore the following research questions:

- **Whether Extended Producer responsibility can be implemented effectively in India?**

To answer this question, following sub-research questions need to be investigated:

- What is the scope of EPR in India? How serious is the e-waste problem in India and what are the future projections?
- What are the awareness levels and expectation of consumer to the problem of e-waste and their management?
- What is the dynamics of e-waste flow in India in terms of the current state and its mapping to the future state?

- **What are the business strategies available to system managers that can promote profitability in the e-waste management initiative for firms adhering to EPR guidelines?**

  As for firms who remain committed to environmentally and socially responsible recovery, discerning ways to improve profitability is crucial. Whether these firms partake in an e-waste recovery system because of governmental mandate or because of a desire to sustain corporate image, the means of success are the same: increase revenue and minimize costs. However, the economic performance of an e-waste recovery system is affected both by collection and market forces. Returns management of e-waste are primarily influenced by collection rate, competition from new products that exist in the marketplace, value of the products at end-of-life, consumer demand and their disposal behavior. Following are the sub questions related to the main question:

  - What is the best system architecture for collecting and treating electronic waste that promotes reuse and design for recovery?
  - What is the anticipated impact of EPR on the firm's supply chain?
  - Which system architectures will drive the most economically efficient and environmentally sound e-waste recovery?
  - What factors impact the level of engagement of manufacturers in the proposed system architecture?

Previous literature identifies markets for recovered products (Thierry et al., 1995; Guide and Van Wassenhove, 2001; Geyer and Jackson, 2004), characteristics of returns flows and consumer behavior as critical factors that determine the profitability of product recovery. Previous literature does not offer much insight into strategic issues at the company level (Guide and Van Wassenhove, 2003; Meade et al. 2007), such as why certain manufacturers chooses to invest into facilities for end-of-life management whereas others, making the same product, develop minimal organizational resources to deal with it. In this thesis EPR refers to take-back measures. Take-back measures are considered to be the heart of EPR policies (Gertsakis et al., 2002). This thesis attempts to propose a hypothetical e-waste system design for recovery through reuse in the context of EPR legislation. In addition the thesis will evaluate the performance of different collection mechanism and theoretically analyze the success of the proposed system architecture in economic terms.

1.11 Objective of Research

The objectives of this thesis in light of the research questions raised can be summarized as follows:

1. Assessment of current and future e-waste generation quantities in India. The findings from this objective will help decision makers to review the necessity of a structured EPR regime for the future.
2. Mapping the current state of e-waste to the future e-waste flows in India. The major contribution of this objective will be to identify the best system architecture for e-waste management in India.
3. A comparative performance analysis of individual and collective e-waste take back collection system will be investigated with focus on India.
4. Investigation into consumer behavior and willingness to participate in e-waste recycling in India.
5. Modeling and assessment of third party remanufacturing under competition. The following contributions are expected from this objective:
   - To model competition of new product sales of the manufacturer from remanufactured products.
   - To identify long term equilibrium prices between the stakeholders under competition
   - To identify strategies to control the demand of new products remanufactured products in a competitive setting.
6. Modeling dual channel remanufacturing flow through manufacturer take-back for the assessment of critical success factors for remanufacturing under co-opetitive setting. The significant contributions from this objective include:
   - To model remanufacturing under the supervision of the manufacturer in a dual setting vis-a-vis the retailers and second hand market.

- Identifying critical factors that affect the demand for returned products and profit margins of the manufacturer.

1.12 Arrangement of the Thesis

In order to answer the previously mentioned objectives, the thesis was organized into eight chapters. Chapter 2 reveals the current e-waste generation quantities in India and also makes a limited attempt to forecast the future e-waste projection in India. Chapter 3 investigates the dynamic nature of e-waste flows across the different stakeholders in the Indian context. It lays the groundwork for a sustainable e-waste management framework in India. In Chapter 4, alternate e-waste collection models with focus on India are proposed to examine the appropriate collection mode taking into account the unique sensitivities prevalent in India. Consumer attitudes, behavior and willingness of residents' to participate in recycling are investigated in Chapter 5. Chapter 6 explores the profitability and price competition between the manufacturer and a third party remanufacturer under the purview of a take back legislation. In Chapter 7, the thesis explores the market conditions of a manufacturer supervised dual channel network for collection and resale of reused and remanufactured goods. The summary of the work done, contributions of the research, limitations of the study and scope for future work is presented in Chapter 8.

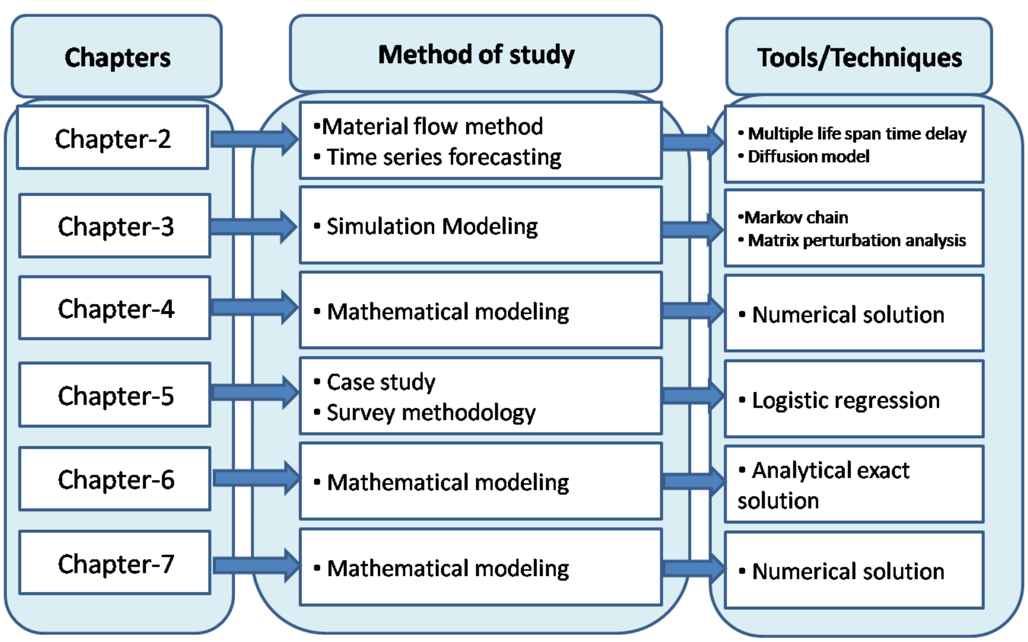

Fig. 1.6: Summary of thesis outline

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Chapter 2

Estimation of current and future outflows of e-waste in India

2.1 Introduction

Successful implementation of e-waste reuse and recycling requires the establishment of appropriate infrastructure. Factors that affect the design of such an infrastructure requires a preliminary assessment of e-waste, the nature of their flows, government regulations and the economics of end-of-life (EOL) products (Kang and Schoenung, 2005). Therefore, it is very imperative that a reliable estimate of current and future e-waste generation quantities in India is available so that the appropriate recycling infrastructure may be planned and developed. To this end, most of the developing countries lack reliable data on e-waste generation. It is difficult to precisely estimate and predict the annual quantity of obsolete e-waste because of the lack of statistical data on their consumption patterns. Traditionally, there have been several approaches for quantifying WEEE generation in developing economies. The practical way is to roughly estimate the waste amount based on the sales amount and the assumed average period of use (Liu et al., 2006). The market supply method, which uses past domestic sales data coupled with the average life of electronic appliances, is widely used for assessing WEEE generation estimates. Such studies extrapolate the assumed lifespan backwards in time to estimate potential WEEE from historical production and sales figures (Streicher-Porte et al., 2005; Jain and Sareen, 2006; Streicher-Porte 2007). The accuracy of such an estimate relies on the accuracy of the assumed average life, which in many cases remains subjective in nature. Though computation is primarily based on sales data, they can also be partially estimated using material flow models (Terazonoo et al., 2006). Alternatively, a variation of this method is the 'Carnegie Mellon Method (Matthews et al., 1997), which explicitly uses the same assumptions but simultaneously is capable of simulating consumer behavior by allowing material flows through different EOL alternatives like reuse, storage, recycling and landfilling. Here, assumptions are made on the quantities flowing through each of the four EOL alternatives, which yet again are product and country specific. The consideration that average life of EEE items does not vary as much as what is observed in developed markets on account of a static market so far as technology and lifestyle changes are concerned, makes it a popular choice for WEEE estimation. Peralta and Fontanos (2004) modified the EOL model proposed by Matthews et al. (1997) to predict the e-waste generation quantities in Philippines. Kang and Schoenung (2006) modified the EOL model proposed by Matthews and Matthews (2003) to assess future outflows of e-waste generation for different scenarios. These EOL models are able to account for the relationship between reuse, storage, recycling and landfills and are more versatile than the market supply method, as they give a more realistic view of the end-of-life disposal strategies. At the same time, the effect of different policy decisions and regulations like ban on landfills on the e-waste generation quantities can be easily captured and studied in a holistic way by adopting the former (Matthews and Matthews, 2003). When it comes to developed and saturated markets, WEEE generations are made through the ‘consumption and use method’ using estimates of stock and average lifetime data. It is reported that about 80 per cent of the WEEE from the recycling industry in US is exported to Asia and 90 per cent of this goes to China (BAN and SVTC, 2002). For this study, it was assumed that there is a total ban on these illegal exports to India as such a law is likely to be put into force in the near future. As the business prospects for e-waste recycling in India are good, several large-scale facilities with formal and advanced technology have been built or are being planned and constructed.

2.2 Methodology

2.2.1 Assessment of current e-waste generation in India

There have been few papers on e-waste focusing on the Indian scenario notably among them is the work by Jain and Sareen (2006) and Babu et al. (2007), but these studies was limited in scope to the state boundary of Delhi and selected areas in the National Capital Region (NCR) of Delhi with focus on CRTs from PCs and TVs. Their WEEE assessments were based on an approximation method using the PC penetration rates for different years and the respective population data. To our knowledge, no known study has been carried out for estimating the e-waste generation and disposition quantities related to entire India encompassing a wide variety of items which includes desktop PCs, notebook PCs, B&W and color television, refrigerators and washing machines. The estimation of domestic e-waste is conducted using the historical sales data or the shipment amounts of these electronic products. The major bottleneck in forecasting these estimations is identification of the rate at which these electronic products reach their EOL. Identification of this component is more pronounced for personal computer systems (Kang and Schoenung, 2006) as it is reported that the useful life of such systems has been rapidly decreasing (Streicher-Porte and Yang, 2007). The accuracy of any computer waste forecasting model is dependent upon the accuracy of the life span of the computer (Leigh et al., 2007). Earlier studies (Streicher-Porte and Yang, 2007; Jain and Sareen, 2006) report using primary and secondary based data from market research and questionnaire based survey to estimate the average lifespan of PCs. According to a recent study by Toxics Link, the life of a computer in India has fallen from 7 years to 3-5 years. Instead of using a uniform life span, there are studies where multiple lifetime spans for estimation of outflows were proposed (Kang and Schoenung, 2006; North Carolina Environmental Department, 1998). Table 2.1 below illustrates the compilation of the average lifetime of electronic products proposed by different authors in the context of developing countries.

Table 2.1: Estimates of average life spans of electronic items by different authors

Method adopted	**Authors**	**Country Specific**	**Average life time (in years)**
Market supply method	Jain and Sareen (2006) and Babu et al. (2007)	India	PC - 5 or 7
	Liu et al. (2006)	China	PC - 5 (1993) and 3.5 (2003) TV - 8 Refrigerator - 9 Washing machine - 9 Air conditioner - 10
	He et al. (2006)	China	PC - 4 to 6 (1990) and 2 to 4 (2006) TV - 7 to 8 Refrigerator - 8 to10 Washing machine - 8 to10 Air conditioner - 10 to11
	Streicher-Porte and Yang (2007)	China	TV - 8 Refrigerator - 9 Washing machine - 9 Air conditioner - 10
Carnegie Mellon Method	Peralta and Fontanos (2006)	Philippines	TV - 8 Refrigerator - 10 Washing machine - 10 Air conditioner - 10

It is quite evident from Table 2.1 that lifespan assumptions of electronic products in emerging markets are different for different countries and are subjective in nature. Hence there is a need in developing a generic model where the user can input different values of lifespan and evaluate the waste generation quantities. For the purpose of this study, a multiple lifetime span time delay Material Flow Analysis (MFA) model was used.

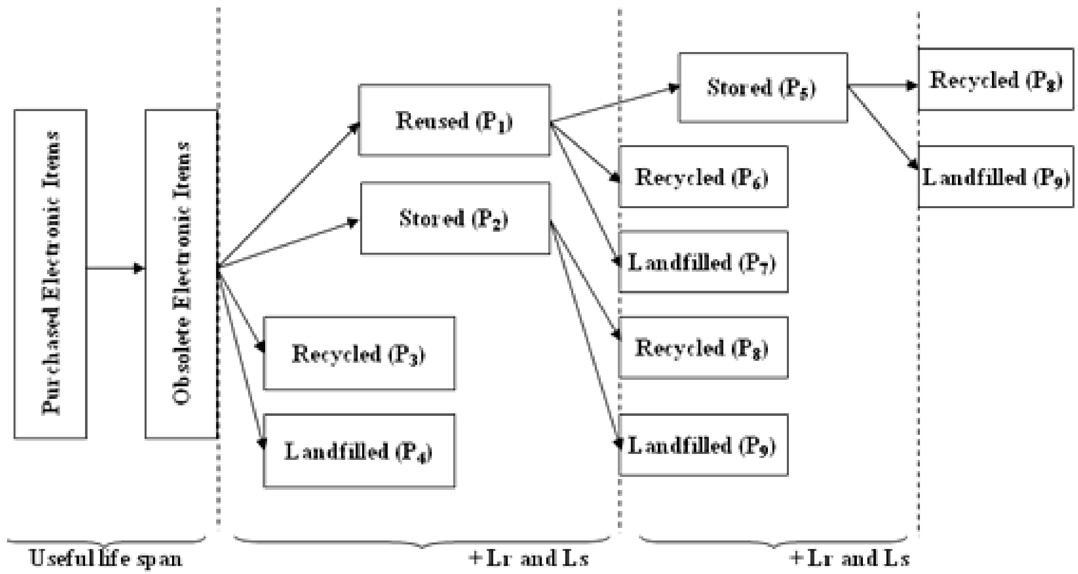

Fig. 2.1: Schematic representation of EOL generic model to predict WEEE estimate

According to this model, shown in Fig. 2.1, electronic goods after the end of their useful life become obsolete. Further, this WEEE has four disposal alternatives. First, it could be reused by way of possibly reselling them or reassigning them to a second user. Second, the original user could also possibly store them. The third and fourth alternative could be recycling and landfilling. The reuse and store options are the intermediate EOL options while recycling and landfilling represent the final disposal options. The model requires few practical assumptions to forecast future WEEE estimates. The case specific model has been coded to make it more generic whereby the analyst can alter different model inputs to suit the country for which the WEEE estimates are required. The algorithm for the proposed application is as follows:

i. Let $D(Y,K)$ denote the domestic sales for various electronic devices for the year (Y) and item (K).

ii. Let us denote $I_1, I_2, \ldots, I_N$ as the electronic items and $L_1, L_2, \ldots, L_N$ be the corresponding average lifespan of the electronic items; Lr and Ls be the average lifespan of reused and stored electronic items respectively.

iii. Identify the percentage of electronic items that go through various EOL alternatives. The variables in Fig. 2.1are defined below.

$P_1, P_2,\ P_3$ - % Obsolete reused, obsolete stored and obsolete recycled respectively

$P_5,\ P_6,\ P_7$ - % Reused stored, reused recycled and reused landfilled respectively

$P_8,\ P_9$ - % Stored recycled and stored landfilled respectively

iv. Calculate $O_{(Y,K)}$ = Obsolete items of type K in year Y from the equations

$$O_{(Y,K)} = D(Y - L_K, I_K) \qquad (1)$$

$$O_{(Y-Lr,K)} = D(Y - Lr - L_K, I_K) \qquad (2)$$

$$O_{(Y-Ls,K)} = D(Y - Ls - L_K, I_K) \qquad (3)$$

where O_Y represents the total obsolete waste disposed of type K in the year Y which were purchased in the year $Y - L_k$. Similarly, O_{Y-Lr} and O_{Y-Ls} represents the quantity of obsolete reused and obsolete stored waste of type K that were purchased in the year $Y - Lr - L_K$ and $Y - Ls - L_K$ respectively.

v. Calculate $R_{U(Y,K)}$ = Reused items of type K in year Y; $S_{T(Y,K)}$ = Stored items of type K in year Y; $R_{C(Y,K)}$ = Recycled items of type K in year Y; $L_{A(Y,K)}$ = Landfilled items of type K in year Y using the equations

$$R_{U(Y,K)} = P_1 \times O_{(Y,K)} \qquad (4)$$

where, $R_{U(Y,K)}$ = Percentage of obsolete items of the current year that goes for reuse

$$S_T = P_2 \times O_Y + P_1 \times P_5 \times O_{Y-Lr} \qquad (5)$$

where, S_T = Percentage of obsolete items of the current year that goes for storage + Percentage reused stored of the obsolete reused from $Y - Lr$ years earlier.

$$R_C = P_3 \times O_Y + P_2 \times P_8 \times O_{Y-Ls} + P_1 \times P_6 \times O_{Y-Lr} + P_1 \times P_5 \times P_8 \times O_{Y-Lr-Ls} \qquad (6)$$

where, R_C = Percentage of obsolete items of the current year + Percentage stored recycled of the obsolete stored from Ls years earlier + Percentage reused recycled of the obsolete reused from Lr years earlier + Percentage stored recycled of the reused stored waste from ($Lr + Ls$) years earlier.

$$L_A = P_4 \times O_4 + P_1 \times P_7 \times O_{Y-Lr} + P_2 \times P_9 \times O_{Y-Ls} + P_1 \times P_5 \times P_9 \times O_{Y-Lr-Ls} \quad (7)$$

vi. Print O_Y, R_U, S_T, R_C and L_A

The application is coded in VB editor of MS Excel software. Graphical user interface are used for data input and model assumptions can be made through the use of drop down menu. The main menu of the application is shown in Fig. 2.2, which allows the user to edit and add to the existing data of shipment values of EEE products for different years. Fig. 2.3 shows the user interface for input data and model assumptions while Fig. 2.4 shows the interface for selecting the product of interest. The results of the analysis are displayed in Fig. 2.5.

Fig. 2.2: Main application window

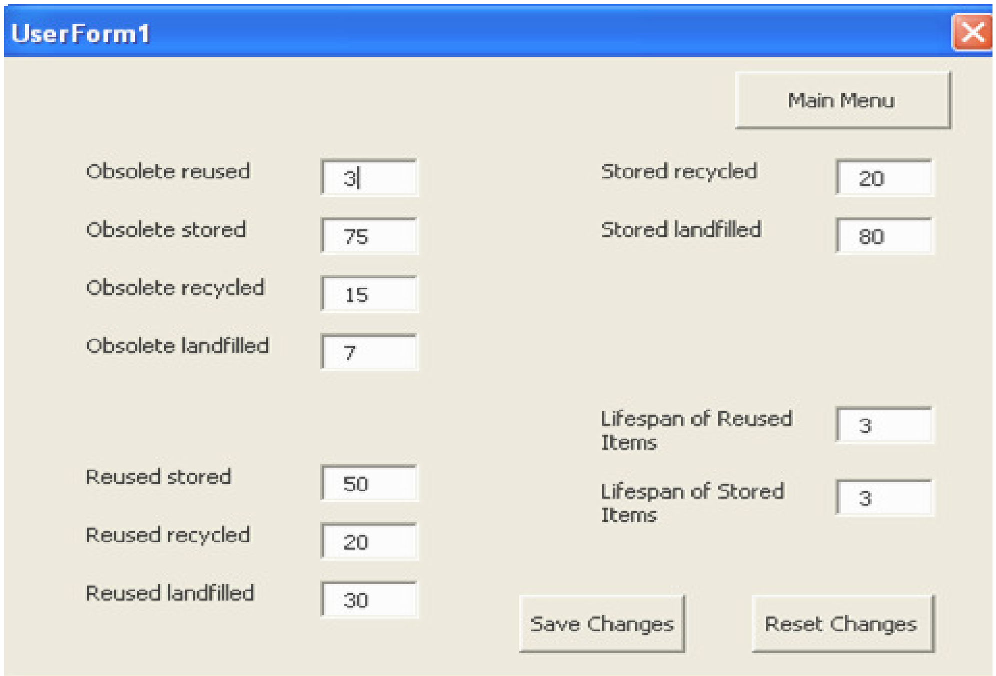

Fig. 2.3: Data input user interface

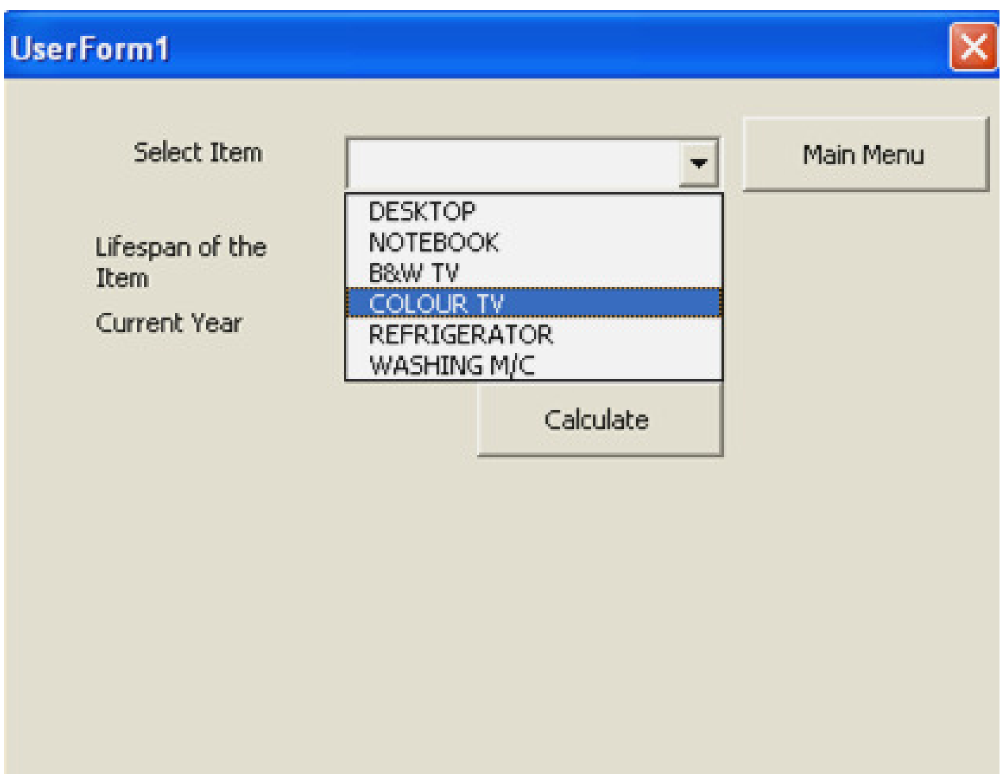

Fig. 2.4: Product selection window

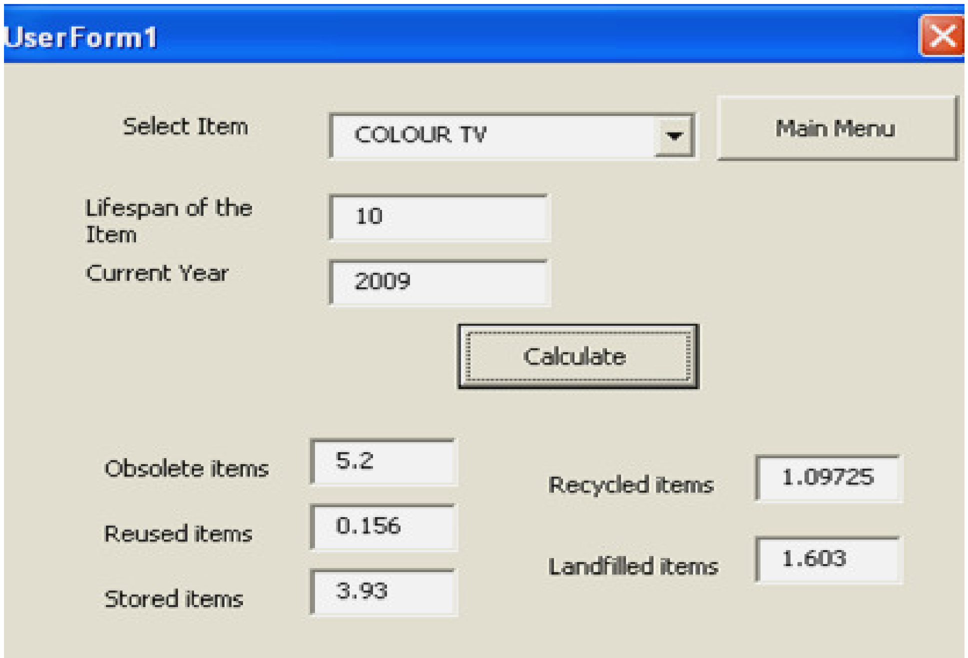

Fig. 2.5: WEEE estimation

The time series material flow model (see Fig. 2.1) illustrates the useful life phase of EEE after which it becomes obsolete. The first user now has the option of either storing it for an extended period of time or reusing by way of donating it to a second user. Else it could possibly be landfilled or recycled. The possible states after being stored or reused could be recycled or landfilled. The store and reuse phases can be considered as another lifespan for the electronic items. Also the model assumes that there is no reuse after the storage by the second user since by this time the item has outlived its design lifecycle. In order to investigate the WEEE estimates under data constraint, several assumptions are made.

Table 2.2: Assumed lifespan of electronic items

Item	Lifespan of EEE
Desktop PC	3 years
Notebook PC	3 years
B&W TV	8 years
Color TV	8 years
Refrigerators	10 years
Washing M/C	10 years
Reused item	3 years
Stored item	3 years

The assumed useful average lifespan of electronic items and the lifespan for the intermediate stages are shown in Table 2.2. For instance, it was assumed that all PC's are used for at least for a period of 3 years, which is quite realistic considering the fact that PC's are made obsolete due to technological obsolescence rather than functional obsolescence. Two scenarios were investigated for evaluating the proposed generic EOL model. Scenario-1 represents the optimistic assumption wherein majority of obsolete items are reused and few are stored (see Table 2.3).

Table 2.3: Disposal percentages of EOL items for different scenarios

EOL options	**Optimistic Scenario (Scenario-1)**		**Pessimistic Scenario (Scenario-2)**	
	Desktop, Notebook and Television	Refrigerator and washing machine	Desktop, Notebook and Television	Refrigerator and washing machine
Obsolete reused	50	70	25	20
Obsolete stored	25	20	50	70
Obsolete landfilled	5	2	5	2
Obsolete recycled	20	8	20	8
Reused recycled	20	8	20	8
Reused stored	70	90	70	90
Reused landfilled	10	2	10	2
Stored recycled	75	80	75	80
Stored landfilled	25	20	25	20

The obsolete reused quantities are assumed to be 50 per cent (for PC and television) and 70 per cent (for refrigerator and washing machine) respectively of the total obsolete items generated for any given year. According to one study conducted in Bangalore by HAWA (Hazardous Waste Management Project Karnataka, 2004), the contribution of large household appliances like washing machines and refrigerators in the overall e-waste stream composition is not that significant. Therefore a higher percentage of them (about 70 per cent) are assumed to go for reuse in the optimistic scenario. The 50 per cent obsolete reuse figure estimate is assumed from the investigation made by Peralta and Fontanos (2006), which focus on a developing country like Philippines. The illustrated assumption is quite realistic for the Indian scenario given that the electronic industries in both the countries are fairly new.

The pessimistic assumption is illustrated by Scenario 2, which has been adopted from the study by Kang and Schoenung (2006) and Goodrich (1999) where a considerable amount of stock remains in storage. It reflects the trend of consumers storing their obsolete electronic items especially large household appliances. This behavior is captured by assuming the obsolete stored quantities to be 50 per cent (in case of PC and television) and 70 per cent (in case of washing machine and refrigerator) respectively of the total obsolete items generated for any given year. A higher percentage is assumed for large household appliances as it aptly reflects the consumer disposal behavior in the pessimistic scenario. In India, e-waste is often dumped in landfill, where it is dismantled for precious materials and 70-90 per cent of such landfills are mere dump sites (TETRAWAMA, 2006). According to one report in an Indian daily (The Hindu, 2009), after recycling only 5 to 10 per cent of e-waste reaches landfill. In this study, the assumed values of obsolete items diverted to landfills are 5 per cent for PC and television and 2 per cent for large household appliances. Additionally, it is also assumed that obsolete electronic items can be further reused and stored for about 3 years. Since the equipment under investigation have already been used for 3 years in case of personal computer system and for 8-10 years in case of television, refrigerator and washing machine, they can be further reused for an additional 3 years, which is well within their maximum intended design life. Peralta and Fontanos (2006) report using a lifespan of 3 years for the store EOL phase while Kang and Schoenung (2006) assumed it to be 2 years, in which case the former would be more appropriate for the Indian scenario considering the fact that consumers there consider it to be a source of revenue. The two scenarios represent the two extreme cases of EOL consumer disposal behavior, hence is the subject of study for WEEE estimates in India. The historical shipment of electronic items, which is the input to the model, is shown in Table 2.4. Table 2.3 shows the assumed values of the variables illustrated in Fig. 2.1 for the two case scenarios.

Table 2.4: Domestic sales data of electronic devices in India (in million units)

Year	Desktop PC[a]	Notebook PC[a]	B&W Television[b]	Color Television[b]	Refrigerator[c]	Washing Machines[d]
1994	0.240300	0.004500	5.95	1.97	1.64	0.550
1995	0.371667	0.011329	5.70	1.70	1.96	0.740
1996	0.451427	0.01596	6.00	2.00	1.93	0.690
1997	0.799058	0.01000	6.00	2.80	2.18	0.890
1998	1.027190	0.02292	6.00	3.50	2.43	0.984
1999	1.405290	0.04167	5.60	5.20	2.62	1.160
2000	1.881640	0.04167	4.90	5.20	2.83	1.275
2001	1.670880	0.044742	4.00	5.80	3.06	1.342
2002	2.293643	0.050974	3.80	6.80	3.34	1.296
2003	3.035591	0.088831	2.80	8.00	3.64	1.360
2004	3.632619	0.177105	2.40	9.10	3.96	1.600
2005	4.614724	0.431834	2.00	10.30	4.36	1.680
2006	5.490591	0.850860	1.80	11.70	4.79	1.700
2007	5.522167	1.822139	1.00	14.80	5.27	1.950

[a] MAIT, Moorthy and Murthy(1999)

[b] Greenpeace(2008), Jain and Sareen(2006)

[c] Srivastava and Srivastava(2006)

[d] Greenpeace(2008), FICCI(2005), Majumdar(2006)

2.2.2 Assessment of future e-waste generation in India

The major objective of this investigation is to predict the future trend of obsolete computer related e-waste generation quantities as a function of time in India. For the purpose of this study, a logistic function based model was proposed and implemented. The logistic model is further analyzed to investigate the effects it has on the computer waste generation. The logistic growth curve assumes that there is an asymptotic value to the computer adoption or penetration rate growth curve and has a characteristic "S" shape. The penetration rate is assumed to increase slowly at the beginning and reaches a maximum rate of growth at the point of inflexion. From this state onwards, there is a gradual decrease in the growth rate until the curve reaches the asymptotic value. Over the years, "S" shaped evolutions have regularly been applied for analyzing demography, biological, technological diffusion and economic models (Jarne et al., 2005). In so far as technology diffusion is concerned, such curves are used because of their ability to describe these processes and at the same time display their typical phases: growth, inflexion and saturation.

The logistic curve was first proposed by Verhulst in 1838 in the journal "Correspondence Mathematique et Physique". A century later, in 1920, Pearl and Reed rediscovered it during the course of their study on the evolution of fly population. Fisher and Pry (1971) proposed a diffusion and innovation model drawing a parallel between epidemic spread and information circulation. Past studies in technological diffusion (Frank, 2004; Boretos. 2007; Yamasue et al., 2006) include innovation such as mobile phones, computers, refrigerators and television. However, only few research papers (Yang and Williams, 2008; Yang and Williams, 2009; Yu et al., 2010; Liu et al., 2006) address and translate this technology diffusion into Waste Electrical and Electronic Equipment (WEEE) obsolete prediction.

Proposition: The general logistic equation for computer adoption expressed in conventional logistic form can be expressed as:

$$\frac{dN}{dt} = rN\,(1-\frac{N}{K}) \tag{8}$$

where N represents the number of computers owned per capita (penetration rate), r represents the rate of adoption or growth rate and K represents the carrying capacity.

Proof: Assuming that increase in the number of PC adopters or adopting units $\left(P^{+}\right)$ is proportional to the rate of encounter of one potential adopter $\left(P^{-}\right)$ and one adopter $\left(P^{+}\right)$, and can be expressed as ${dP^{+}}/{dt} = r_1 P^{+} P^{-}$. Here r_1 represents the rate of adoption and measures the power of imitation. In other words, it measures how long it takes for an adopter to infect a potential adopter. For a constant r_1, given that adopters and potential adopters make up the whole population (Q), leads to $P^{+} + P^{-} = Q$. So plugging this into the fundamental assumption, gives ${dP^{+}}/{dt} = rP^{+}\left(1 - {P^{+}}/{Q}\right)$, where $r = Qr_1$. Defining N

as the number of computers owned per capita, and C the total number of computers, implying that $N = C/Q$ and C is proportional to the number of adopters $\left(C = \beta P^{+}\right)$, where β is the number of computers per adopter. Substituting, we get $P^{+} = NQ/\beta$. Further assuming that Q changes relatively slowly, and through substitution results in $dN/dt = rN(1 - N/K)$, where $K = \beta$ represents the carrying capacity which is the average maximum number of PCs a person is likely to have. The proof is complete.

The rate of adoption 'r' refers to the relative speed with which computers are adopted and for a logistic model this parameter remains constant. However, Yang and Williams (2008) in their technology diffusion model had investigated the effects of a variable rate of change of the adoption rate and report that there is no significant difference in their analysis. The carrying capacity for this case refers to the average number of computers a person is likely to possess. It follows therefore that $'K'$ represents the limiting value of the output. The solution of $Eq.(8)$ at time t is of the form:

$$N_t = \frac{K}{e^{-(rt+C)} + 1} \tag{9}$$

At reference time $t = 0$, the initial penetration rate is denoted by N_0. Thus,

$$N_0 = \frac{K}{1 + e^{-C}} \; or \; K = N_0 \, (1 + e^{-C}) \tag{10}$$

that is, the maximum carrying capacity K will be $(1 + e^{-C})$ times larger than N_0 or alternatively e^{-C} could be interpreted as the number of times N_0 must grow to reach K. The value of C can be computed from the expression:

$$C = \ln\left(\frac{N_0}{K - N_0}\right) \tag{11}$$

Eq. 9 illustrates that the logistic models have three unknown parameters (K, N_0 *and* r), which are to be estimated. Yang and Williams (2009) argue that though in principle the value of carrying capacity (K) could be identified from statistical fits of the historical time-series penetration rates, it would be not justified for the case when the historical data-series is still in its early stage and is yet to reach their inflection point. To overcome this problem, a bounding approach was incorporated by determining the lowest and the highest conceivable values of K to evaluate the logistic model for a range of outcomes within these two bounds. Skiadas et al. (1993) report that the asymptote or the saturation value (K) is the most critical factor for understanding the behavior of the system to which the logistic curve is applied.

Though time-series data on historical computer penetration rate exist for India, they remain few but unreliable and conflicting. Therefore, the following approach was outlined to recreate a time-series of computer penetration rates based on estimates of stock, historical sales and assumptions on lifespan (see $Eq.(12)$ *and* (14)). The procedure followed was to assume a lifespan distribution L_j where $'j'$ represents the year after which the computer becomes obsolete and using the historical sales S_i the annual obsolete quantities (O_i) for a given year $'i'$ was estimated from the expression:

$$\begin{aligned} O_i &= \sum[\text{Sales in the year } (i-j) \times \text{Percentage of computers that become obsolete after } 'j' \text{ years}] \\ &= \sum \mathrm{S_{i-j} L_j} \end{aligned} \tag{12}$$

Assuming that computers enter the national stock after being purchased, the possession amount or stocks in use (St_i) in year $'i'$ was estimated as:

$$\begin{aligned} St_i &= \text{Stocks in use in year } (i-1) + \text{Sales in year } 'i' - \text{Obsolete stock in year } 'i' \\ &= St_{i-1} + S_i - O_i \end{aligned} \tag{13}$$

The penetration rate in year i, N_i is computed from the relationship:

$$N_i = \frac{St_i}{Q_i} \tag{14}$$

where Q_i is the population in year $'i'$.

Statistical fits are performed on the generated time-series historical penetration rate in order to identify the parameter values r and N_0 of the logistic model. The approach here was to separately identify these parameters for both the upper and lower bound carrying capacity. The optimal logistic curve was identified by minimizing the sum of the squared residual (SSR) or error term λ (see $Eq.(8)$) between the fitted curve and the generated historical penetration rate and the corresponding best values of r and N_0 is obtained as:

$$\lambda = \sum(\bar{N}_t - N_t)^2 \tag{15}$$

where $\bar{N}_t$ is the predicted penetration rate from the logistic fit, N_t is the observed historical penetration rate and $(\bar{N}_t - N_t)$ is the residual term for a given year.

If λ possesses a minimum, it will occur for values of $r \text{ and } N_0$ that satisfy the equations:

$$\frac{\partial \lambda}{\partial r} = 0 \text{ and } \frac{\partial \lambda}{\partial N_0} = 0 \tag{16}$$

Eq. (16) represents a system of linear equations in r and N_0.

The computer penetration rates from the logistic curve are translated to their corresponding sales using Eq. (14). The knowledge of the market share of laptops and desktops are utilized to determine their estimated sales from the projected computer sales. The projected sales figures of laptops and desktops coupled with their respective first lifespan distribution are utilized to generate the projected obsolete amounts of computers. The next step is to determine the EOL estimates from the computed obsolete quantities. For this, a time-series EOL multiple lifespan material flow model stated in section 2.2.1 was used.

2.3 Results and Discussion

2.3.1 Discussion on the current estimate

Tables 2.5 - 2.6 show the WEEE generation estimates for Scenario-1 and Scenario-2 respectively for each type of equipment.

Table 2.5: Generation estimates for individual EOL items in million units (Scenario-1)

Item	Year	Obsolete	Reused	Recycled	Landfilled	Stored
Desktop PC	2007	3.632	1.816	1.476	0.304	1.492
	2009	5.490	2.745	2.464	0.497	2.435
	2011	5.605	2.802	3.049	0.608	3.016
Notebook PC	2007	0.177	0.088	0.054	0.012	0.059
	2009	0.850	0.425	0.206	0.048	0.243
	2011	2.900	1.450	0.717	0.172	0.876
B&W TV	2007	5.600	2.800	4.417	0.759	3.500
	2011	2.800	1.400	3.543	0.551	2.415
	2015	1.000	0.500	1.940	0.270	1.090

Item	Year	Obsolete	Reused	Recycled	Landfilled	Stored
Color TV	2007	5.200	2.600	2.074	0.415	2.000
	2011	8.000	4.000	3.830	0.774	3.820
	2015	14.800	7.400	7.098	1.410	6.885
Refrigerator	2007	2.180	1.526	0.352	0.088	1.526
	2011	3.060	2.142	0.524	0.131	2.227
	2015	4.360	3.052	0.728	0.182	3.093
Washing machine	2007	0.890	0.623	0.123	0.030	0.543
	2011	1.342	0.939	0.217	0.054	0.922
	2015	1.680	1.176	0.289	0.072	1.197

Table 2.6: Generation estimates for individual EOL items in million units (Scenario-2)

Item	Year	Obsolete	Reused	Recycled	Landfilled	Stored
Desktop PC	2007	3.632	0.908	1.571	0.274	2.108
	2009	5.490	1.372	2.635	0.442	3.276
	2011	5.605	1.401	3.383	0.531	3.610
Notebook PC	2007	0.177	0.044	0.057	0.011	0.096
	2009	0.850	0.212	0.213	0.047	0.440
	2011	2.900	0.725	0.770	0.167	1.525
B&W TV	2007	5.600	1.400	4.456	0.632	3.850
	2011	2.800	0.700	3.430	0.437	2.257
	2015	1.000	0.250	1.745	0.205	0.920
Color TV	2007	5.200	1.300	2.119	0.375	2.950
	2011	8.000	2.000	4.177	0.684	4.910
	2015	14.800	3.700	7.588	1.245	8.992
Refrigerator	2007	2.180	0.436	0.309	0.077	1.837
	2011	3.060	0.612	0.449	0.112	2.603
	2015	4.360	0.872	0.629	0.157	3.686
Washing machine	2007	0.890	0.178	0.114	0.028	0.727
	2011	1.342	0.268	0.189	0.047	1.126
	2015	1.680	0.336	0.245	0.061	1.4224

The generation estimates over all the EOL options are shown in Tables 2.7 - 2.8 for Scenario 1 and 2 respectively. Looking at the estimates of scenario-1 for the period 2007 - 2011 (see Table 2.7), it was observed that the predicted values of recycling, reuse and store quantities fall in the same band. However, for the same period during scenario-2, there is a significant difference in the reused and stored estimates with more than 68 million units remaining in storage. Over a span of 5 years, from 2007 to 2011, more than 50 million units are reused and stored during Scenario-1 while more than 24 million units are reused in Scenario-2.

Table 2.7: Generation estimates for all EOL items in million units (Scenario-1)

Year	Obsolete	Reused	Recycled	Landfilled	Stored
2007	17.679724	9.453862	8.498222	1.6104475	9.1232487
2008	18.560558	9.963079	9.243791988	1.755682263	10.16555545
2009	19.921451	10.7167255	9.8941084	1.90648885	10.95221045
2010	22.049306	11.845653	11.00545563	2.146833435	12.4620299
2011	23.7075	12.73415	11.88280539	2.292367673	13.2783803
2007-2011	101.918539	54.7134695	50.52438341	9.711819721	55.9814248

Table 2.8: Generation estimates for all EOL items in million units (Scenario-2)

Year	Obsolete	Reused	Recycled	Landfilled	Stored
2007	17.679724	4.26643100	8.628738088	1.399168763	11.57019585
2008	18.560558	4.46943950	9.486723325	1.519403650	12.42638698
2009	19.921451	4.79136275	10.33636199	1.649624613	13.42379935
2010	22.049306	5.30707650	11.65589729	1.858395193	14.98565470
2011	23.707500	5.70677500	12.40012613	1.979870299	16.03345765
2007-2011	101.918539	24.54108475	52.50784682	8.406462518	68.43949453

As observed from the item wise break-up of obsolete items in Table 2.9, the number of obsolete PC's (both desktop and notebook) and color television during the period 2007-2011 are both each equal to 31 million units and account for approximately 30 per cent of the total units of WEEE during the same period. In the span of 5 years until 2011, the projected total obsolete electronic items will be expected to reach upwards of 100 million units.

Table 2.9: Item wise break-up of obsolete WEEE estimates in million units

Year	Desktop	Notebook	B&W TV	Color TV	Refri-gerator	Washing Machines	Total obsolete WEEE
2007	3.63	0.17	5.60	5.20	2.18	0.89	17.67
2008	4.61	0.43	4.90	5.20	2.43	0.98	18.56
2009	5.49	0.85	4.00	5.80	2.62	1.16	19.92
2010	5.52	1.82	3.80	6.80	2.83	1.27	22.04
2011	5.60	2.90	2.80	8.00	3.06	1.34	23.70
2007-2011	24.86	6.18	21.10	31.0	13.12	5.65	101.91

Table 2.10: Average weight of electronic items

Electronic item	Average weight per unit (kg)
Desktop PC	27.2
Notebook PC	2.9
Television	24
Refrigerator	30
Washing machine	27

Source: Kumar and Shrihari (2007) and Toxics Link

The estimated units of WEEE are converted to weight in metric ton (see Table 2.10) by taking into account the average weight of each electronic item as shown in Table 2.11. An important finding that emerged from the study is that the PC waste during the period 2007-11 would be approximately 0.7 million MT which includes both desktop and notebook. Overall around 1.95 million MT of e-waste is generated from PC and television accounting for 78 per cent of the total e-waste weight. The waste from television, refrigerator and washing machines during the same period will be respectively 1.25, 0.3936 and 0.152 million MT. The total WEEE estimates during 2007-11 will be around 2.49 million MT. Table 2.12 demonstrates the sensitivity of the model to changes in the lifespan of reused and stored obsolete electronic items. As the lifespan of reused and stored phase increases, the reused, recycled, landfilled and stored quantities respectively decrease. This purportedly signifies that the decisions of the second user which encompasses the reuse and store phase have no bearing on the outflow of e-waste and is in conformity with the results obtained by Kang and Schoenung (2005).

According to the Greenpeace assessment report (Greenpeace, 2008), India in 2007 generated 0.38 million tons of e-waste from discarded computers, television and mobile phone. The report further states that this figure is projected to grow to more than double by 2012, to 0.8 million tons per annum with a growth rate of 15 per cent. A similar study made by Manufacturers' Association for Information Technology (MAIT) and German Technical Cooperation Agency (GTZ) on e-waste assessment in India (MAIT-GTZ, 2007) reported that India in the year 2007 generated about 0.33 million metric tons of e-waste and further stated that the figure will reach 0.47 million metric tons by 2011. However the assessment study focused on the waste streams of computers, televisions and mobile phones. The estimation was done using the obsolescence rate of the electronics items under investigation. The MAIT-GTZ study reports that about 40 per cent of e-waste is recycled while the rest 60 per cent remains stored. However, the MAIT-GTZ report as opposed to our study did not consider multiple lifespan approach and reportedly did not account for reuse and landfilling phase as an EOL option.

Unlike other studies, our modeling effort focused on waste from PC, television, refrigerator and washing machine. The same study further reports that in the year 2007, close to 0.6 and 2.7 million metric tons of obsolete items were generated from the waste streams of computers and television respectively (Greenpeace International, 2008). This however comes close to our projected arising of 0.98 and 2.59 million metric tons respectively from obsolete computers and television (see Table 2.11).

Table 2.11: Generation estimate of WEEE in metric ton

Year	Desktop	Notebook	Television	Refrig-erator	Washing Machines	Total obsolete WEEE
2007	98807.2368	513.6045	259200	65400	24030	447950.8413
2008	125520.4928	1252.3186	242400	72900	26568	468640.8114
2009	149344.0752	2467.4940	235200	78600	31320	496931.5692
2010	150202.9424	5284.2031	254400	84900	34425	529212.1455
2011	152469.6	8410	259200	91800	36234	548113.6
2007-2011	676344.3472	17927.6202	1250400	393600	152577	2490848.967

The variations in the projected values are attributed to the differences in the assumed lifespan of the items under investigation. For instance, considering a 5 year lifespan, the e-waste arising from desktop computer would be 0.62 million metric ton, which is very close to the value predicted by the MAIT-GTZ study. Our study confirms the MAIT-GTZ assessment results by predicting that around 30 per cent and 34 per cent of e-waste is recycled annually in Scenario-1 and Scenario-2 respectively (see Table 2.12 and Table 2.13).

Table 2.12: Sensitivity analysis of EOL outflows during the period 2007-2011 for all items in million units when the reuse and store lifespan are changed

Parameter	Scenario-1			Scenario-2		
	Recycle	Landfill	Store	Recycle	Landfill	Store
Reused and stored life span is 2 years	55.015	10.337	59.287	56.586	8.846	69.866
Reused and stored life span is 3 years	50.524	9.711	55.981	52.507	8.406	68.439
Reused and stored life span is 4 years	46.456	9.253	52.896	48.797	8.007	67.121

Table 2.13: e-waste recycled (in %) during 2007-2011

Year	2007	2008	2009	2010	2011	2007	2008	2009	2010	2011
	Scenario-1					Scenario-2				
Obsolete items generated after lifespan of electronic item (in million units)	17.67	18.56	19.92	22.04	23.70	17.67	18.56	19.92	22.04	23.70
Obsolete items generated after reuse/store phase (in million units)	11.00	12.56	13.54	15.41	16.48	8.18	9.34	10.27	11.75	12.41
Grand total obsolete generated (in million units)	28.67	31.12	33.46	37.45	40.18	25.85	27.9	30.19	33.79	36.11
Recycled Quantity (in million units)	8.49	9.24	9.89	11	11.88	8.62	9.48	10.33	11.65	12.4
Percentage Obsolete Recycled	29.61	29.69	29.55	29.37	29.56	33.34	33.97	34.21	34.47	34.33

On an average, our study reports, the amount of electronic waste in India is growing at 7 per cent every year. This confirms the finding by yet another study conducted by the Department of Scientific and Industrial Research (Tom Young, 2009) which reports this figure to be 10 per cent. It had been reported previously that predicted values of WEEE estimates by different authors report contradictory results. For instance, Streicher and Yang (2007) reports that China generates more than 4.48 million PC waste each year as against the higher figure of 10 million projected by Liu et al. (2006).

2.3.2 Discussion on the Future Estimate

2.3.2.1 Bounding analysis

According to CIA World Factbook (2008) estimates for India, the annual population growth rate has been consistently decreasing since the 1990s. Further, the study reports a country comparison listing of decreasing growth rates, showing India occupying the 87th position as against 134th position of the U.S. As per the projection by the Registrar General and Census Commissioner of India, a growth rate of 1.3%, assuming the highest level of fertility, is possible by 2011. A low population growth rate suggests that the population is growing slowly. The present study utilizes the population projection from the Census of India, 2001. The historical sales data of desktop and laptop computers for India are drawn from Table 2.4. The original data series are from the annual publications of MAIT, an association of IT manufacturers in India (see Table 2.14). On account of non-availability of statistical data on the reused computer market for India, this aspect was not considered in this analysis.

Table 2.14: Domestic sales data of electronic devices in India (in million units)

Year	Desktop PC	Notebook PC
1994	0.240300	0.004500
1995	0.371667	0.011329
1996	0.451427	0.01596
1997	0.799058	0.01000
1998	1.027190	0.02292
1999	1.405290	0.04167
2000	1.881640	0.04167
2001	1.670880	0.044742
2002	2.293643	0.050974
2003	3.035591	0.088831
2004	3.632619	0.177105
2005	4.614724	0.431834
2006	5.490591	0.850860
2007	5.522167	1.822139

The accuracy of any computer waste forecasting model is dependent upon the accuracy of the estimated life span of the computer (Leigh et al., 2007). Earlier studies (Streicher-Porte and Yang, 2007; Jain and Sareen, 2006) report using primary and secondary based data from market research and questionnaire based survey to estimate the average lifespan of PCs. According to a recent study by Toxics Link, the life of a computer in India has fallen from 7 years to 3-5 years. Instead of using a uniform life span, there are studies where multiple lifetime spans for estimation of outflows have been proposed (Kang and Schoenung, 2006; North Carolina Environmental Department, 1998). For the purpose of this study, a first lifespan distribution of computers as shown in Table 2.15 was assumed.

Table 2.15: Assumed lifespan distribution of computers

Case		**Average lifespan** (in years)	**Years in use**			
			5	**4**	**3**	**2**
Upper line	Desktop	4	25%	50%	25%	
	Notebook	3.5	20%	20%	50%	10%
Baseline	Desktop	3.5	20%	20%	50%	10%
	Notebook	3.0		25%	50%	25%
Lower line	Desktop	3.0		25%	50%	25%
	Notebook	2.5			50%	50%

In order to corroborate the assumption on lifespan, the approach outlined by Yang and Williams (2009) was utilized. According to the report by Frost and Sullivan (2007), the total number of household computer stocks was 5 million in the year 2006. The population during the period was 1112 million which gives a penetration rate of 0.0045 computers per capita from the household sector. For the business sector, it was assumed that each information worker has a computer. In the year 2006 (Ilavarasan, 2007), the total number of IT workers (which included direct, indirect employment and ITES jobs) in India were 8.08 million. This translates to a penetration rate of 0.0073 computers per capita from the business sector. Together these two sectors yield a penetration rate of 0.012 computers per capita. This empirical data is cross-checked by combining the lifespan assumptions with the historical sales data and through the use of Eq. (5) to (7) yielded a per capita computer penetration rate of 0.013, 0.015 and 0.016 for the lower line, base line and upper line, respectively. The two values are in very close agreement for the lower line. The reasons for higher values for the baseline as well as upper line could be the lack of sales data for the years prior to 1994, as the market was still in its infancy. The obsolete quantities during the period 1994-1998 cannot be determined resulting in marginal overestimation of stocks-in-hand and, hence, the penetration rate. After this consistency check, the computer penetration rate for the year 1994 to 2008 for all the three lifespan distributions are made using Eq. (12) to (14) and shown in Fig. 2.6.

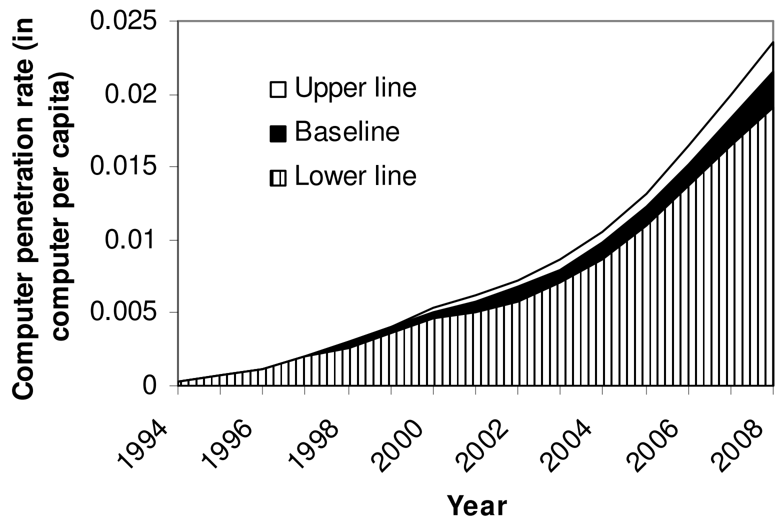

Fig. 2.6: Historical computer penetration rate

A bounding analysis on the historical computer penetration rates is the next step. Yang and Williams (2009) have reported the difference between a bounding analysis from a conventional best and worst case scenario analysis. The scenario analysis reflects the range of achievable possibilities, while a bounding approach may give results which are unlikely to achieve, but are capable of giving insight into the constrained future. For estimating the bounds, the approach outlined by Yang and Williams (2009) was used. A lower bound for carrying capacity from the commercial sector is set by assuming that all IT (Information Technology) employees possess a computer at work. The computer penetrations among wealthy families represent the lower bound carrying capacity from the household sector. As per the estimates from the study conducted by McKinsey (2007) and KPMG & IMRB (2006) for the year 2005, about 6 million of the 208 million households have an annual income exceeding 2.15 lakh Indian rupees.

The National Family Health Survey (2005) estimates the mean Indian household size to be 4.8 persons per household. This translates to 28.8 million wealthy people among the total population of 1095.722 million in the year 2005 rendering a lower bound penetration rate of 0.0263 computers per capita. So the total lower bound from the residential and commercial sector yields a carrying capacity of 0.0336 computers per capita. For the upper bound parameter estimation, it was assumed that that all employed persons own a computer at work and every person aged from 15 to 64 years have a computer at home. The total worker population in 2001 (Census of India, 2001) is estimated to be around 400 million constituting around 39.10 % of the total population. The percentage of population aged between 15 and 64 years, was 63.6 of the total population (CIA- World Factbook-India). These figures are very close to the forecast by Adlakha (1997). Combining the two results yield the upper bound estimate of carrying capacity of 1.027 computers per capita.

The computed historical computer penetration data (see Fig 2.6) from 1994-2008 are fitted to the logistic model (Eq. (9)) subject to the bounds estimated on the carrying capacity. The Nelder-Mead unconstrained non-linear minimization function of MATLAB is used for logistic function parameter estimation by minimizing the function in Eq. (8). Fig. 2.7 to Fig. 2.12, show the results of the logistic fit for the lower line, the base line and the upper line, respectively.

Table 2.16: Parameter estimation from bounding analysis

	Upper Bound*					**Lower Bound***				
	SSR	K	N_0	r	1% K	SSR	K	N_0	r	1% K
Upper line	0.0000046	0.0336	0.0011	0.208	55 yrs	0.0000082	1.027	0.000502	0.323	27 yrs
Base line	0.0000043	0.0336	0.00108	0.203	56 yrs	0.0000059	1.027	0.000562	0.3013	28 yrs
Lower line	0.00000314	0.0336	0.000965	0.202	57 yrs	0.00000355	1.027	0.000554	0.29	30 yrs

*: The base year for all calculation is 1993

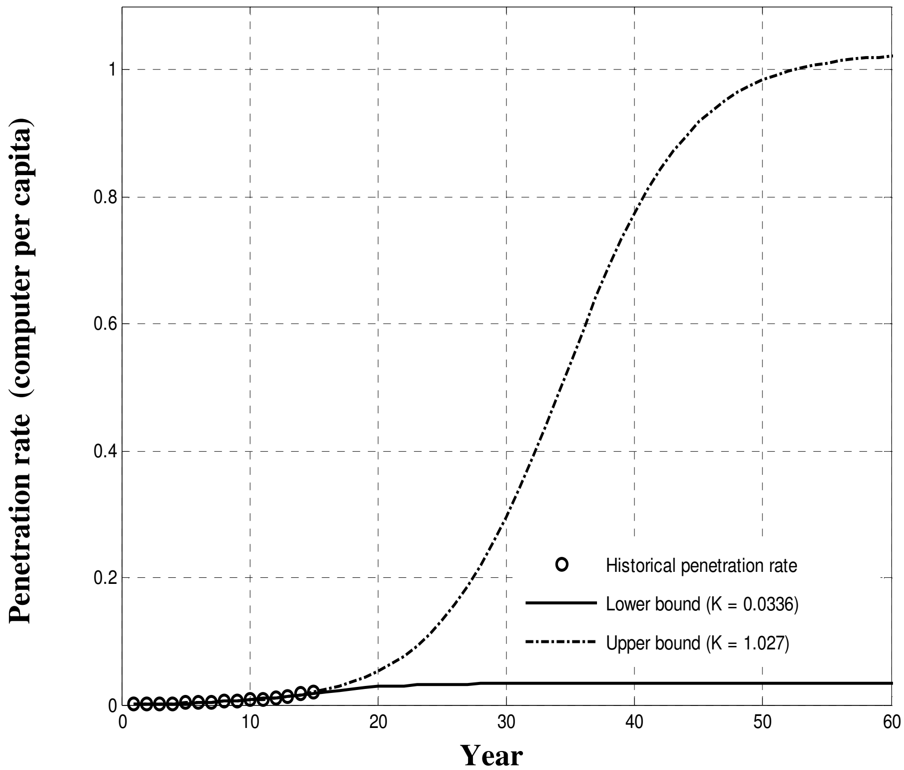

Fig. 2.7: Lower line penetration rate forecast

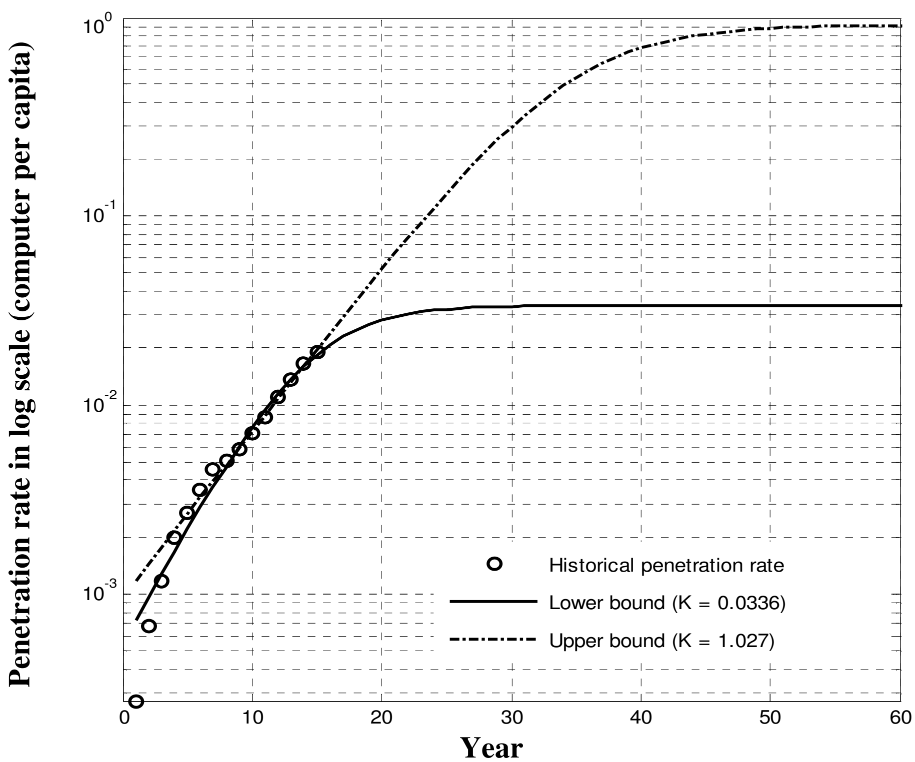

Fig. 2.8: Lower line penetration rate forecast

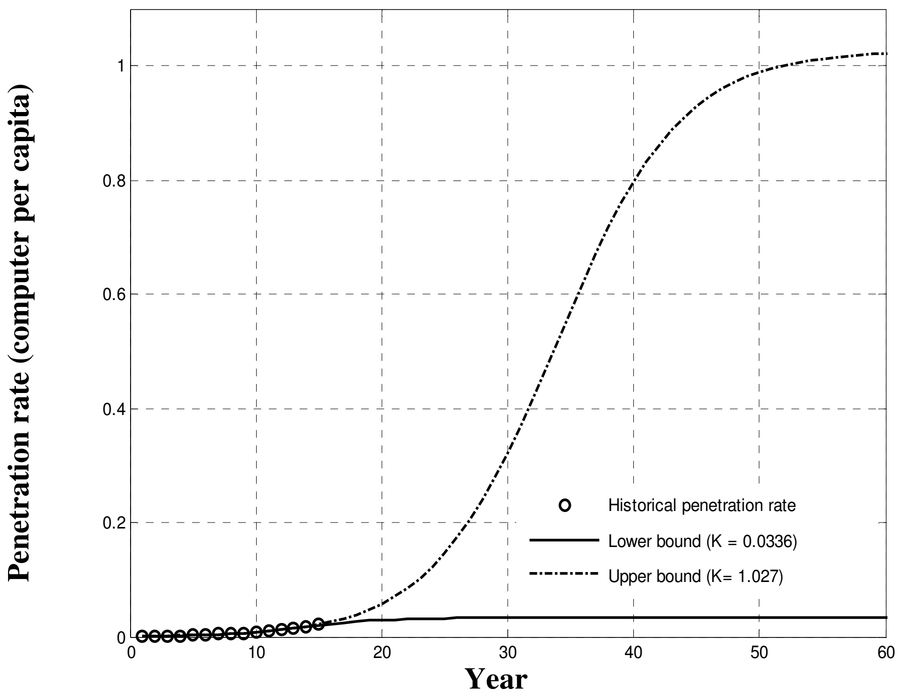

Fig. 2.9: Baseline penetration rate forecast

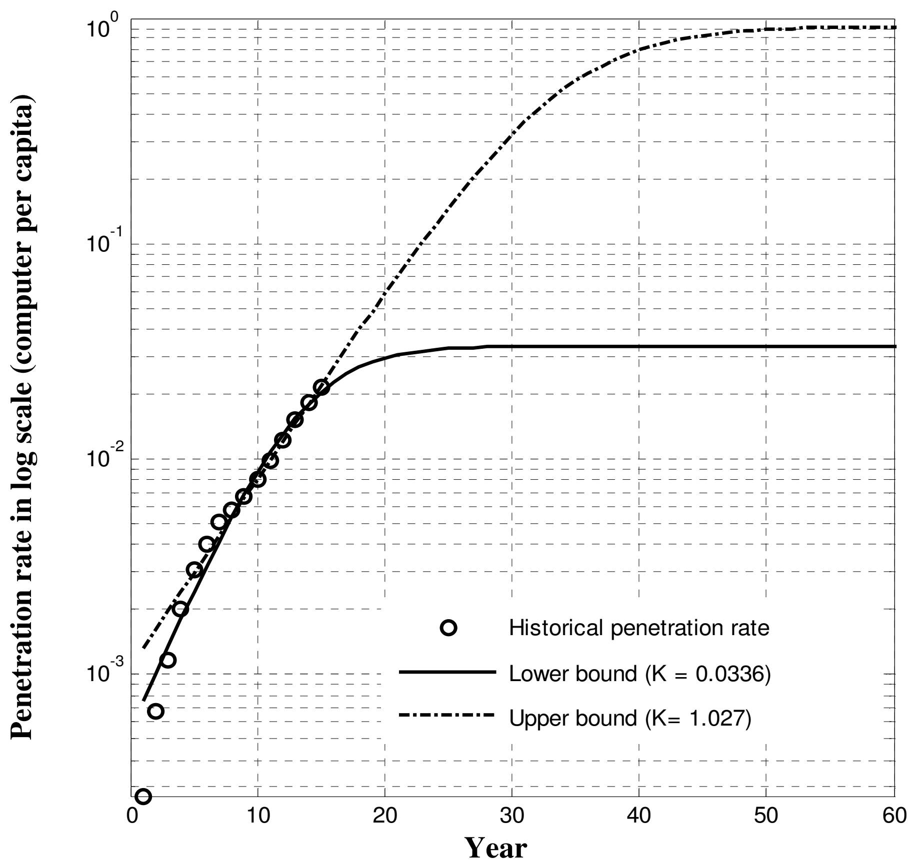

Fig. 2.10: Baseline penetration rate forecast

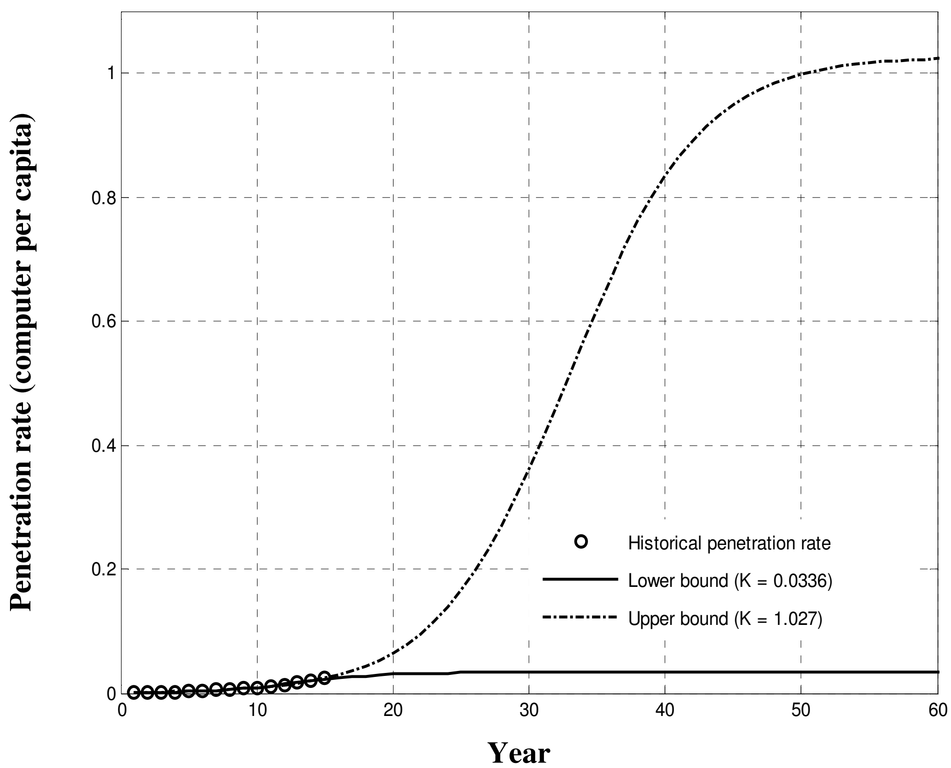

Fig. 2.11: Upper line penetration rate forecast

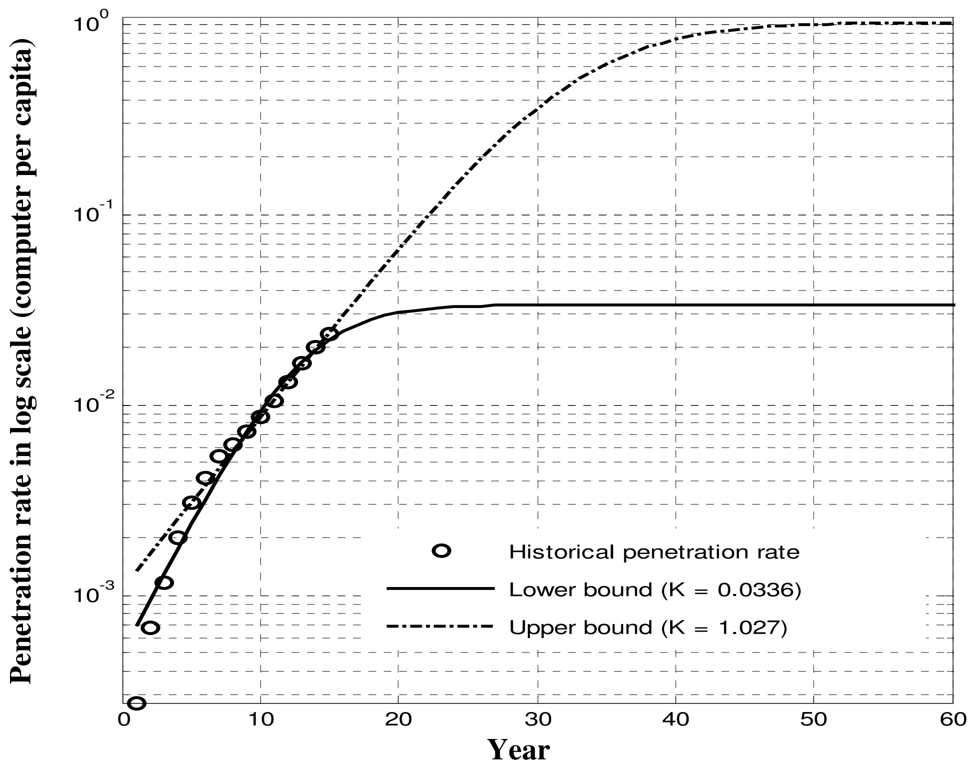

Fig. 2.12: Upper line penetration rate forecast

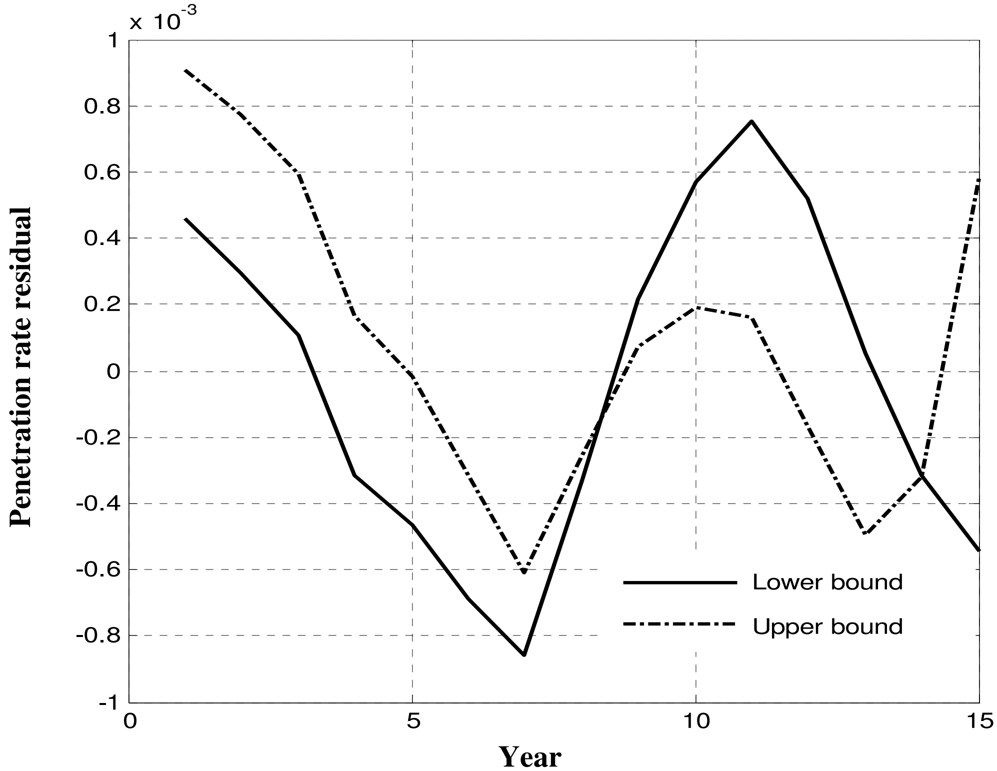

Fig. 2.13: Lower line residual plot

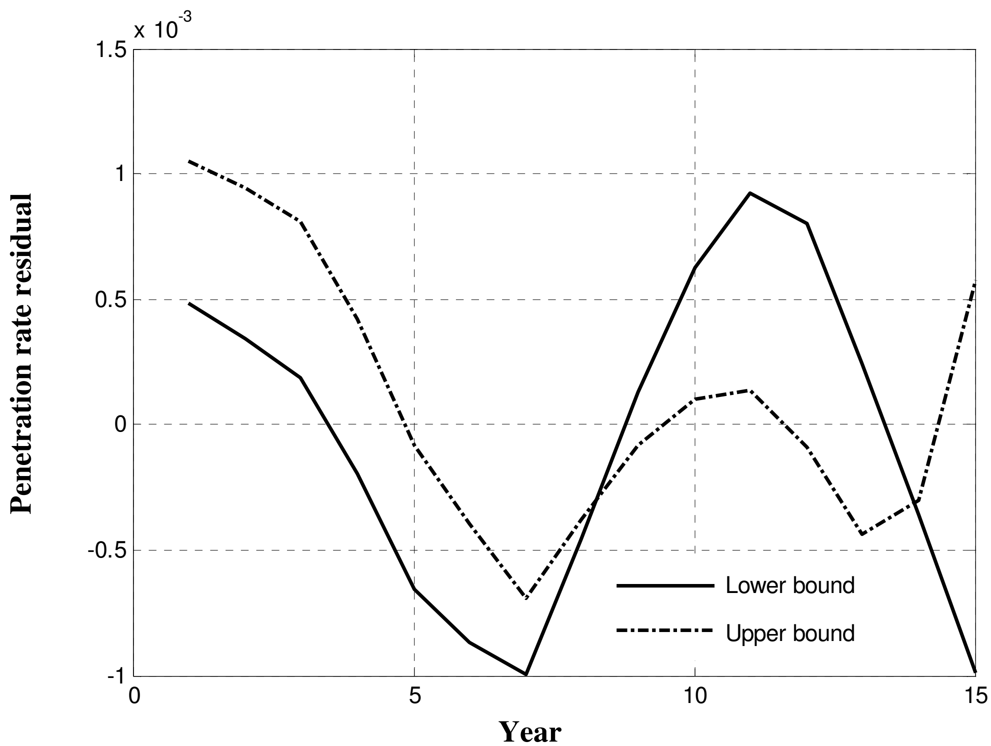

Fig. 2.14: Baseline residual plot

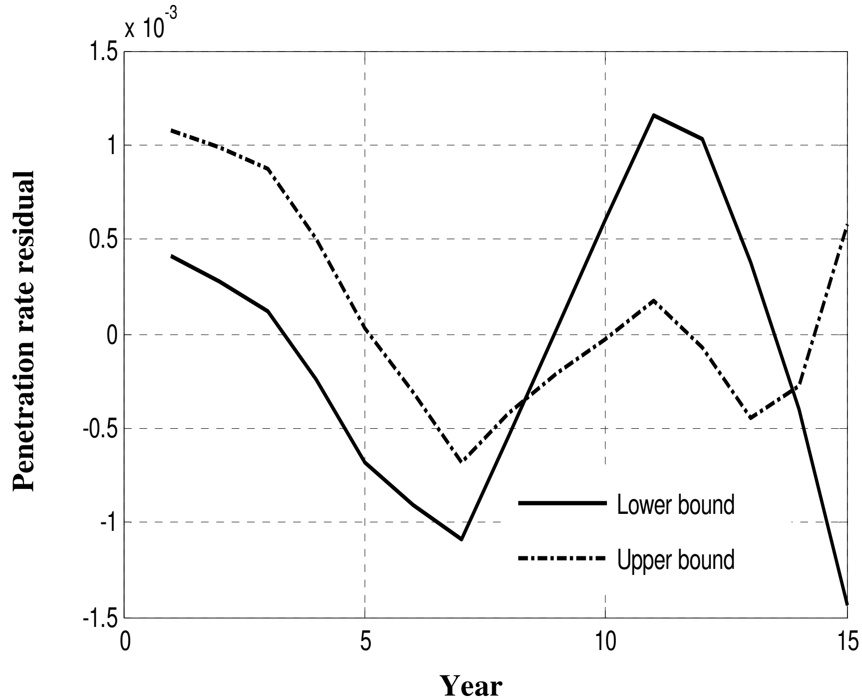

Fig. 2.15: Upper line residual plot

The results from curve fitting for all the lifespan distributions, shown in Table 2.16, prove that the lower line gives a better estimation for both the bounds on the carrying capacity. Further, the results indicate that forecasting with the upper bound gives the best fit on account of the smallest error. However, all the curve fitting errors which are obtained after optimal parameter estimation and through the use of Eq. (15) are found to be equally comparable and therefore acceptable (see Figs. 2.13 - 2.15).

For the case of lower line (see Figs. 2.7 and 2.8), the estimated computer penetration rate in the year 2010 will be 2.3 and 2.9 computers per 100 people for the lower and upper bound, respectively. Additionally, it is expected to reach within 1% of the asymptotic carrying capacity of 0.0336 and 1.027 computers per capita anytime during the year 2023 and 2050 for the lower and upper bound case, respectively (see Table 2.16).

In other words, the long-term equilibrium on carrying capacity could be achieved sometime in the next 30-57 years, 28-56 years and 27-55 years following the base year 1993 for the lower line, baseline and upper line scenarios, respectively. Our results confirm the findings of Yu et al. (2010) where they report that the Asia/Pacific region will reach the long term equilibrium in penetration rate carrying capacity in 30-60 years. The Eleventh Five Year Plan (2007-2012) report prepared by the Department of Information Technology, Government of India outlines the market projection for computers forecasted by MAIT, and cite a penetration rate of 3.25 computers per 100 people, which is very close to our prediction. The report further states that with government intervention, the penetration rate could be enhanced to 6 computers per 100 people by the year 2012. For the year 2012, our analysis predicts a value of 5.37 and 2.94 computers per 100 people for the upper and lower bound, respectively.

2.3.2.2 Estimation of future sales and obsolete stock

The forecasted computer penetration rates are converted to their corresponding sales (see Figs. 2.16 and 2.17) by using the population projection data from 2001 Census of India for the years 2009-2026. From the historical sales data, it was observed that during the period 1995-2008, the average year-on-year increase of market share of notebook PC was approximately 2.5% of the total computer sales. Along with the extended market share of notebooks and the first lifespan distribution, the projected sales data are translated to corresponding generation of obsolete desktop and notebook PCs. From Fig.2.16 and 2.17, it is observed that the combined obsolete computer generation estimates for 2010 will be around 6.74-7.89 million units which is very close to the value of 7.344 million units predicted by us. The projected obsolete computer generation estimate at the end of 2026 will be within 45-46 million units and 432-457 million units for the lower bound and upper bound, respectively.

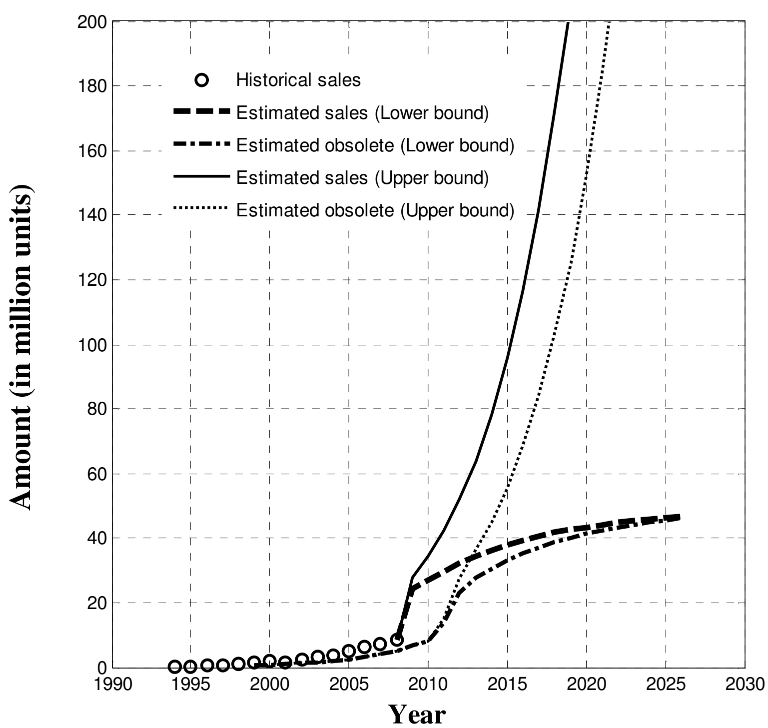

Fig. 2.16: Computer sales and obsolete amount

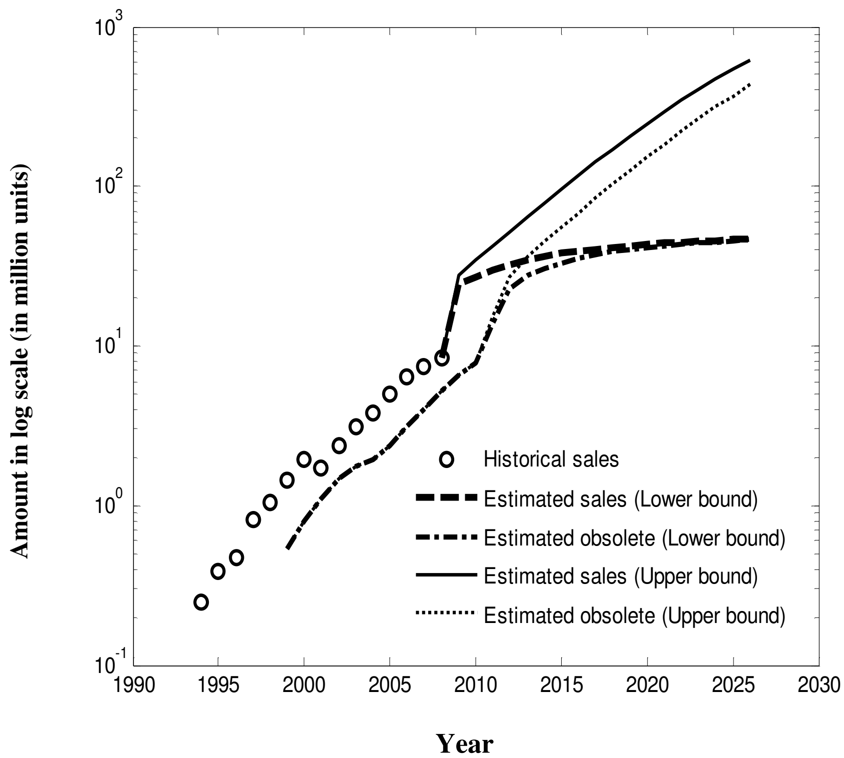

Fig. 2.17: Computer sales and obsolete amount

It is also observed from Figs. 2.16 and 2.17, that the projected computer sales quantity will equal the estimated obsolete generation quantities in and around the year 2026 for the lower bound case. By 2020, India's e-waste from obsolete computers are likely to increase rapidly by 500 per cent from the 2010 levels of around 8 million units for the lower bound lower limit case. A similar study by the UNEP (2007) predicts that e-waste from old computers to rise by 500 % from the 2007 levels by extrapolating the current linear growth in computer sales to estimate the future obsolete quantities.

2.3.2.3 EOL material flow analysis

The computed obsolete generation quantities are then utilized to estimate the EOL stock. The expanded EOL model shown in Fig. 2.1 forms the basis of our investigation. This model is simulated by making several assumptions on the EOL disposal behavior considering the fact that data inadequacy exists for a developing country like India. The investigation was extended by considering two EOL scenarios. Scenario-1 represents the optimistic assumption where about 50% of obsolete computer stocks are diverted to reuse while for the pessimistic assumption represented by Scenario 2, a considerable amount of obsolete computer stock remains in storage (about 50%). The two scenarios represent the two extreme cases of EOL consumer disposal behavior. Table 2.17 shows the assumed disposal percentages of the EOL model for the two scenarios. The extended reuse and stored lifespan are explicitly taken from Table 2.2.

Table 2.17: EOL Disposal percentages for different scenarios

EOL options	Optimistic Scenario (Scenario-1)	Pessimistic Scenario (Scenario-2)
Obsolete reused (P_1)	50	25
Obsolete stored (P_2)	25	50
Obsolete recycled (P_3)	20	20
Obsolete landfilled (P_4)	5	5
Reused stored (P_5)	70	70
Reused recycled (P_6)	20	20
Reused landfilled (P_7)	10	10
Stored recycled (P_8)	75	75
Stored landfilled (P_9)	5	5

From the aforesaid assumptions and by using Eqs. (1) - (7), the EOL model gives the quantities which are recycled, reused, stored and landfilled. The results of the EOL model indicate that during the period 2010-2020, the projected lower bound potential recycling quantity for both Scenario 1 and 2 shall exceed 150 million units. This figure is likely to touch 300 million units for the upper bound case (see Fig. 2.18).

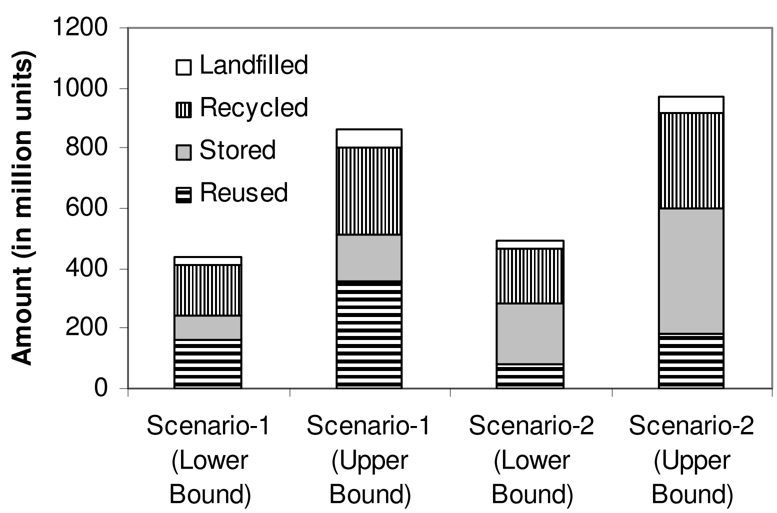

Fig. 2.18: EOL estimates during 2010-2020

The expected minimum number of reused computers for the same period will be likely to reach upwards of 80 and 160 million units in Scenario 1 and 2, respectively. The total obsolete computers during this time are expected to reach a staggering 329-720 million units. The EOL estimates for every five year period in Scenario-1 and Scenario-2 are shown in Figs. 2.19 - 2.22, respectively.

Estimates shown in Table 2.18 illustrate that the average annual recycling capacity of India are close to 35% of the total obsolete PC arising assuming a constant proportion of disposal and/or recycling options. The recent findings by the MAIT-GTZ (2007) study reporting on the e-waste inventory from computers, television and mobile phones in India, predict that of the total e-waste arising, only about 40 per cent finds its way into the recycling stream of which 95% are recycled in the informal sector.

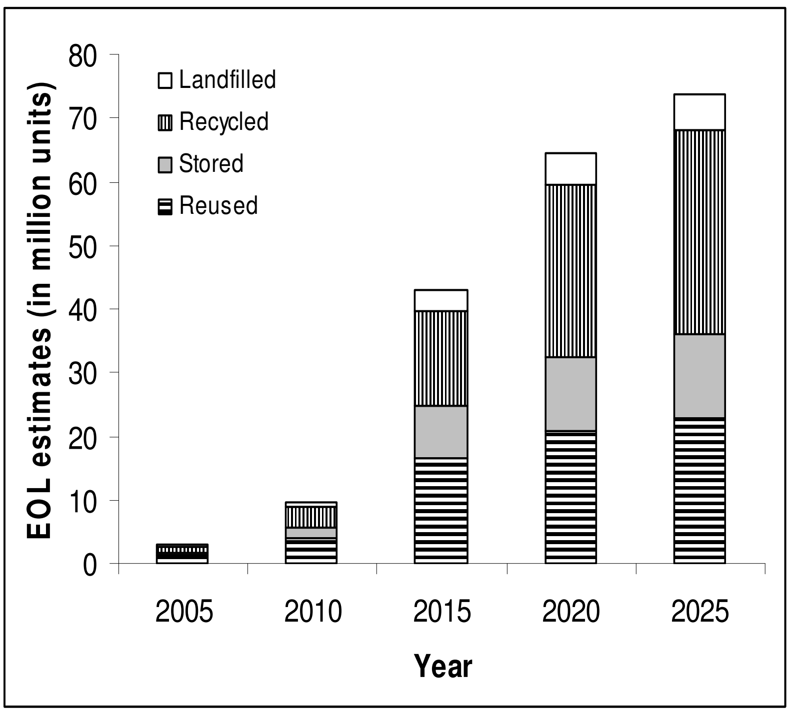

Fig. 2.19: Scenario-1 estimates (Lower Bound Lower Limit)

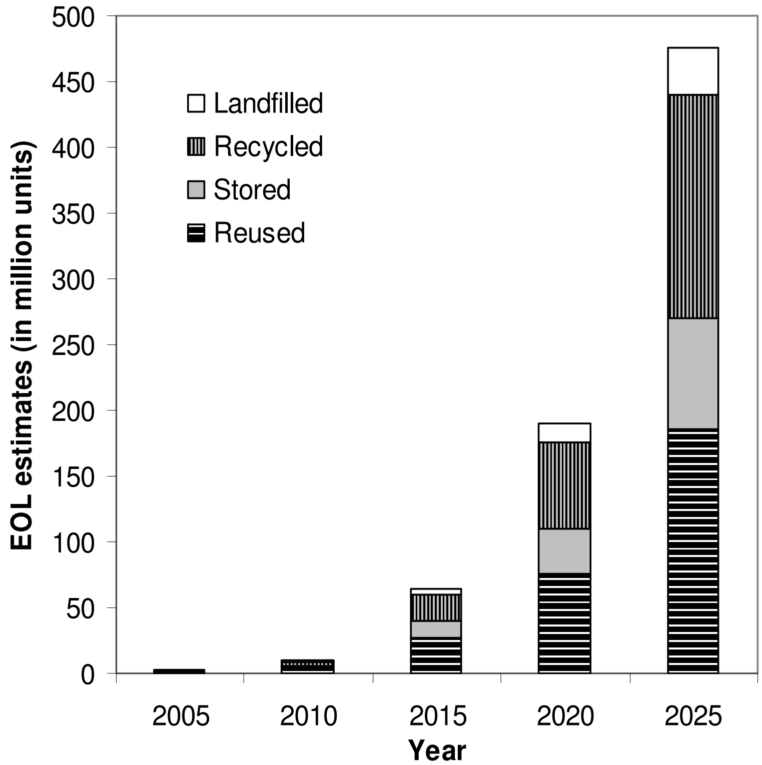

Fig. 2.20: Scenario-1 estimates (Upper Bound Lower Limit)

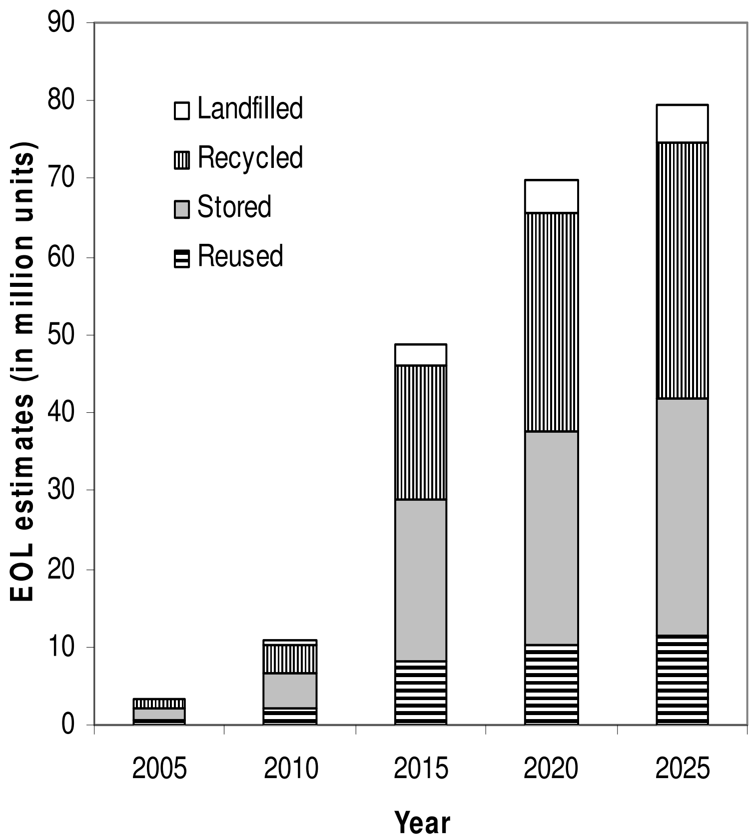

Fig. 2.21: Scenario-2 estimates (Lower Bound Lower Limit)

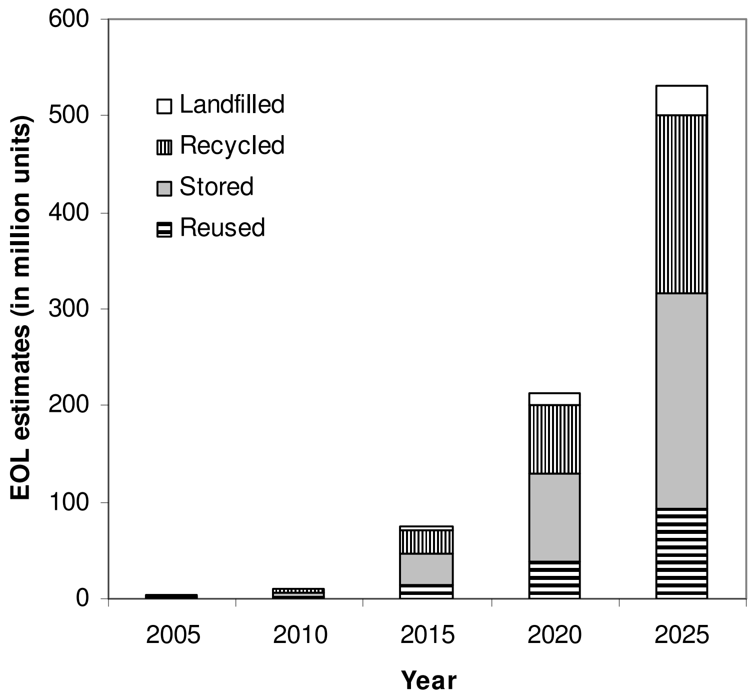

Fig. 2.22: Scenario-2 estimates (Upper Bound Lower Limit)

Table 2.18: Percentage obsolete e-waste recycled in million units during 2010-2025

Year	**2010**	**2015**	**2020**	**2025**	**2010**	**2015**	**2020**	**2025**
	Scenario-1				**Scenario-2**			
Obsolete items generated after lifespan of electronic item	7.89	33.08	41.40	45.54	7.89	55.62	152.21	370.21
Obsolete items generated after reuse/store phase (Lower Bound/Upper Bound)	2.76	19.50	38.57	46.59	3.36	18.34	33.21	39.56
	3.69	22.73	78.77	209.88	3.36	21.57	70.87	187.95
Grand total obsolete generated (Lower Bound/Upper Bound)	10.66	52.58	79.98	92.14	11.25	51.42	74.62	85.10
	11.59	78.36	230.9	580.1	11.25	77.20	223.08	558.17
Recycled Quantity (Lower Bound/Upper Bound)	3.25	14.94	27.0	32.12	3.54	17.22	28.08	32.81
	3.24	20.69	66.42	170.58	3.54	23.56	72.05	184.57
Percentage Obsolete Recycled (Lower Bound/Upper Bound)	30.42	28.41	33.75	34.86	31.49	33.49	37.63	38.56
	27.98	26.40	28.75	29.40	31.49	30.52	32.29	33.06

Note: Figures do not sum up due to truncation after two decimal places

On account of no reliable statistical data or projection on the changing consumer disposal behavior with time, the study relied on average estimates. The dynamic nature of disposal options could be captured through periodic annual surveys over a period of time from which future disposal percentages could be forecasted. Random sample populations from rural and urban India covering all income groups are to be collected to estimate their behavior. Alternatively, RFID (Radio Frequency Identification Devices) tags could be assigned to new shipments which can track the PCs over its entire lifecycle. A dedicated nodal agency supported by either the government or the manufacturing associations like MAIT and other environmental NGOs could be entrusted with this activity. To utilize the forecasted disposal options, the present EOL model needs to be adjusted accordingly. This leaves some scope for future research. In India, e-waste is considered to be an important resource and an emerging business opportunity. In the last 4 years, several recycling facilities have come up in the organized sector to address this problem. Though these recycling facilities are in varying levels of infancy, it is expected that in the near future, consumer attitude towards recycling will be favorable resulting in increased e-waste collection for recycling.

Alternatively, this could be construed as any increase in the number of obsolete computers disposed for recycling will result in few computers being stored. This may be pursued by tracking the historical recycling volumes over time and curve fitting the past data to forecast the future. Additionally, one can use the system dynamics tool to capture this behavior using appropriate growth models for simulating increasing recycling volumes and decay models for simulating the storage option. However, extensive historical data collections are necessary to freeze any of these methods. A conservative approach could be identifying the long-term equilibrium year when 95% of obsolete PCs could be available for recycling from the current levels of 40% predicted by the MAIT-GTZ study. Given that the long term carrying capacity of 1.027 computers per capita could be achieved anytime during the year 2050 (see Table 2.16), in the next forty years from now, India could scale-up its investment in setting-up appropriate collection and recycling mechanism for managing its annual e-waste arising to the level of 95% from its current level of 40% (see Fig. 2.23).

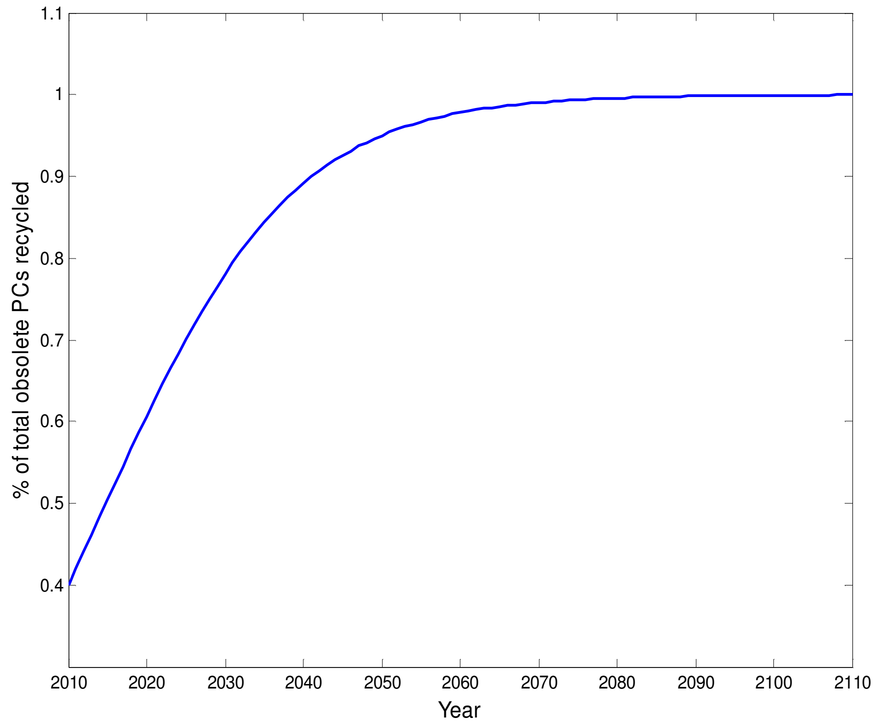

Fig. 2.23: Future proportion of PCs available for recycling

Table 2.19: Recycling capacity with variable obsolete recycling percentages during 2010-2025

Year	**2010**	**2015**	**2020**	**2025**	**2010**	**2015**	**2020**	**2025**
	Scenario-1				**Scenario-2**			
Total obsolete generated (Lower Bound/Upper Bound)	10.66	52.58	79.98	92.14	11.25	51.42	74.62	85.10
	11.59	78.36	230.9	580.1	11.25	77.20	223.08	558.17
Percentage of total obsolete that could be recycled in future	40.0%	50.33%	60.63%	70.07%	40.0%	50.33%	60.63%	70.07%
Annual recycling capacity in million units (Lower Bound/Upper Bound)	4.26	26.46	48.49	64.56	4.50	25.88	45.24	59.63
	4.63	39.44	140.0	406.49	4.50	38.85	135.26	391.12

Note: Figures are truncated after two decimal places

The future annual recycling capacity assuming a logistic growth is shown in *Table* 2.19. By the year 2025, India would need a recycling capacity of around 60 and 400 million computers for the lower and upper bound case, respectively, necessitating investment in infrastructure to accommodate a recycling capacity of 70%. This is fairly attainable given the fact that the current existing national systems in Europe have an e-waste recycling capacity of 60% (Yu et al., 2010). Looking at the estimates from Tables 2.18 and 2.19, the number of units available for recycling considering a variable recycling rate is close to twice those predicted from average assumptions on the recycling rate as year 2025 approaches.

2.3.2.4 Geographical divide: a case of US vis-à-vis India

The historical computer penetration rates of US from 1978-2008 recreated from the approach outlined earlier was fitted to the logistic model subject to lower and upper bound of 1.0 and 1.3 computers per capita as outlined earlier in the work by Yang and Williams (2009). All unknown model parameters from the curve fit ($r_{lower\ bound}$: 0.1784449581, $N_{0(lower\ bound)}$: 0.0189767840, $r_{upper\ bound}$: 0.1466145442, $N_{0(upper\ bound)}$: 0.0289774991, $SSR_{lower\ bound}$: 2.025772185680502e-002, $SSR_{upper\ bound}$: 8.774260786537274e-003) confirm the findings of the original authors. Yang and Williams (2009) report that the PC penetration rates in US is expected to reach its long term equilibrium not until the year 2023 and 2033 for the lower and upper bound cases, respectively. Our analysis pegs the expected year for reaching equilibrium (99% of the assumed bounds) at 2024 and 2034 respectively, the variation though insignificant could be attributed to round-off to the nearest decimal place pursued by the original authors.

It is evident from Figs. 2.24 and 2.25 that though India starts from a low base of PC penetration rate (0.733 and 1.18 computer per 1000 people, respectively, for lower and upper bound) in the year 1994 as against the US figure of 22.6 and 33.4 computers per 1000 people in the year 1978, India in the upper bound scenario could well in all possibility overtake the lower bound per capita PC penetration rate (1 computer per capita) of the US sometime by the year 2046.

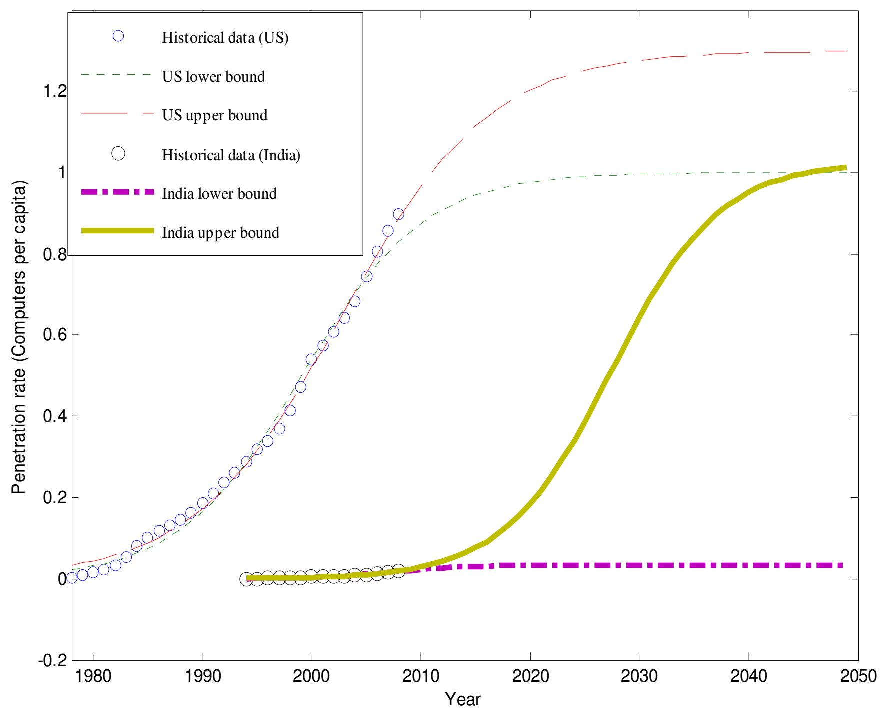

Fig. 2.24: Comparative growth in PC penetration rate projections

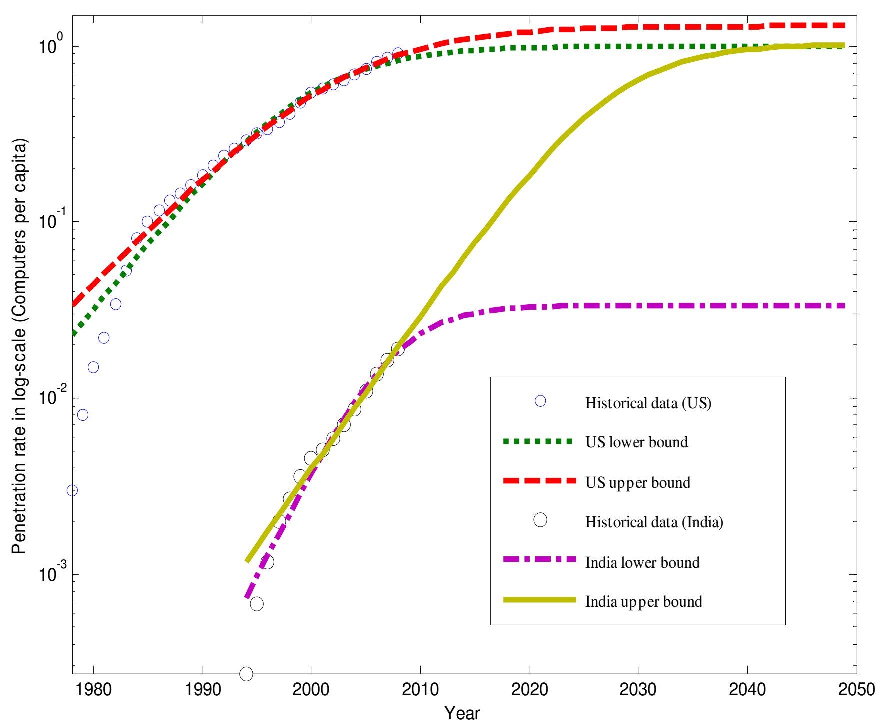

Fig. 2.25: Comparative growth in PC penetration rate projections

The estimated number of obsolete computer inventory in India for the upper bound lower limit scenario (around 221 million units) will be double that of the US by the year 2022 while the cross-over taking place sometime between the year 2017-2018. A similar study by Yu et al. (2010) report that the generation of obsolete PCs in the developing regions (within 400-700 million units) will double that of the developed regions (within 200-300 million units) by the year 2030, with the cross-over expected to occur between 2016 and 2018.

They further report that the generation of obsolete PCs after the crossover will rise dramatically in the developing regions. For instance our study predicts, in the next 4 years until 2022 after the crossover, the obsolete PC generation in India is likely to increase rapidly by more than 100% from the projected figure of 102 million units of 2018 for the upper bound lower limit case. At the end of 2026, obsolete computer volumes in India for the upper bound case will reach in excess of 430 million units which are significantly higher than double the corresponding upper bound estimate of Yang and Williams (2009) for the US.

2.4 Conclusions

The results of the study indicate that the major factor that influence the WEEE estimate are the inflow amount which in this case is the sales data and the decisions of the first user. The accuracy of the summarized results is dependent on how accurate are the available data as well as on how representative are the assumptions on the average life span of electronic items. The WEEE generated in the coming years would be even greater in view of increasing penetration rate and the obsolescence rate of such appliances, added to the huge import of junk electronics from the developed nations. Estimates from the future projection clearly outlines that the obsolete amount will continue to increase rapidly up to and beyond the year 2026 on account of better socio-economic conditions in both rural and urban India. In all likelihood, e-waste from obsolete computers could follow the lower bound lower line trend of our forecast, in which case, a penetration rate close to 0.0336 computers per capita could be achieved not until 2023. However, with favorable government policies directed to achieve the upper bound case, it might take another 40 years time from now to achieve the magical figure of 1 computer per capita. This growth has significant economic and social impact. The estimates predicted in this study can be used to develop strategies at the national level to develop ways and means for formal recovery and recycling of electronic waste thereby diverting them from landfills. Given the large population trend in India and its growing economy, e-waste arising emanating from PCs will continue to rise abnormally. The management of e-waste is a growing concern cutting across all boundaries. Therefore, effective take back policies, collection and recovery/recycling programs needs to be charted out through appropriate national legal and regulatory instruments. Adequate EPR regimes need to be conceptualized and explored to resolve the problems emanating from such waste in India.

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Chapter 3

An Investigation into e-waste Flows in India: Mapping the Current State to the Future State

3.1 Introduction

It is evident from our study that in India, e-waste is becoming an important waste stream in terms of both quantity and toxicity, as typical of any developing economy in transit. The Indian electronics industry has emerged as a fast growing sector in terms of production, internal consumption and export (Dimitrakakis et al., 2006). According to our assessment, the total WEEE estimates during 2007-11 will be around 2.49 million MT. During the same period, the number of obsolete PC's (both desktop and notebook) and color television was estimated at 31 million units and account for approximately 30 percent of the total units of WEEE during the same period. In the span of 5 years until 2011, the projected total obsolete electronic items will be expected to reach upwards of 100 million units. Roughly, around 1.95 million MT of e-waste are estimated to be generated from PC and television accounting for 78 per cent of the total e-waste weight. The study reports the current annual growth rate of e-waste in India to be within 7 to 10 per cent.

According to Electronic Industries Association of India (ELCINA), the service/commercial sector accounts for 80 per cent of the total market penetration rate of computer and IT hardware in India. The major e-waste inventory that will drive the development of e-waste management system in India will be personal computers (Jain, 2010a). For instance, our study reports that India could overtake the PC penetration of the U.S. (1 computer per capita) sometime by the year 2046. The authors estimated that the number of obsolete computer inventory in India will double that of the US by the year 2022 while the cross-over taking place sometime between the year 2017-2018. This notwithstanding, the generation of obsolete PCs in India, after the crossover will dramatically rise. The economic performance of an e-waste recovery system depends significantly on the return product mix (Boma et al., 2010). Though laptops have a higher concentration of valuable commodities, it is their low mass limit that renders them unfavorable for recovery in comparison to desktop PCs. The existing system of e-waste processing in India is mostly handled by a very well-networked informal sector (Sinha and Mahesh, 2007) involving key players like the vendors, scrap dealers, dismantlers and the recyclers. However, the disposal and recycling of computer specific e-waste in the informal sector are very rudimentary as far as the recycling techniques employed and safe recycling practices are concerned resulting in low recovery of materials. There is a huge potential for organized recycling industry in India given the fact that about 95 per cent of e-waste is processed by the informal sector (MAIT-GTZ, 2007). Presently, around 23 recycling facilities in varying levels of infancy have come up in the organized or the formal sector to address this problem, which when fully operational could recycle 60 per cent of the estimated annual e-waste inventory (Jain, 2010b). The other major source of e-waste in India apart from the household and the business sector are the illegal imports from developed countries where it is expensive to recycle the discarded electronics.

Despite India being a signatory of the Basel Convention for Transboundary Movement of Hazardous Substances, there has been a spurt in such imports in the absence of proper import regulations. This notwithstanding, the presence of cheap labor has contributed to a flourishing trade where the products are repaired and reused to extend their useful life. The major driver for the planning, design and implementation of sustainable e-waste management system in India will be personal computers (Jain, 2010a). The compounded annual growth rate of PC sales in India during 2004-2010 is expected to reach 16 per cent (MAIT, 2010). It is the business sector in India which alone accounts for about 80 per cent of overall annual PC sales (MAIT-GTZ, 2007). Regulation of disposal practices in the business sector will significantly help in tackling the e-waste problem in India. Though there have been several studies documenting the major stakeholders in the e-waste trade value chain including the assessment of environmental, social and health impacts from their disposal, there are no empirical research investigating the repercussion of the disposal behavioral patterns of the concerned stakeholders in the e-waste trade chain that exist in India. Therefore an attempt is made here to simulate alternate e-waste disposal policy scenarios from the business sector in India and their long term ramifications towards reuse and lifetime extension of e-products. The tracer item for our assessment are personal computers.

3.1.1 Reuse/lifetime extension of WEEE

Fiksel (2006) points out that industrial ecology lays the foundation for rethinking current product and process technologies and discovering innovative pathways for recovery and reuse of waste streams in place of virgin resources. Extension of this concept in the context of WEEE, are primarily focused on minimizing environmental harm through lifetime extension and reuse. Though reuse is at the top of the hierarchy (see $Fig.$ 3.1) for any waste management policy, the business sectors have focused more towards the recycling compatibility of products.

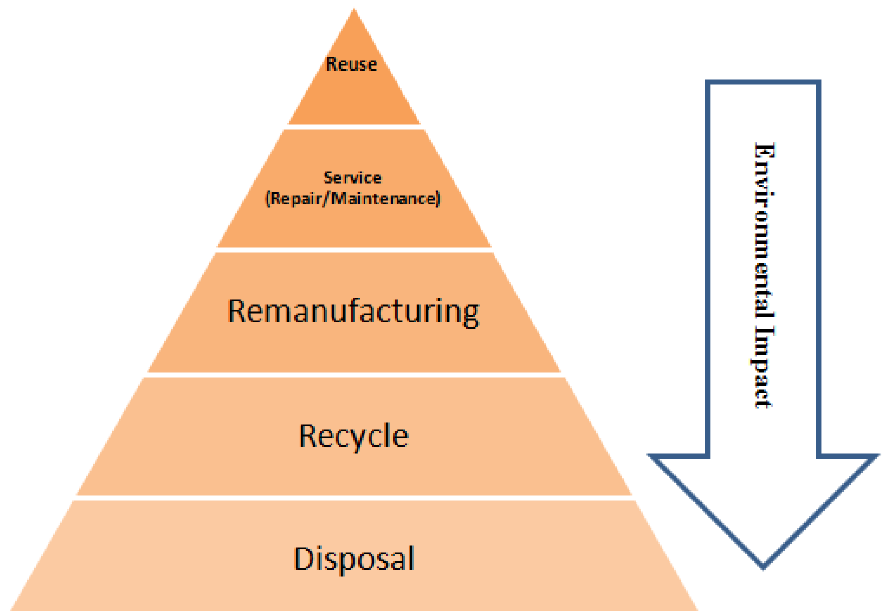

Fig. 3.1: WEEE management impact hierarchy

A closed loop material reuse cycle typically involves repairing, reconditioning and remanufacturing. According to King et al., (2006), repairing involves correction of specified fault in a product, while remanufacturing is a systematic process where returned products are brought back at least to original equipment manufacturer (OEM) performance specification. From the customer's perspective, remanufacturing entails giving warranties that are equivalent to those of new products. In between these two extremities, is reconditioning which involves less work content than remanufacturing, but more than repairing. Comparisons of the three reuse chains vis-à-vis their different performance measures are shown in Fig. 3.2.

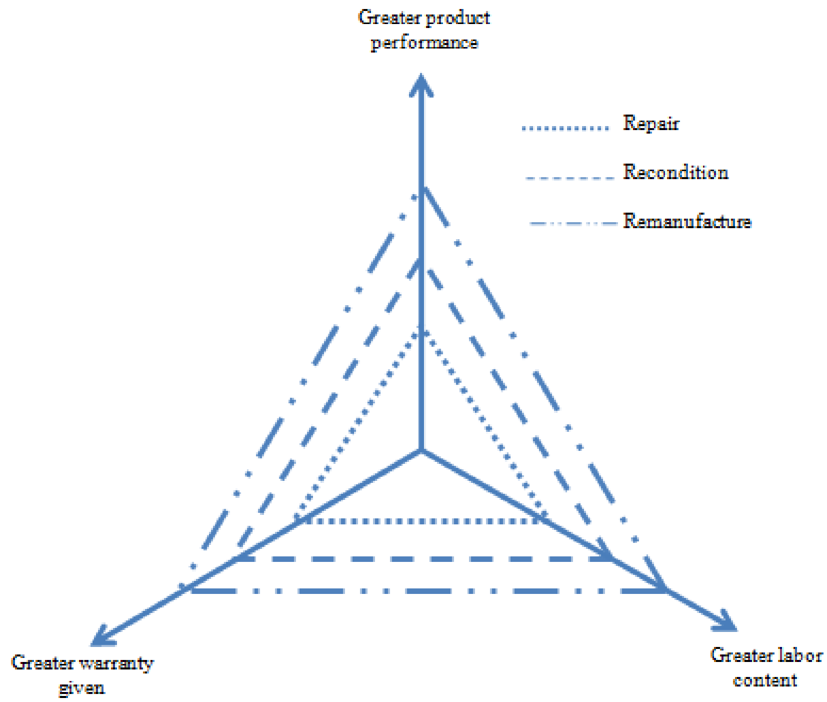

Fig. 3.2: Performance measures of reuse/refurbish chain (King et al., 2006)

Subramoniam et al., (2010) argue that at the strategic level, companies have till recently focused more on innovative product design approaches giving much less thinking towards reuse/remanufacture. Tasaki et al., (2006) report the only study quantifying the level of WEEE reuse in society. The authors' show that the levels of virgin material consumption in society could be significantly reduced to two-third when the demand for new products is readily met by the second hand market. Williams et al., (2008) report that the total energy required in the manufacture of a desktop computer could be as high as 4 times greater than the electricity consumed by the computer while in use. Griese et al (2004) argue that from the environmental perspective, reuse and recycling have quite different environmental impact. Therefore, extension of lifespan by making reuse as a national strategy can go a long way in mitigating the lifecycle impacts of WEEE. This requires making appropriate interventions in the existing practices followed in developing economies. Reuse of computers being a part of the reverse supply chain, mitigation of lifecycle impacts could partly be explored by studying the current WEEE reverse supply chain network that exist in India.

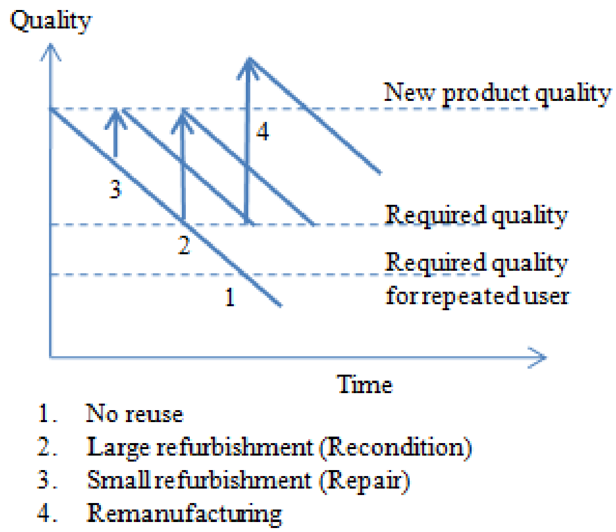

Fig. 3.3: WEEE refurbish categories (Kimura et al., 1998)

Product reuse through refurbishing includes process not limited to inspection, cleaning, storage and testing but also may include disassembly, reprocessing and reassembly (Matsumoto, 2010; Subramoniam et al., 2009; Pagell et al., 2007). Reuse through refurbishing can again be classified according the intended quality level required as can be seen in *Fig.* 3.3. Matsumoto (2010) argue that the success of reuse business depends largely on consumer preferences for reuse products. The increased consumer exposure to WEEE reuse business in India is the result of widening economic disparity resulting in digital divide, penetration of IT in the rural educational sector, affordability and rising demand for reusable e-products.

3.1.2 Reuse/recycling system

The aspect which is often neglected while designing a reverse supply chain is the economics of reuse/recycling system. No wonder that such systems could be a significant employment generator in developing economies. Delhi alone employs 25,000 workers in informal scrap yards handling about 10,000 to 20,000 tons of e-waste annually (MAIT-GTZ, 2007). While the European models have a well-developed system of visible and invisible fees for the recycling of WEEE, in India the consumers in contrast are paid an amount of money for their resource. Recently, on account of societal pressures and anticipated government legislation towards safe disposition of WEEE, formal recycling practices are increasingly being advocated. Additionally, the presence of limited landfill space combined with an increased cost of disposal in landfill has renewed focus on recycling by all original equipment manufacturers. However, it is only economics of scale which can justify the commitment towards reuse/recycling. Williams et al., (2008) report that informal reuse/recycling practiced in developing countries are economically driven because it runs on a net profit basis as opposed to the net cost for recycling in the U.S. Electronic scrap typically comprises metals, plastics and refractory oxides (Sodhi and Reimer, 2001) approximately in the ratio 40:30:30. The precious metals reclaimed from electronic recyclables make recycling a potential profit making business. The recovery of precious metals is the major driver of all the e-waste recycling activities in India. While bulk recycling in developed nations have reached a certain level of automation to fulfill and sustain mandatory recycling targets, manual disassembly and segregation remains the preferred method for developing nations like India. It can be argued here that pure recycling towards precious metal reclamation though seems economically feasible, alternative approaches like reuse/recycling systems should also be explored. Truttmann and Rechberger (2006) clearly document the fact that resource consumption is more sensitive to changes in recycling efficiency compared to changes in product life. From $Fig. 3.4$, it is clearly evident that a 25% reduction in resource consumption can be achieved either through extending the product life by 34% or from increase in recycling efficiency by 5%.

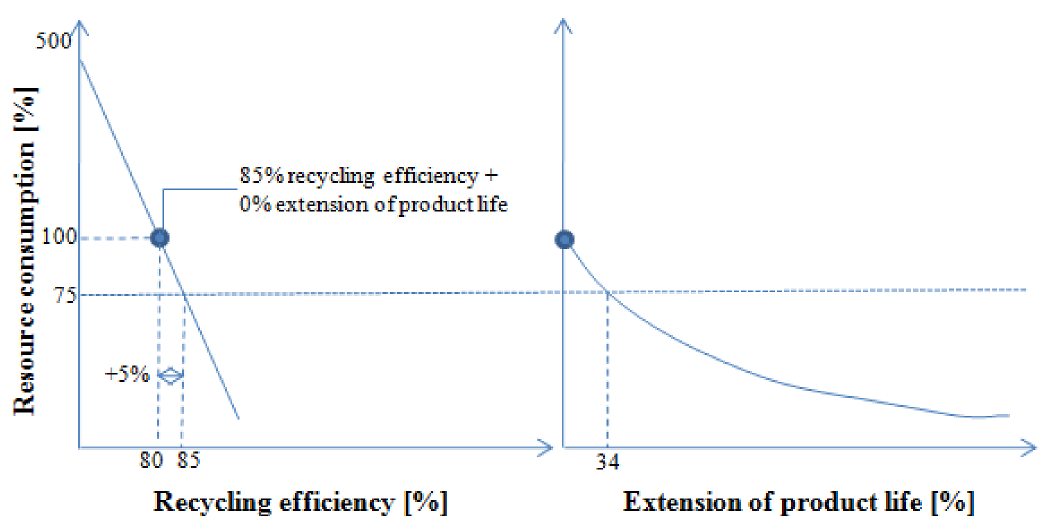

Fig. 3.4: Strategy to reducing resource consumption (Truttman and Rechberger. 2006)

However, Williams et al., (2008) report that increase in reuse significantly lowers the net environmental impacts but are poorly understood. Product take back in recycling/reuse system where the reverse supply chain partners make concerted efforts to prioritize reuse over recycling by diverting a proportion collected back to the consumers needs to be properly investigated before such systems could be put into place. Kronenberg (2007) argues that “reasonable” consumption is necessary for long-term survival of ecosystem where economic reasoning should complement environmentally “reasonable” behavior. Tasaki et al., (2006) emphasize that the so-called rebound effects where while environmental efficiency inevitably increases from recycling, the absolute level of total consumption increases even faster. Williams et al., (2008) believe that WEEE recycling by definition mobilizes material and depending on the level of process control can emit lead, mercury and other hazardous substances. They further argue that just because formal recycling lowers the lifecycle emission of heavy metals, does not mandate it as the default environmentally preferable alternative.

While an attempt was made to emphasize the benefits of domestic reuse/recycling in developing countries, there is an increasing body of literature contending the efficacy of international trade-in quality of used equipments to poor countries, something which Williams et al. (2008) espouse citing mitigation of digital divide, low recycling cost and employment generation as positives from such flows in these countries. The authors state that even if heavy metals and brominated flame retardants are removed from future e-products, there would still be considerable generation of toxins from the informal recycling process. As Carter (2003) contends that ecological modernization through clean technologies takes place in the developed countries while outsourcing polluting activities to the poor countries where both regulation and implementation are non-existent. Presumably, what has not been factored in this international trade concept is the exponential spurt in domestic WEEE generation, the increasing numbers of formal recycling entrepreneurs and the growing awareness of the environmental impact of such products in India.

Although system level mappings of reuse business have been studied in detail (Matsumoto, 2009; 2010), this concept was extended by analyzing the operational framework of e-waste trade chain for the case of India in the context of reuse and lifetime extension. Several scenarios are studied for investigating the possibility of reuse business by focusing on how the transitions take place in the e-waste trade chain. The micro level interventions within the system boundary are modeled and evaluated.

3.2 Methodology

The e-waste trade flow in the business sector is modeled as a Markov chain. Such a model involves a sequence of stochastic events completely characterized by a set of states and the transition probabilities associated with various state changes. While a simple univariate analysis is feasible for examining current or past relationship, a Markov chain model is more effective since it provides likelihood estimations for future outcomes. Also, it offers the advantage of statistically examining multiple transitions simultaneously. The major stakeholders involved in the WEEE flow are the primary consumers depicting the business sector, the consumers from the household sector, collectors, the second hand market vendors, dealers and the recycler. The scope of this study is limited to the primary consumers i.e., the business sector which accounts for about 80 per cent of the e-waste generated in India. Furthermore, the study was restricted to only PCs given the fact that this tracer analysis will have a greater impact on any future e-waste management models. The primary input to the WEEE flow model is the data representing the disposal behavior of the consumer in question. The only available study is the survey conducted by MAIT-GTZ (2007) for the state boundary of Delhi. The survey instruments used in the study were in-depth interviews with the major stakeholders supported by secondary information. A total of 203 respondents which included 98, 59 and 46 respondents respectively from small, medium and large business organizations, participated in the stated survey. The study also reports unstructured interviews with the unorganized key channel members like collectors and recyclers in and around Delhi. Additionally, formal recyclers from Bangalore, Chennai and Mumbai were reportedly interviewed.

The survey summarizes that at the corporate/business level, 11 per cent of the replaced computers are sold to scrap collector, 21 per cent of the replaced computers enter the second hand market, 48 per cent are returned to dealers through exchange and buy back scheme, 7 per cent are donated and 11 per cent are sold to employees while the rest 2 per cent are recycled. Apparently, 70 percent of the collected e-waste are refurbished and sold at the second hand market while the rest 30 per cent are sold to recyclers. At the dealer end, 50 per cent of the computers replaced through buy back and exchange schemes, end up in the formal sector at the retail outlet, the rest being refurbished (Jain, 2010a). The survey is silent on what transpires to the 11 per cent e-waste disposed to the collector. Much of the trade in this channel is clandestine and illegal. Therefore, an attempt is made here to model the uncertainty in the disposal behavior of the collectors through a scenario analysis, the objective of which is to capture the range of achievable possibilities. Scenario-1 was defined as the case of scrap collectors refurbishing the major chunk of returned products (70%) with few being sold directly at the second market (5%). Likewise, scenario-2 addresses the case of the majority returned products sold at the second hand market (70%) by the scrap collector and a small proportion getting refurbished (5%). In either of the cases, 20 per cent of returned products are recycled.

3.2.1 Basic Markov chain model

A Markov chain is a stochastic process which is completely specified by the state definition or the set of states ($s_i \forall i$); the transition probabilities ($p_{ij} \forall i, j$) which represents the probability associated with going from state i to state j; and the set of unconditional probabilities for the initial states. This knowledge assists us to determine the probability of being in any particular state at any future point in time. With this information, the state transition network diagram of a Markov chain could be constructed using a set of arcs passing from state i to state j given the associated transition probability are positive (i.e., $p_{ij} > 0$). Following are the assumptions made for constructing the WEEE Markov chain network (see Fig. 3.5):

i. The system describes the process of disposing computer specific e-waste from the business or corporate sector. The business sector is the primary consumer.
ii. The Markov chain state space includes the consumer, scrap collector, second hand vendor, dealer (or retailer), refurbishment and recycler. Intermediate traders are not modeled as a separate state.
iii. The stage donee (or recipient) and employees represent the same state which is the consumers. In other words, the statement representing the probability that computers disposed off as donation is therefore equivalent to the probability that the computers stay in the same state 'consumer'.
iv. Refurbished products from the state 'Refurbishment' are entirely sold forthwith.
v. Recycling is an absorbing state.

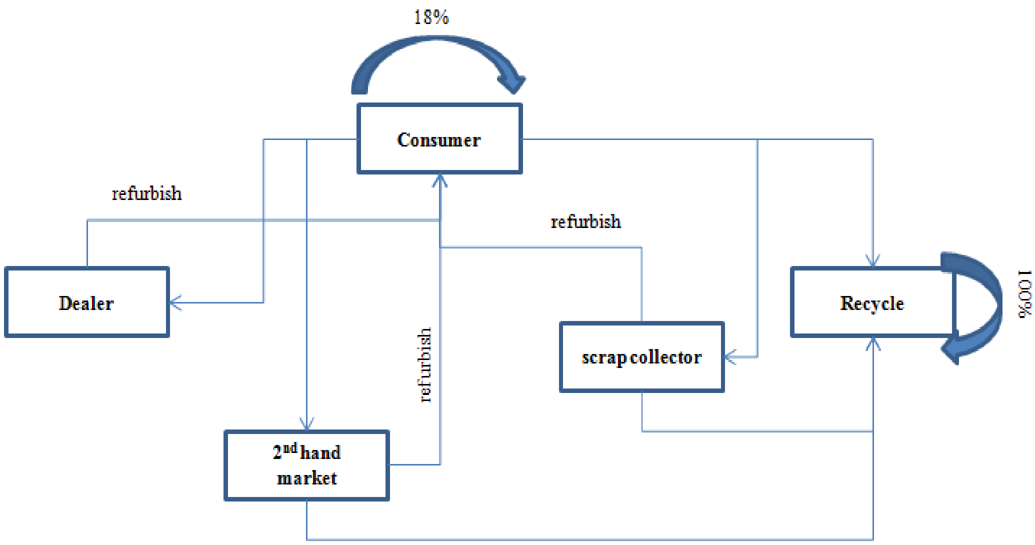

Fig. 3.5: WEEE trade chain in India

The one step stationary transition probability matrix for scenario-1 (P_1) and scenario-2 (P_2) are shown in $Eq. (1) and\ Eq. (2)$ respectively.

$$P_1 = \begin{array}{r} \text{Consumer} \\ \text{scrap} \\ \text{2nd hand} \\ \text{delaer} \\ \text{refurbish} \\ \text{recycling} \end{array} \begin{bmatrix} 0.18 & 0.11 & 0.21 & 0.48 & 0 & 0.02 \\ 0.01 & 0 & 0.05 & 0.04 & 0.70 & 0.2 \\ 0.01 & 0 & 0 & 0 & 0.69 & 0.3 \\ 0.5 & 0 & 0 & 0 & 0.5 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

$$P_2 = \begin{array}{r} \text{Consumer} \\ \text{scrap} \\ \text{2nd hand} \\ \text{delaer} \\ \text{refurbish} \\ \text{recycling} \end{array} \begin{bmatrix} 0.18 & 0.11 & 0.21 & 0.48 & 0 & 0.02 \\ 0.01 & 0 & 0.70 & 0.04 & 0.05 & 0.2 \\ 0.01 & 0 & 0 & 0 & 0.69 & 0.3 \\ 0.5 & 0 & 0 & 0 & 0.5 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

Since in $Eqs. (1)\ and (2)$, $p_{66} = 1$, both scenario-1 and scenario-2 are absorbing Markov chain consisting of both transient states and an absorbing recycling state. The transition matrix (P) of a generic absorbing Markov chain having $'t'$ transient states and $'r'$ absorbing states can be expressed in the following canonical form as:

$$P = \begin{array}{c} TR. \\ ABS. \end{array} \begin{pmatrix} Q & R \\ 0 & I \end{pmatrix} \tag{3}$$

In $Eq. (3)$, the first t- states are transient followed by the next $'r'$ absorbing states. Here, the matrix $'Q'$ is a t-by-t matrix, $'R'$ is a t-by-r matrix and $'I'$ is a r-by-r Identity matrix. Given that the starting state is s_i, the probability of being in state s_j after n- steps is given by,

$$P^n = \begin{array}{c} TR. \\ ABS. \end{array} \begin{pmatrix} Q^n & f(Q,R) \\ 0 & I \end{pmatrix} \tag{4}$$

The form of P^n shows that the entries of Q^n give the probabilities for being in each of the transient states after n-steps for each possible transient starting state. As n approaches infinity, the probability of being in the transient states (see $Eq. (4)$) must approach zero $(Q^n \to 0)$. The fundamental matrix (N) of P can be computed from the expression, $N = (I - Q)^{-1}$ where the entry n_{ij} of N represents the expected number of times that the process is in the transient state s_j given that it starts in the transient state s_i. This fundamental matrix is used to compute the basic descriptive quantities of Markov chains. Several interesting probabilistic quantities can be expressed in terms of the fundamental matrix.

Theorem 3.1: In an absorbing Markov chain, the probability that the process will be absorbed is 1 (i.e., $Q^n \to 0$ as $n \to \infty$).

Proof: From each non-absorbing state s_j it is possible to reach an absorbing state, starting from s_j. Let m_j be the minimum number of steps required to reach an absorbing state starting from s_j. Let p_j be the probability that, starting from s_j, the process will not reach an absorbing state in m_j steps. Let m be the largest of m_j and p be the largest of p_j. The probability of not being absorbed in m steps is less than or equal to p, in $2n$ steps less than or equal to p^2, etc. Since $p < 1$, these probabilities $p^n \to 0$ as $n \to \infty$. Since the probability of not being absorbed in n steps is monotone decreasing, these probabilities all tend to 0, hence, $Lim_{n \to \infty} Q^n = 0$. This completes the proof.

Theorem 3.2: $Q^n \to 0$ (zero matrix) as $n \to \infty$, then $I - Q$ has an inverse, and

$$(I - Q)^{-1} = I + Q + Q^2 + \cdots = \sum_{k=0}^{\infty} Q^k$$

Proof: Consider the identity $(I - Q).(I + Q + Q^2 + \cdots + Q^{n-1}) = I - Q^n$. By hypothesis, the RHS of the identity tends to I. This matrix has determinant 1. Hence for sufficiently large n, $I - Q^n$ must have a non-zero determinant. But the determinant of the product of two matrices is the product of the determinants, hence $I - Q$ cannot have a zero determinant. The determinant not being equal to zero, is a sufficient condition for the matrix $I - Q$ to have an inverse. Since this inverse exits, we multiply both sides of the identity by it to get $I + Q + Q^2 + \cdots + Q^{n-1} = (I - Q)^{-1}(I - Q^n)$. As it can be observed now that the RHS of the new identity tends to $(I - Q)^{-1}$. This completes the proof.

Theorem 3.3: For an absorbing Markov chain, the matrix $I - Q$ has an inverse N and $N = I + Q + Q^2 + \cdots$. The ij^{th} entry n_{ij} of the matrix N is the expected number of times the chain is in state s_j, given that it starts in state s_i. The initial state is counted if $i = j$.

Proof: Let $(I - Q)x = 0$; that is $x = Qx$. This is the standard eigenvalue formulation, where it is observed that $x = Q^n x$. Since $Q^n x \to 0$, so $x = 0$. Therefore, since $x = 0$, $(I - Q)$ exists. Thus the inverse $N = (I - Q)^{-1}$ also exists. To find out whether the infinite sum is the same as $(I - Q)^{-1}$, the sum is multiplied by $(I - Q)$. $(I + Q + Q^2 + \cdots)(I - Q) = I + Q + Q^2 + \cdots - Q - Q^2 - \cdots = I$, which gives, $N = I + Q + Q^2 + \cdots = (I - Q)^{-1}$. Letting s_i and s_j be two transient states and assuming that i and j are fixed in the remainder of the proof. Let $X^{(k)}$ denote be the random variable which equals 1 if the chain is in state s_j after k steps and equals 0 otherwise. For each k, this random variable depends upon both i and j; we choose to not to explicitly show this dependence in the interest of clarity. Therefore $P\left(X^{(k)} = 1\right) = q_{ij}^{(k)}$ and $P\left(X^{(k)} = 0\right) = 1 - q_{ij}^{(k)}$, where $q_{ij}^{(k)}$ is the ij^{th} entry of the matrix $Q^{(k)}$. Since $X^{(k)}$ is a 0-1 random variable, $E\left(X^{(k)}\right) = q_{ij}^{(k)}$. Therefore, the expected number of times the chain is in state s_j in the first n steps, given that it starts in state s_i, can be stated as $E\left(X^{(0)} + X^{(1)} + \cdots + X^{(n)}\right) = q_{ij}^{(0)} + q_{ij}^{(1)} + \cdots + q_{ij}^{(n)}$. Letting n tend to infinity, results in $E\left(X^{(0)} + X^{(1)} + \cdots\right) = q_{ij}^{(0)} + q_{ij}^{(1)} + \cdots = n_{ij}$. This completes the proof.

The fundamental matrix for scenario-1 and scenario-2 are shown in $Eqs. (5) and\ (6)$ respectively.

$$N_1 = \begin{array}{r} \text{Consumer} \\ \text{scrap} \\ \text{2nd hand} \\ \text{delaer} \\ \text{refurbish} \end{array} \begin{bmatrix} 9.38 & 1.03 & 2.02 & 4.54 & 4.39 \\ 7.36 & 1.81 & 1.64 & 3.61 & 4.20 \\ 6.56 & 0.72 & 2.41 & 3.18 & 3.76 \\ 9.38 & 1.03 & 2.02 & 5.54 & 4.89 \\ 9.38 & 1.03 & 2.02 & 4.54 & 5.39 \end{bmatrix} \tag{5}$$

$$N_1 = \begin{array}{r} \text{Consumer} \\ \text{scrap} \\ \text{2nd hand} \\ \text{delaer} \\ \text{refurbish} \end{array} \begin{bmatrix} 7.81 & 0.86 & 2.24 & 3.78 & 3.48 \\ 4.61 & 1.51 & 2.02 & 2.27 & 2.61 \\ 5.46 & 0.60 & 2.57 & 2.65 & 3.13 \\ 7.81 & 0.86 & 2.24 & 4.78 & 3.98 \\ 7.81 & 0.86 & 2.24 & 3.78 & 4.48 \end{bmatrix} \qquad (6)$$

For instance, if one starts from state-1 which is the consumer, the expected number of times the replaced computer remains in state-1, 2, 3, 4 and 5 before getting finally recycled is 10, 2, 3, 5 and 5 for scenario-1 and 8, 1, 3, 4 and 4 for scenario-2, respectively. Noteworthy outcome from the simulation is the entry N_{11}which explicitly states the number of times the computer will remain in the consumer state given that it starts at the same state. In other words, a computer disposed by the business sector has 10 lives in scenario-1 and 8 lives in scenario-2. The model does not take into account the end-of-life store phase, which explains the high computed value of N_{11}. But certainly, a computer will remain in use for a longer period when a scrap collector additionally gets involved in refurbishing instead of taking the route of disposing the same directly to the second hand market.

An equally important index of a Markov chain is the average total time to absorption. It represents the expected number of steps before a transition state is absorbed and is given by $t = Nc$, where c is the unit column vector. Therefore, the average time to absorption in both the scenarios are calculated as,

$$t_1 = \begin{array}{r} \text{Consumer} \\ \text{scrap} \\ \text{2nd hand} \\ \text{dealer} \\ \text{refurbish} \end{array} \begin{bmatrix} 21.36 \\ 18.61 \\ 16.64 \\ 22.86 \\ 22.36 \end{bmatrix} \text{ and } t_2 = \begin{bmatrix} 18.17 \\ 13.01 \\ 14.41 \\ 19.67 \\ 19.17 \end{bmatrix} \qquad (7)$$

Though a Markov chain does not allow for an analysis of time, what is obvious from $Eq.(7)$ is that the case of scrap collectors involved in the refurbishing of collected computers, eventually delay the process of computers disposed to recycling and therefore contribute towards reuse as compared to the case when they are directly sold in the second hand market. Another interesting inference is that for scenario-1, the shortest route to recycling is the second hand market while in scenario-2; computers at the scrap collectors' end take the least number of steps before they could be ultimately recycled.

Therefore, the operational efficiency of scenario-1 as far as lifetime extension of WEEE is concerned are more palpable than scenario-2.

3.3 Investigation into Recycler's Strategy

In this scenario, some proportion of the WEEE sourced from the corporate sector could be potentially refurbished while the rest recycled for material recovery. This is true particularly with computer specific waste given that most of the organizations of this sector replace annually at least 10 to 40 per cent of their PC installed base. Incompatibility with latest technology amongst others is the single most important factor driving the replacement decision. The MAIT-GTZ (2007) survey reports that 60 per cent of the organizations look for best monetary offers while disposing off their computers. With the current Indian structure bereft of any legislative mandate, the recycling activity cannot be environment friendly. The major concern of the formal recycler's in India is the collection rate given that the compensation paid by the formal recyclers for the resources are lower compared to the informal sector, where the labor and processing costs are much lower.

3.3.1 Case 4a: Recycler refurbishing a part of the proceeds

Recycling companies have to pay a price affront for sourcing a regular supply from the corporate sector. Therefore, it makes real sense to refurbish some of the quality replaced computers and resold at higher revenue as compared to limited profits made from recycling. In retrospect, through refurbishing, an attempt is made to delay the environmental burden through lifetime extension of the computers. For example, a formal recycling company in Chennai, Ash recyclers refurbishes old monitors into TV entertainment system which are sold at the second hand market. To realize this case, changes in at least two entries of transition matrix P are made i.e.,

$$p_{65}= p \ \ and\, p_{66} = 1 - p,\ \ given\, 0 < p < 1 \tag{8}$$

This (see $Eq. (8)$) reflects the case where certain proportion of computers collected for recycling (p_{66}) are diverted to refurbishing (p_{65}). By making these changes, the new Markov chain having transition probability ($\bar{P}$) is no more absorbing, but ergodic in nature. A Markov chain is ergodic, if it is possible to move from every state to every other state, not necessarily in one move. Ergodic Markov chains are sometimes also referred to as irreducible chains. The characteristic equilibrium probability of these ergodic Markov chains represents the limiting probability (W) that the system will be in each state j after a large number of transitions, and this probability is independent of the initial state given as $W = \lim_{n\to\infty} \bar{P}^n$. Here, W is the matrix all of whose rows are the fixed probability positive row vector w satisfying $wP = w$, where $\sum_{j=1}^{s} w_j = 1$. This vector w is also called as the stationary distribution vector.

Definition: A transition matrix of a Markov chain is regular if and only if for some N, P^n has all non-zero entries.

Theorem 3.4: Let P be an $r \times r$ transition matrix of a regular Markov chain. Let ε be the smallest entry of P. Let x be any r-component column vector, having maximum component M_0 and minimum component m_0, and let M_1 and m_1 be the maximum and minimum components for the vector Px. Then $M_1 \leq M_0$, and $m_1 \geq m_0$.

Proof: Let x' be the vector obtained from x by replacing all components, except one m_0 component, by M_0. Then $x \leq x'$. Each component of Px' will then be of form, $am_0 + (1-a).M_0 = M_0 - a(M_0 - m_0)$, where $a \geq \varepsilon$. Therefore each component of the inequality will be $\leq M_0 - \varepsilon(M_0 - m_0\,)$. But since $x \leq x'$, implies $Px \leq Px'$ which means $M_1 \leq M_0 - \varepsilon(M_0 - m_0\,)$. Similarly, if x' be the vector obtained from $-x$ by replacing all components, except one $-M_0$ component, by $-m_0$, then $-x \leq x'$. Each component of Px' will then be of form, $a(-M_0) + (1-a).(-m_0) = -m_0 - a(M_0 - m_0)$ and given that $a \geq \varepsilon$, results in $-m_1 \leq -m_0 - \varepsilon(M_0 - m_0)$. Together, the sum of these two inequalities give, $(M_1 - m_1) \leq M_0 - m_0 - \varepsilon(M_0 - m_0) \leq (1-2\varepsilon)(M_0 - m_0)$. Hence, $M_1 \leq M_0$, and $m_1 \geq m_0$. This completes the proof.

Theorem 3.5: If P is a regular transition matrix, then (a) the powers of P^n approach a probability matrix W, (b) each row of W is the same probability vector $w = \{w_1, w_2, \dots, w_s\}$, (c) the components of w are all positive.

Proof: Let ε be the minimum entry of the regular transition matrix P and $\rho_j$be a column vector with a 1 in the j^{th} component and 0 otherwise. Let M_n and m_n be the maximum and minimum components of the vector $P^n\rho_j$. Since $P^n\rho_j = PP^{n-1}\rho_j$, and using $Theorem$ 3.4, $M_n - m_n \leq (1-2\varepsilon)(M_{n-1} - m_{n-1})$. If we let $d_n = M_n - m_n$, and given $n \geq 1$, the resulting expression becomes $d_n \leq (1-2\varepsilon)^n d_0 = (1-2\varepsilon)^n$. Thus as $n \to \infty$, $d_n \to 0$ and, M_n and m_n approach a common limit, and therefore $P^n\rho_j$ tends to a vector with all components the same. Let w_j be this common value. It is clear that for all n, $m_n \leq w_j \leq M_n$. In particular, since $m_1 > 0$ and $M_1 < 1$, leads to $0 < w_j < 1$. Now $P^n \rho_j$ is the j^{th} column of P^n. Thus the j^{th} column of P^n tends to a matrix W with all rows the same vector w. Since the row sum of P^n are always 1, the same must be true for the limit. This completes the proof.

Much as with an absorbing chain, an ergodic Markov chain can best be analyzed through its fundamental matrix given by, $Z = (I - \bar{P} + W).^{-1}$ Given the fundamental matrix of the ergodic Markov chain whose ij^{th} entry is z_{ij}, the mean first passage time matrix (M) can be computed from:

$$m_{ij} \ of \ M = \frac{z_{jj} - z_{ij}}{w_j} \tag{9}$$

where, w_j is the j^{th} state entry of the fixed probability vector w and m_{ij} is the mean first passage time or the expected number of steps to reach state s_j for the first time given that the ergodic Markov chain starts in state s_i for $i \neq j$. Another parameter of importance is the mean recurrence time r_i which essentially gives the expected number of steps to return to state s_i for the first time, assuming that the ergodic Markov chain starts in state s_i for $i = j$ which is calculated from:

$$r_j \ (or \ r_i) = {}^1/_{w_j} \tag{10}$$

where, w_j has its usual meaning.

Veenstra et al. (2010) report that the ideal way to analyze the impact of different policy scenarios is through perturbation of the transition matrix. For a stochastic matrix such as P, the associated eigenvalue is 1 of multiplicity one, and all other eigenvalues λ_i will have magnitude strictly less than 1 ($|\lambda_i| < 1$). Additionally, the authors state that if the second largest eigenvalue is also close to 1, then the Markov chain is very sensitive to small perturbations. For our case, the second largest eigenvalue of matrix P is 0.82 and 0.85 for scenario-1 and scenario-2 respectively, underlying the fact that the base case model will behave unpredictably for small changes in any entries of the matrix P. Given that the n-state ergodic Markov chain $\bar{P}$ (where $\bar{w}\bar{P} = \bar{w}$; $\bar{w} > 0$; $\bar{w}e = 1$ and e is the column vector of all ones) is perturbed to $\bar{\bar{P}}$ (where $\bar{\bar{w}}\bar{\bar{P}} = \bar{\bar{w}}$; $\bar{\bar{w}} > 0$; $\bar{\bar{w}}e = 1$ and e is the column vector of all ones), then the perturbation matrix (E) is given as $E = \bar{P} - \bar{\bar{P}}$ with respective equilibrium component wise probabilities $\overline{w_j}$ and $\overline{\overline{w_j}}$.

In studying the sensitive measure through perturbation, the objective is to estimate the changes in $\overline{w_j} - \overline{\overline{w_j}}$ in terms of the changes in E using the norm wise expression, $\|\overline{w} - \overline{\overline{w}}\| \leq k\|E\|$ or the component wise expression $\left|\overline{w}_j - \overline{\overline{w}}_j\right| \leq k_j\|E\|$ for suitable values of condition numbers k $(and\ k_j)$. In other words, an attempt is made to check whether the stationary probability values are sensitive to perturbations in $\bar{P}$. The condition numbers expressed in terms of mean first passage times proposed by Cho and Meyer (2001) was used for the calculation of component wise perturbation bound as follows:

$$|\overline{w}_j - \overline{\overline{w}}_j|_\infty \leq \frac{1}{2} max_j \left[\frac{max_{i \neq j} \bar{m}_{ij}}{\bar{r}_j}\right] \|E\|_\infty \tag{11}$$

where, $\|E\|_\infty$ is the maximum absolute row sum norm. A bound in terms of component wise perturbation gives us detailed information about the sensitivity of the chain to perturbations. The condition number provides qualitative interpretation of error bound. Yet another measure of sensitivity for a s-state Markov chain is the Hunter's statistic (Hunter, 2003) defined by $v_i = \sum_{j=1}^{s} m_{ij}\, w_j$, having lower bound given by $v = s$. For our analysis, different values of p_{65}= p was used and through adjusting the probabilities of p_{66}, the relative impact of such changes on the performance of the e-waste management system was studied. $Table$ 3.1 and $Table$ 3.2 show the equilibrium probabilities for the ergodic Markov chain representing scenario-1 and scenario-2, respectively and the associated steady state characteristics. The decrease in the second highest eigenvalue for both the scenarios (0.94 to 0.63 in Scenario-1 and 0.93 to 0.61 in Scenario-2), clearly suggest that the Markov chain equilibrium probabilities are less susceptible to perturbations with increase in proportion of e-waste diverted from recycling to refurbish. This is confirmed by the decrease in Hunter's statistic from 20 to 5.9 for Scenario-1 ($Table$ 3.1) and 18 to 5.7 in Scenario-2 ($Table$ 3.2).

It is also observed that the upper bound stated in $Eq.(11)$ are high for the recycling state, specifically at lower values of p_{35}, but steadily decrease for higher values of p_{35}. For instance in scenario-1, the highest upper bound for the recycling state related to $p_{35} =$ 0.2 and $p_{35} =$ 0.3 is 0.04177 which gradually increases to 0.1868 during $p_{35} =$ 0.01 and $p_{35} =$ 0.02.

Table 3.1: Sensitivity analysis for recycle-refurbish (Scenario-1)

	***p*=0.01**	***p*=0.05**	***p*=0.1**	***p*=0.2**	***p*=0.3**
Consumer	7.6632e-002	2.2136e-001	2.8978e-001	3.4274e-001	3.6497e-001
Scrap	8.4295e-003	2.4350e-002	3.1875e-002	3.7701e-002	4.0147e-002
2nd hand	1.6514e-002	4.7704e-002	6.2447e-002	7.3860e-002	7.8651e-002
Dealer	3.7120e-002	1.0723e-001	1.4037e-001	1.6602e-001	1.7679e-001
Refurbish	4.4028e-002	1.2718e-001	1.6649e-001	1.9692e-001	2.0969e-001
Recycle	8.1728e-001	4.7217e-001	3.0905e-001	1.8276e-001	1.2975e-001
second EV	9.4256e-001	9.0042e-001	8.4750e-001	7.4079e-001	6.3261e-001
(r_1, r_6)	(13.05, 1.22)	(4.52, 2.12)	(3.45, 3.24)	(2.92, 5.47)	(2.74, 7.71)
Hunter's	20.629	13.260	9.7777	7.0815	5.9496

Apparently, the mean time for a computer to return back again to the consumer state given that it currently exists with the consumer (r_1) expectedly decreases with increase in p for either of the scenarios. This notwithstanding, for both the ergodic cases, the mean first passage time to reach the consumer state from the i^{th} state (m_{41}) are both identical and smallest for the dealer state (results not shown due to lack of space). It is also observed from $Table$ 3.3, that m_{46} which is the time for e-waste to reach the recycler from the dealer state are highest amongst the remaining starting states. This arguably demonstrates that consumers prefer the dealers closely followed by the second hand market for purchasing second hand computers.

Table 3.2: Sensitivity Analysis for recycle-refurbish (Scenario-2)

	p=0.01	**p=0.05**	**p=0.1**	**p=0.2**	**p=0.3**
Consumer	6.5508e-002	1.9931e-001	2.6765e-001	3.2303e-001	3.4695e-001
Scrap	7.2059e-003	2.1924e-002	2.9441e-002	3.5533e-002	3.8165e-002
2nd hand	1.8801e-002	5.7203e-002	7.6815e-002	9.2708e-002	9.9576e-002
Dealer	3.1732e-002	9.6547e-002	1.2965e-001	1.5647e-001	1.6806e-001
Refurbish	3.7591e-002	1.1437e-001	1.5359e-001	1.8536e-001	1.9909e-001

	p=0.01	**p=0.05**	**p=0.1**	**p=0.2**	**p=0.3**
Recycle	8.3916e-001	5.1064e-001	3.4286e-001	2.0690e-001	1.4815e-001
second EV	9.3363e-001	8.9062e-001	8.3648e-001	7.2657e-001	6.1377e-001
(r_1, r_6)	(15.27, 1.19)	(5.02, 1.96)	(3.74, 2.92)	(3.10, 4.83)	(2.88, 6.75)
Hunter's	18.243	12.321	9.2969	6.8461	5.787

Table 3.3: Time to reach recycle state from i^{th} state

m_{i6} of M	Scenario-1	Scenario-2
	Recycle	Recycle
Consumer	2.1358e+001	1.8167e+001
Scrap	1.8610e+001	1.3011e+001
2nd hand	1.6640e+001	1.4407e+001
Dealer	2.2858e+001	1.9667e+001
Refurbish	2.2358e+001	1.9167e+001

3.3.2 Case 4b: Recycler sells some refurbished products to second hand market

This analysis was further extended to the case of recyclers refurbishing part of their collection and selling the refurbished computers to the second hand market. It was also assumed that the second hand market sell all the refurbished shipment directly to the consumers. Nischalke (2007) report in their study, that this kind of disposition by recyclers is not quite uncommon in India. The proposed changes necessitate a revaluation of some of the entries of the matrix $\bar{P}$. This was incorporated by increasing the proportion p_{31} followed by a corresponding decrease in p_{36}. The results of Scenario-2 are shown in $Table$ 3.4.

Table 3.4: Stationary probabilities for scenario-2 (case-4b)

	$*p_{31} = 0.11$ $p_{36} = 0.2$	$*p_{31} = 0.21$ $p_{36} = 0.1$	$**p_{31} = 0.11$ $p_{36} = 0.2$	$**p_{31} = 0.21$ $p_{36} = 0.1$
Consumer	3.4205e-001	3.6346e-001	3.6260e-001	3.7972e-001
Scrap	3.7626e-002	3.9981e-002	3.9886e-002	4.1770e-002
2nd hand	9.8169e-002	1.0431e-001	1.0407e-001	1.0898e-001

	$^{*}p_{31} = 0.11$ $p_{36} = 0.2$	$^{*}p_{31} = 0.21$ $p_{36} = 0.1$	$^{**}p_{31} = 0.11$ $p_{36} = 0.2$	$^{**}p_{31} = 0.21$ $p_{36} = 0.1$
Dealer	1.6569e-001	1.7606e-001	1.7564e-001	1.8394e-001
Refurbish	1.8646e-001	1.8770e-001	1.9766e-001	1.9610e-001
Recycle	1.7000e-001	1.2848e-001	1.2014e-001	8.9488e-002
second EV	0.7445	0.7621	0.6358	0.6571
MRT(r_1, r_6)	(2.92, 5.88)	(2.75, 7.78)	(2.76, 8.32)	(2.63, 11.17)
Hunter's	7.0983	7.3820	5.9353	6.0975

Note: $^{*}p_{65} = 0.2, p_{66} = 0.8$ and ** $p_{65} = 0.3, p_{66} = 0.7$

From $Table$ 3.4, it is evident that when the recycler increases the quantity refurbished (p_{65}) from 20% to 30%, the instability in the equilibrium probabilities reduces. This is evident from the second highest eigenvalues and also the Hunter's statistics given that the lower bound of this statistic for six states is 6. The analysis of equilibrium probabilities which gives the proportion of times the process is in each of the states in the long run, for both the cases (Sec 3.4.1 and 3.4.2) show some interesting outcomes. For instance, the maximum proportion of time a computer remains in the first case is the recycling state and by increasing refurbishing even by a small amount (case 4a), the equilibrium probability of the recycle state substantially decreases (see $Table$ 3.1 and $Table$ 3.2) which means in the long run there is a potential of reducing the recycling volumes by focusing on refurbishing and reselling. On the other hand, when the refurbished computers are sold to the second hand market who in turn sells them directly to consumers (case 4b, $Table$ 3.4), a more powerful impact can be attained as can be seen from the increasing equilibrium probabilities of the consumer state.

This is confirmed from the fact that the eventual time to return to the recycle state (r_6) is substantially delayed when recycler sells the refurbished computers to consumer through the second hand market. Similarly, the case 4a show marginally lower values of indicator r_1 over that of case 4b, given that this indicator invariably decreases with increase in p for both the cases. Apparently, the behavior of the scrap collectors have the least influence on the outcome of the case 4b as observed from their impact which are not entirely different.

3.3.3 Case 4c: Recycler sells small proportion to scrap collectors without refurbishing

Nischalke (2007) state that the recyclers in India not only have access to the second hand market, but are also in liaison with the scrap collectors too. Therefore an attempt was made to assess the third case, where a proportion of the recycler's collection is sold back to the scrap dealers without refurbishing. Needless to say that this case situation does not reveal any significant impact as far as lifetime extension of computers is concerned. The proposed study was conducted by increasing the entry p_{62} with a matching decrease in p_{66}. It was observed from the Hunter's statistic that the equilibrium probabilities are highly unstable for small values of p_{62}, but converge to stability with increase in units sold to the scrap collectors.

3.4 Case 5: Investigation of the Second Hand Market

The aim of this exercise is to investigate the case of refurbishing (or reselling) more at the second hand market over disposal to recycling. This was realized by gradually reducing the entry p_{36} while making a corresponding increase in p_{35}. Such an exercise is fairly plausible for a country like India where e-waste is the main source of livelihood of the second hand market driven by the economics of scale that justify refurbishing over selling the same at a reduced price to the recyclers. In fact, in smaller cities of India such as Chandigarh, Jaipur and Bangalore, around 65 per cent of the population prefers second hand goods (Raghavan, 2010). Though, the size of the organized and unorganized second hand market in India is difficult to estimate, there is no ambiguity that it will make economic sense if these markets are taken into deliberation when the business sector dispense off their stockpile of WEEE. The results of this case are shown in Table 3.5.

Table 3.5: Time to absorption for case-5

State	Scenario-1			Scenario-2		
	$p_{36} = 0.3$ $p_{35} = 0.69$	$p_{36} = 0.2$ $p_{35} = 0.79$	$p_{36} = 0.1$ $p_{35} = 0.89$	$p_{36} = 0.3$ $p_{35} = 0.69$	$p_{36} = 0.2$ $p_{35} = 0.79$	$p_{36} = 0.1$ $p_{35} = 0.89$
Consumer	21.36	27.02	36.52	18.17	23.70	33.73
Scrap	18.61	23.20	30.88	13.01	18.00	27.05

State	Scenario-1			Scenario-2		
	$p_{36} = 0.3$ $p_{35} = 0.69$	$p_{36} = 0.2$ $p_{35} = 0.79$	$p_{36} = 0.1$ $p_{35} = 0.89$	$p_{36} = 0.3$ $p_{35} = 0.69$	$p_{36} = 0.2$ $p_{35} = 0.79$	$p_{36} = 0.1$ $p_{35} = 0.89$
2nd hand	16.64	23.41	34.76	14.41	20.75	32.24
Dealer	22.86	28.52	38.02	19.67	25.20	35.23
Refurbish	22.36	28.02	37.52	19.17	24.70	34.73
N_{11}	9.38	11.75	15.74	7.81	10.06	14.14

The parameter of significance is the number of times the product returns to the consumer state (N_{11}) and the time to absorption (t_j). The entry $N_{11}$from our analysis gradually increases from 9.38 in the base case to 15.74 in scenario-1 and from 7.81 to 14.14 in scenario-2 (Table 3.5). Similarly, a steady increase in time to absorption is found for either of the scenario's indicating the strategy of selling more through refurbishing by the second hand market has a positive effect in extending the lifespan of computers in use, more so when fewer than 10 per cent are sold to recyclers. Invariably in both the scenarios, the shortest route to recycling is the scrap collector while products that are with the dealer end up last at the recycler.

3.5 Investigation into Producer Responsibility for Product Take-back

With growing consumer awareness on corporate practices, businesses are forced to reciprocate with greener practices such as "Extended Producer Responsibility" (EPR) a notion or concept that make producers take responsible for their activities not only in production and distribution of goods but also towards the safe disposal of such products. The underlying assumption here is that the stakeholders along the product chain are expected to share responsibility for lifecycle impacts of products. Kautto and Melanen (2004) emphasize that the primary pressure for the business sector to upgrade their environmental performance come from their customers. In a product take back program, the company's responsibility is not only limited to managing its own waste, but also working with distributors and customers to take back products for potential reuse (French, 2008). WEEE take back or exchange though not mandated in India upto now, there was evidence of select companies like Nokia, HCL, DELL, Panasonic and Wipro to name a few who have institutionalized this program obliging to their moral and ethical responsibility; brand protection and IPR issues, in addition to the economic gains made from reuse business. However, this scenario will likely change in the coming days, more so after the e-waste handling rules comes into force after May, 2012. Matsumoto (2009) emphasize that original equipment manufacturers (OEMs) may favor reuse over recycling so long as reuse business do not impact their new product sales.

3.5.1 Case 6: Product returns through dealers

Product returns through dealers replicating the corporate take-back are modeled assuming that any increase in collection by this channel will result in a proportional decrease in collection by the scrap collectors. In other words, higher probability was assigned to p_{14} and correspondingly adjusting the probability p_{12}. The dealers on an average was assumed to refurbish 80 per cent of their products selling the rest directly to the customers ($p_{45} = 0.8\ and\ p_{41} = 0.2$). Additionally, three different possibilities were also investigated: all refurbished products from the dealers are directly sold to customers ($p_{51} = 1$), all refurbished products from the dealers are directly sold to second hand market ($p_{53} = 1$), and exactly half the refurbished products are sold directly to the customers while the rest half sold at the second hand market ($p_{51} = 0.5\ and\ p_{53} = 0.5$). Further, if the total collected and refurbished computers from the dealers are to be resold to the consumer through the second hand route, then the proportion sold to consumers (p_{31}) shall in all likelihood increase necessitating a reduction in entry p_{35}.

3.5.1.1 Case 6.1a: Dealers refurbish and sell to consumers

For the case where all refurbished computers at the dealer end are earmarked for resale to the consumers, the parameter of interest is the time to absorption especially of the consumer state and N_{11}. As observed from $Table$ 3.6, the number of transitions in steps before a computer is eventually recycled gradually increases with increase in collection of EOL computers from the consumers.

Table 3.6: Time to absorption for case 6.1a

	$p_{14} = 0.48$ $p_{12} = 0.11$	$p_{14} = 0.5$ $p_{12} = 0.09$	$p_{14} = 0.55$ $p_{12} = 0.04$
Consumer	22.72	23.66	26.41
Scrap	19.69	20.43	22.59
2nd hand	17.59	18.25	20.18
Dealer	24.52	25.46	28.21
Refurbish	23.72	24.66	27.41
N_{11}	9.3765	9.770	10.917

From Table 3.6for instance, with increase in EOL product collection by the dealers (p_{14}) from 48% to 55%, the average time that a product takes to reach the recycling state increases from 22.72 to 26.41 units. Additionally, this trend also persists for N_{11} too, reinforcing the fact that the number of potential lives of a product will increase gradually when producers take responsibility in the collection of their products. Another perspective that emerges from the analysis is that in all possible eventualities, it is the second hand market that shows the shortest route to recycling.

3.5.1.2 Case 6.1b: Dealers refurbish and sell to second hand market

In this section, the case of dealers collecting and refurbishing WEEE and selling the same to the thriving second hand market was investigated. To make the analysis tractable, the assumption that all refurbished products at the dealer are sold to the second hand market ($p_{53} = 1$) was made. Further, if the total collected and refurbished computers from the dealers are to be resold to the consumer through the second hand route, then the proportion sold to consumers (p_{31}) shall in all likelihood increase necessitating a reduction in entry p_{35}. To better understand the implications of this all important e-waste trade chain, a complete investigation is required so as to capture the influence of the different parameters on the model's behavior.

Table 3.7: Time to absorption for case 6.1b (Scenario-2)

	p_{31}=0.21, p_{35}=0.49, p_{12}=0.04, p_{14}=0.55	p_{31}=0.11, p_{35}=0.59, p_{12}=0.04, p_{14}=0.55	p_{31}=0.21, p_{35}=0.49, p_{12}=0.09, p_{14}=0.50	p_{31}=0.11, p_{35}=0.59, p_{12}=0.09, p_{14}=0.50
Consumer	10.46	10.76	10.17	10.45
Scrap	8.24	8.48	8.07	8.31
2nd hand	8.81	9.12	8.61	8.91
Dealer	9.81	10.12	9.61	9.91
Refurbish	11.46	11.76	11.17	11.45
N_{11}	3.78	3.78	3.69	3.69

A Markov chain simulation of this case reiterate the limited benefit from increased refurbishing vis-à-vis the base case scenarios. The case was analyzed by selectively varying the proportion sold by the second hand market to consumers (p_{31}) followed by the proportion collected by the dealers, one factor at a time while assuming that the dealers on an average refurbish 80 per cent of their products. So far as the case of scrap dealers refurbishing a major portion of collected units (Scenario-1) is concerned, there is practically very little evidence of improvement in overall reuse business efficiency as the time to absorption decreases with increase in proportion collected by dealers. On the contrary, extended producer responsibility through increased involvement of dealers has a positive effect on the entire reuse business for the case where scrap dealers sell a major portion of collected units to the second hand market (Scenario-2) as observed from $Table$ 3.7. It is obvious from $Table$ 3.7 that with increase in dealer collection by 5%, the time to absorption to the recycling state increases from 10.17 units to 10.46 units. A similar increasing trend in number of lives of computer (N_{11}) is also observed.

3.5.1.3 Case 6.1c: Dealers only collect but do not refurbish and sell to scrap and second hand market

Here an attempt was made to investigate the case where the dealer under the purview of extended producer responsibility limit their role only to collect the returns from consumers and sell the same to scrap collectors and second hand market where they are refurbished and sold to the consumers. This case reflects the case of OEMs selling new products, and is negatively disposed towards the reuse business. The OEMs invariably are uniquely positioned for undertaking reuse business, but they shy away from this prospect given their disproportionate profit structures (Matsumoto, 2010). To investigate this case, changes in scenario-1 were made ($p_{41} = 0, p_{42} = 0.4, p_{43} = 0.4, p_{46} = 0.2$) reflecting the case where dealers sell all collected units to scrap collectors, second hand market and recyclers. This model can further be extended to analyze the case where the dealers make a conscious choice of not selling the returned products to recyclers, rather preferring to sell them to the scrap collectors and the second hand market ($p_{42} = 0.5$, $p_{43} = 0.5,\ p_{46} = 0,\ p_{21} = 0.05\ and\ p_{24} = 0$). Such a case stems from the fact that the returns are fairly new, technologically not obsolete and having a market value as is generally the case of returns from the business sector. In other words, the case situation mimics the case where producers are absolved from collecting orphaned or historical WEEE, a term referenced for old obsolete items that have been upgraded several times during their lifespan leaving no trace of the original equipment manufacturers. This is always the case when a nation have just established and legalized extended producer responsibility concept. The (N_{11}, t_1) values are found to be (3.26, 8.9) and (4.34, 12.44) respectively, for the case where dealers dispose and do not dispose to recyclers. For either of the cases, there is a marginal increase in both N_{11} and time to absorption, when the dealers sell more to the scrap collectors over the second hand market. Additionally, there is no significant effect of increase in dealer collection on the performance parameters, which evidently are much worse than the base case. This signifies that any future take back policy where retailers and dealers resell via the second hand market will not be successful. The implication of this is that reselling directly to consumers (Case 6.1a) or directly monitoring the second hand sales would be better alternatives.

3.6 Empirical Findings

3.6.1 Environmental and social implication

A preliminary insight into the relevant implications of the illustrated case scenarios could be constructed by analyzing their environmental impact from recycling and associated social impact from increased reuse. The relevant statistic used for analyzing environmental impact are the proportion waste handled by the recyclers as observed from the equilibrium probabilities in addition to time to absorption to the recycling state.

Similarly, the social impact from increased reuse is observed by analyzing the proportion of disposed products at the consumer state, increased use of second hand market along with the number of extended lives of the product (N_{11}). It is observed that scenario-1 where scrap dealers maximize their revenue through refurbishing as against selling to the second hand market, objectively outperforms as far as lifetime extension of products is concerned. According to the recent report by Toxics Link (2012), a leading environmental NGO, about 1 tonne of e-waste is daily passed through the hands of about 300 dismantling units alone at Seelampur in Delhi. It is obvious that consumers are conscious about the quality of used products (Case 4a) since they prefer the dealers over the second hand market in purchasing used e-products.

From the perspective of scenario-2 where the scrap collectors sell a major portion of returned products to the second hand market, the case 4b (see $Table$ 3.5) shows similar and identical performance. Much of the assumptions for both the scenarios remain the same except for the disposition behavior of the scrap collectors. Therefore, the scrap collectors have the least influence on the lifetime extension of WEEE. However, it is the second hand market that is expected to have a major stake in any policy decision towards reducing the environmental burden originating from the recent spurt in domestic generation of e-waste. Assuming that the dealers take back their EEE products at the end of their useful life, appropriate mechanism for integrating the recyclers with the second hand market have to be pursued. Also the producers have to be proactive in implementing buy-back and resell strategy by mandating the dealers to refurbish and sell the products that are returned. The analysis of reuse and lifetime extension in conjunction with dealer take back, purportedly outlines that positive impact from dealers refurbishing and selling the proceed directly to consumers can be achieved as against the case of selling with or without refurbishing to the second hand market. Clearly, the implementation of even limited extended producer responsibility through voluntary collection by the producers, results in lower environmental impact. Even in the event of mandated EPR regime, the current network of scrap collectors needs to be kept insulated from hazardous dismantling/disassembly activities for refurbish/reuse while consolidating their effort towards improving the collection efficiency only. $Table$ 3.8 shows the evaluation of the different cases by benchmarking their performance with the base case scenarios.

Table 3.8: Benchmarking with base case

Case	Environmental Impact	Social Impact	Profit
4a	+	++	
4b	++	++	
4c	+	+	
5	++	++	
6.1a	++	++	±
6.1b	–	–	±
6.1c	–	–	±

The positive environmental impact of Case 4a and 4b is the outcome of decrease in the volume of recycling, while the positive social impact for Case 4b is more pronounced on account of the increased use of second hand market in addition to the observed increase in the time to absorption to the recycling state. For Case 4c, the impacts though positive are not significant on account of more proportion of products at the recycler end. Similarly, the positive effect of impacts from Case 5 and 6.1a are spectacular resulting from increase in time to absorption, number of lives and the increased usage of the second hand market.

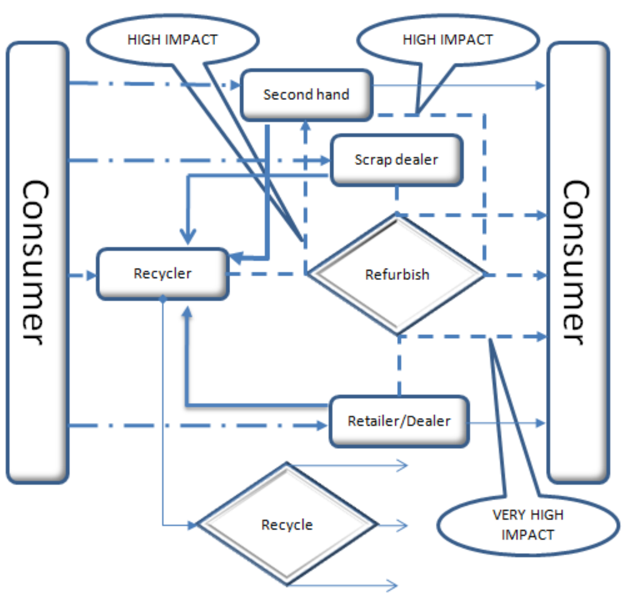

Fig. 3.6: Cases of high impact

The resulting cases of interest are shows in Fig. 3.6. The rest of the cases (Case 6.1b and 6.1c) show negative impact given that they perform much worse than the base case. However, any future policy resulting from extended role of dealers in a take back regime will in all likelihood translate to neutral profits as a consequence of the additional role of dealers (−) and the revenues from refurbish/resell (+).

3.6.2 Survey result

The study focused on sampling the perceptions and reuse experience of consumers by conducting an online survey through a well structured questionnaire in a university set-up. The respondents included university students, teachers, the non-teaching community and their families. A request for taking the survey was made through root mail to all and a total of 80 responses were received. The sampled population comes from different ethnic and religious background, is educated, represents both high and low-income groups and is predominantly from semi-urban and urban areas. The survey instruments focused on respondent's general awareness about the secondary market structure and their environmental attitudes towards reuse chains. About 64%, 81%, 98%, 85%, 69%, 38% of the respondents owned a desktop PC, laptop PC, mobile phone, refrigerator, washing machine and air conditioners respectively. While 16% of the respondents were highly aware about the environmental and human health concerns emanating from WEEE, 73% of the respondents were limitedly aware, where much of this awareness came from electronic and the print media. Data from the survey indicate that respondents preferred to exchange their old electronic goods with the dealer/retailer followed by the alternative 'selling to second hand shops' (see Fig. 3.7).

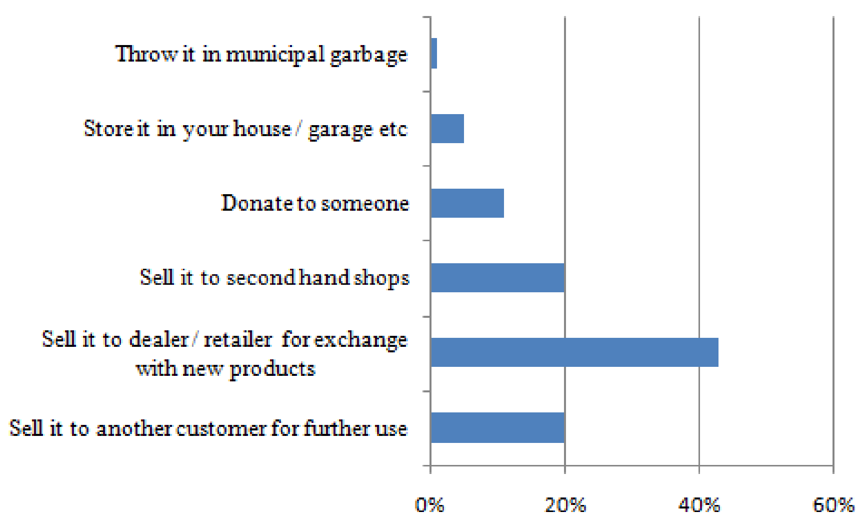

Fig. 3.7: Consumer WEEE selling strategy

To the question "When you will dispose – off your used electronic equipment?", a majority of the respondents (about 65%) stated functional obsolescence, while 20% of them choose the alternative 'better and improved features in newly launched product' as a triggering point for disposing off their e-waste. A further breakdown of survey responses for the purchasing decision of the respondents indicate that only 14% have actually purchased a reusable product and about 45% of the respondents are willing to purchase with an additional 5% strongly willing to purchase a reusable electronic product. The results compare well with 42% willing to buy second hand electronics in Ireland, 46% in the UK and 31% in Belgium (O'Connell et al., 2011).

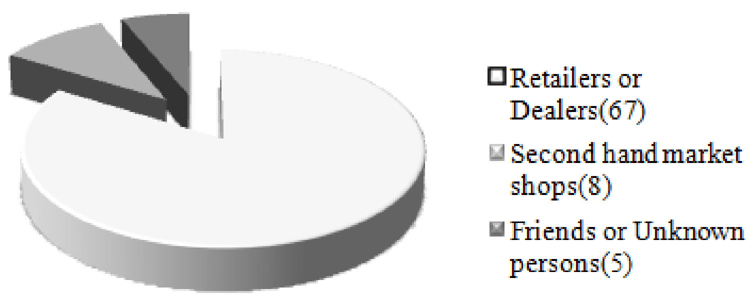

Fig. 3.8: Consumer preference for remanufactured products

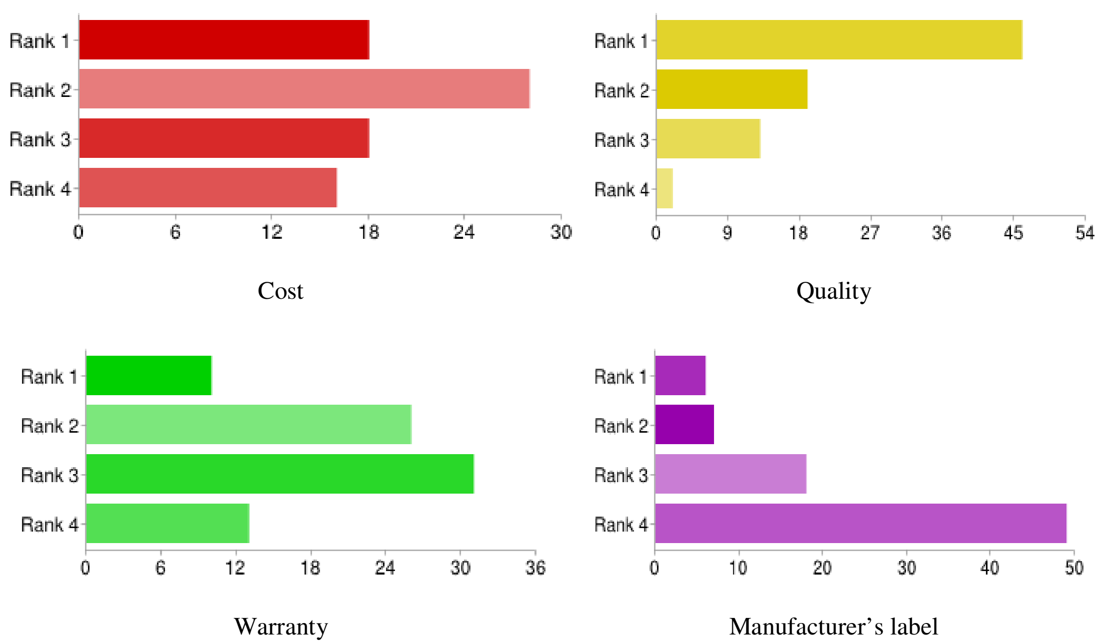

Fig. 3.9: Ranking of attributes for a remanufactured product

As observed from Fig. 3.8, the respondents prefer to purchase remanufactured or new-like products specifically if the manufacturer through his dealer/retailer gets involved in the remanufacturing business. This confirms the finding of our simulation effort. Furthermore, as is evident from Fig. 3.9, majority of the respondents have indicated quality and cost as the deciding factors in the purchase of a remanufactured product followed by warranty and label.

Surprisingly, in contrast to remanufactured products, the attributes the respondents look for in a generic reusable product are in the decreasing order of quality, warranty and cost. So, reusable e-products in the secondary market like second-hand shops can be competitively positioned by offering warranty to the consumers.

3.7 Conceptual EPR System Architecture

The concept of a reuse based EPR framework for the management of e-waste in India, as observed from our study seems more promising given the current Indian conditions. However, the implementation of such a strategy will remain a challenge considering the number of stakeholders involved. The primary concern is the integration of scrap dealers and scrap collectors into any formalized take-back scheme offered by the manufacturers. The major operational factor for the success of reuse business in India is customer service requirement. Here the consumer as observed from the study is principally concerned about the quality standards of the product. Therefore, the demand for remanufactured products which guarantees repeatable and consistent quality levels equivalent to virgin products is evidently high. For instance, the Japanese manufacturer Fujitsu has been successful in creating a demand for remanufactured PCs in India. With 20 major Japanese reuse companies operating, the flow of reused computers from 2001 to 2004 increased dramatically by a whopping 2.59 million units, majority of which exported to India and China (Yoshida et al., 2007). Yet another estimate (Akenji et al., 2011) states that Japan in 2006 exported 30% of all home appliances to developing countries. In US alone, remanufacturing business in the year 2001 peaked to an astonishing $100 billion (Loomba and Nakashima, 2012). Similarly appropriate systems for effective supply management along with the different EOL processing activities have to be developed. High level recovery for reuse (Zoeteman et al., 2010) which is possible through remanufacturing in the original supply chain, not in another alternate supply chain is yet another factor which affects consumer preferences for reused e-products.

The decision to refurbish or to recycle will depend on the cost/benefit ratio of refurbishing. This decision requires knowledge of incoming EOL product quality parameters such as its age, functional condition, physical condition, functional age, remaining useful life etc which can be estimated if there is adequate product information (Parlikad and McFarlane, 2005). The current legislation of e-waste handling rules in India enforces manufacturers to adopt EPR with effect from May, 2012. This regulatory pressure will motivate companies to implement projects faster (Subramoniam et al., 2010). The proposed EPR system should take financial measures for collecting and treating “orphans,” including products assembled by small-scale industries, imitation products, and smuggled products since they are considered to be the most important precondition for applying EPR policies in developing countries (Kojima et al., 2009). In other words, identification of the producer is the major detriment in the implementation of EPR in India. This is a burden which has to be equally shouldered by all the identified producers.

Recycling and reuse targets, though not part of the current Indian legislation, are vitally essential for any EPR scheme to succeed. Currently, India has a license scheme for formal recyclers, and for it to be effective, the disposers have a responsibility to sell to license holders (Shinkuma and Managi, 2010). This means recycling as well as reuse targets are vitally essential in the near future. Hammond and Beullens (2007) prove that even a token legislation that all new products must be recoverable at some minimum target can be sufficient in creating reuse and recycling activities within closed loop supply chains. They also further emphasize that legislating collection targets instead of recoverable targets are detrimental since manufacturers might choose their own devices like preferring recycling over reuse. Some authors (Manomaivibool, 2009) argue that a national mandatory programme that at least puts collection responsibility on the producers will scale up the incentive for formalization in India. This being already there in the current legislation, what is lacking is some form of recoverable target.

With licenses and targets comes the responsibility of compliance monitoring and the capacity to enforce regulations at all levels. Formal reuse activity necessitates accreditation of refurbishers and incentives in the form of subsidy. Kojima et al. (2009) cautions that, any future subsidy to formal collectors and recyclers might create incentives to over-report the amount of collected e-waste. Additionally, incentives need to be disbursed for selling these collected units to the second hand market. So, appropriate monitoring mechanisms are to be in place for proper checks and balances.

Amongst the strategic factors (see Fig. 3.10), commitment of management resource is critical to the success of reuse business followed by the choice of take-back scheme. The total collection and logistics expenses incurred in the collection of WEEE were almost 22.5% of the total Advance Recycling Fee (ARF) received in Switzerland (Bandyopadhyay, 2010). So, by having common collection points, the Producer Responsibility Organizations (PROs) are better able to manage logistics, benefit from economies of scale and provide a consumer friendly, all-inclusive solution instead of a prohibitively expensive brand specific take-back scheme. Some argue that in a collective take back scheme (Webster and Mitra, 2007), products from different manufacturers gets co-mingled, the outcome of which is recycling tends to dominate instead of reuse.

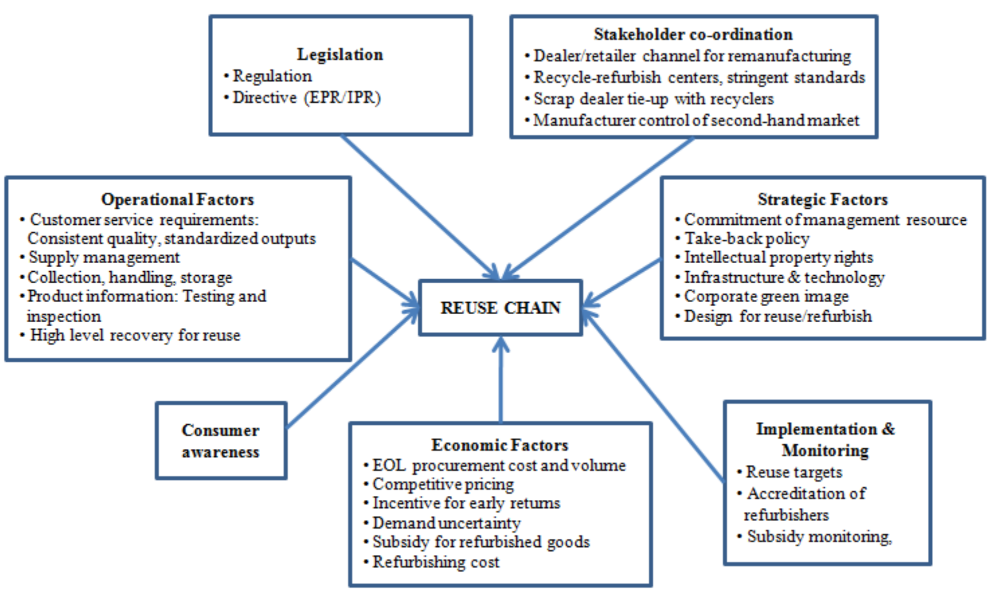

Fig. 3.10: Critical factors affecting reuse chain

However, the current EU WEEE legislation following the lobbying of several leading manufacturers (McKerlie et al., 2006), stipulates individual responsibility for all new products launched from August 2005 onwards. The legislation allows no visible fees to fund the management of waste resulting from new electrical and electronic products. The reasoning was that individual responsibility offers the best feedback for design change and provides the highest incentive for Design for Environment (DfE). Further, it also allows the companies a competitive choice in the marketplace for recyclers and the freedom to form a collective group outside the national PROs. Forslind (2009) reports that EPR finances are more efficiently managed when the producers develop an insurance fund to finance future waste generation quantities as against creating funds to manage the immediate waste generation quantiles.

In a survey carried out by (Subramoniam et al., 2010), majority of the respondents supported positively the need to protect the intellectual property (IP) rights of their product thereby influencing their decisions to remanufacture. The same authors further argue that design for remanufacturing is a strategic factor affecting remanufacturing which ensures the need for better product design guidelines and engagement of product designers as well as the company leaders in the product design process. Our study clearly proves the positive impact of retailer involvement in the reuse chain. This is corroborated by Hong and Yeh (2012) who analytically proved that a retailer collection model which captures the reality that electronics manufacturers of consumer products typically are not remanufacturers outperforms the non-retailer collection model (where the retailer may sub-contract the EOL processing activity to a PRO) for the return rate, manufacturer's profits and total profits of the system.

Amongst the economic factors, refurbish/remanufacturing cost is the major factor affecting the decision making process (Chen and Chang, 2012) for firms trying to compete with secondary markets in selling refurbished/remanufactured products, in addition to manufacturing new products. They further state that so long as the manufacturer is able to remanufacture at lower rates than the secondary market, remanufacturing will not affect sales of new products. For the second scenario, it is profitable to focus only on manufacturing new products as competition to remanufactured products from the secondary market. However, our study reports that in the EPR regime, products that are with the second hand dealers are first to be absorbed to the recycling state. Experiences from Taiwan (Lua et al., 2006) clearly indicate that that the prices offered by the second hand market are much higher than the collection subsidy offered by the Taiwan WEEE system. This means that any form of recycling fund needs to dynamically evolve so as to create a level playing field and subsidize the formalized processes. Therefore the second hand market necessitates monitoring and control from the manufacturer. Additionally, the pollution control boards have to strengthen pollution control measures against the downstream informal processes that exist in India.

With EPR becoming a policy instrument in India, the possibility of increased returns through the dealer/retailer channel is forthcoming. Michaud and Llerena (2006) and Subramoniam et al., (2010) emphasize that when an OEM collects and successfully remanufactures its own products, a high willingness to return the products by the consumer can be expected.

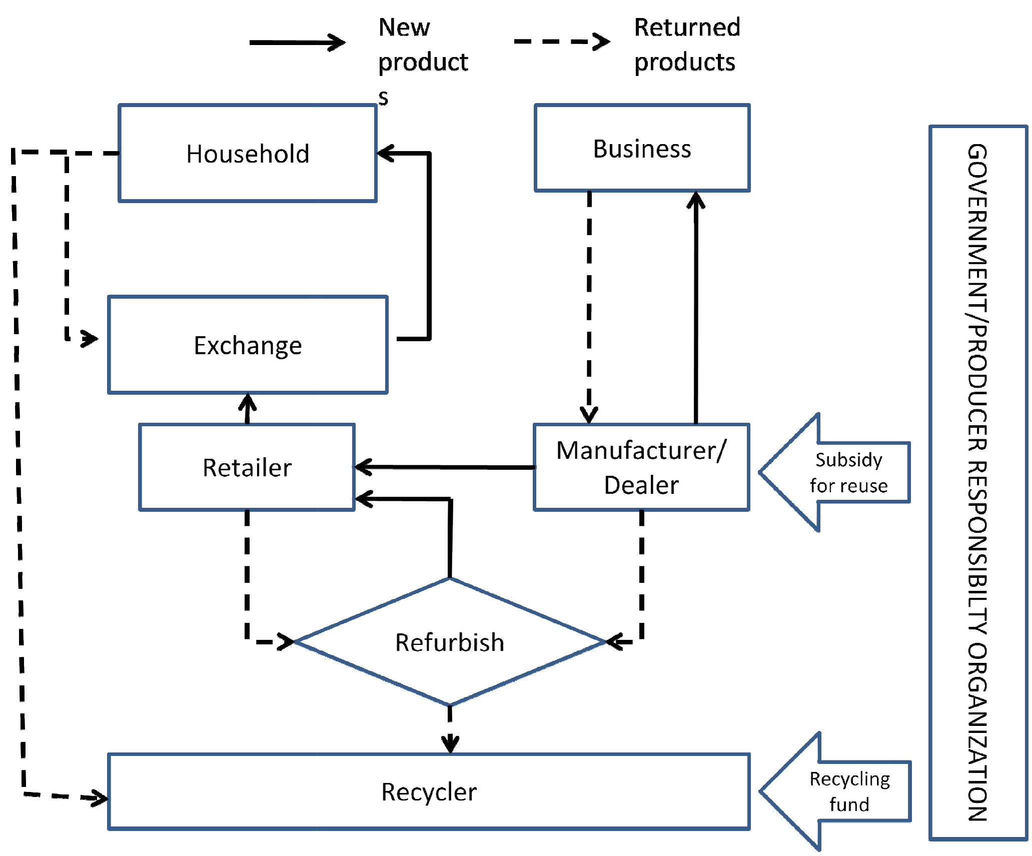

Fig. 3.11: EPR system architecture

The manufacturer in an EPR regime (with recoverable targets) and having absolute possession over the cores can control the profits of the remanufacturer through competitive pricing so that the sales of new products are not hampered (Webster and Mitra, 2007). The lifetime of products used by first users primarily governs the level of material use of a system (Tasaki et al., 2006) in case that second-hand product demand is ‘‘suppliable’’ and constant. Hence, incentives for early returns are vital for the success of reuse business. The respective stakeholder’s co-ordination is critical to reuse business. Currently, the business sector is the major source of returned products to the existing formal recyclers in India. For instance, Nokia India has recently set-up about 1,400 collection points for its customers. The formal recycling sector in India should explore ways and means to integrate with the other two stakeholders: scrap dealers and second hand market for an uninterrupted supply of WEEE. The recyclers as our study suggest should additionally also involve in refurbishing. In contrast, formal scrap dealers should be banned from refurbishing, engaging them to collection alone. All refurbished units from recycler are best served by selling to second hand market while all units collected by scrap dealer must route to the recycler. These supply dynamics are in addition to the dealer take-back. Furthermore, the business sector in India should be given economic incentives through appropriate disposal subsidy for prematurely reselling their quality WEEE inventory for refurbish/reuse.

The results from our simulation effort interestingly show high values of the number of lives of a computer (8-10) in the reuse chain that currently exists in India. For instance, the ‘Mean Time between Failures’ (MTBF) for an IBM z-series server is designed to be around 50 years (Parlikad and McFarlane, 2005), whereas on average it is returned by the customer in 5-10 years. Evidently, e-waste reuse business in India can become a multiple revenue stream generation model. $Fig.$ 3.11 shows the conceptual framework and the system architecture for the adoption of EPR principles in the context of India. Accordingly, a recycling fund is created either directly by the government or by a conglomeration of producers called as Producer Responsibility Organization (PRO) in order to finance the recycling of returned products. The consumers are expected to pay recycling fees at the time of purchase of the product, which could be either visible or invisible. The manufacturers could collect the returned products either individually or collectively. Reuse through refurbish or remanufacturing activities are encouraged through appropriate subsidy mechanism. The fundamental assumption which was made for the success of this conceptual framework at the strategic level is the existence of nationwide legislation with mandated recycling and reuse targets. Furthermore, compliance, monitoring and book keeping are tactical objectives which are to be enforced either by the government or the PRO.

3.8 Conclusion

While this study emphasize that domestic generation of WEEE in developing country is rising rapidly, corresponding growth in recycling infrastructure whether formal or informal are far from evident. It can be argued that the secondary EEE market in the developing world is robust and growing. In India, recovering and refurbishing EEE products are a source of income and livelihood to thousands of people. The primary concern among policymakers is the fear that the current EPR system would lead to collapse of the secondary market. A WEEE program devised just to collect and recycle will be of limited objective. On the economic side, the high lifecycle cost of recycling WEEE and the ensuing environmental pressure from the recycling residue justifies reuse prior to recycling. Sustained mass flow of used e-products to refurbish/reuse business sector is central for competing with new products. Apart from the requirement of a well organized take-back strategy, appropriate measures for refurbishment as well as quality assurance are other concerns of this business. The entire reverse logistic focus for collecting WEEE should be reorganized so that not only the defective units reach the recycler, but also quality used products which could be further refurbished. Illegal imports of WEEE have the potential to undermine future EPR legislation. Illegal imports together with the informal downstream processes are existing market anomalies that needs to be addressed since they represent major dysfunctions of the current EPR legislation.

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Chapter 4

Modeling and Analysis of WEEE Take-Back Schemes in India

4.1 Introduction

In the developed world, e-waste take back legislation through directives are implemented under the guiding principle of Extended Producer Responsibility (EPR). The EPR concept holds manufacturers responsible for the collection and environment friendly disposal of products at the end of their useful life. Take back policy that invokes EPR principle mandates the manufacturers to develop adequate systems for the collection and environmentally safe treatment of such products. The long term goal of EPR (Nnorom and Osibanjo, 2008) was to improve product reusability and recyclability, reducing material usage, downsizing products, and incorporating Design for Environment (DfE) principles in the product design process to significantly reduce the life cycle environmental impact of products put into the market. Take back legislation in developed economies (Atasu et al., 2009) principally follow either of the two approaches: consumer pay and producer pay. The Japanese and the Californian state in particular have chosen the consumer pay principle, where the end-user is overtly charged for the safe treatment of used products. Contrarily, several European countries favor the producer pay principle which holds the manufacturer responsible for the environment friendly treatment of used products.

Several policies have been implemented to address the critical issue of e-waste management, particularly e-waste recycling. The European Union (EU) framed two recent policies. The WEEE (Waste Electrical and Electronics Equipment) directive (Directive 2002/96/EC, 2003) transfers the burden of recycling to manufacturers by requiring them to take back and recycle waste electrical and electronic equipment. Another EU initiative, the RoHS (Restriction of Hazardous Substances) directive (Directive 2002/95/EC), restricts the use of certain hazardous materials in electrical and electronic equipment. Yet another initiative, the Basel Convention (Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal, 1989), legally banned the export of hazardous waste and their disposal from developed countries to developing countries. The WEEE directive clearly imposes collection, recovery and recycling targets on its member countries. The WEEE directive stipulates a minimum collection target of 4 kg/capita per year free of charge from the consumers for all the member states. These collection and recycling threshold targets seeks to reduce the amount of hazardous substances disposed to the landfills together with the increase in the availability of recyclable materials which indirectly encourages less virgin material consumption in new products. Netherland was the first member state to fully implement these directives through their own national legislation. Alongside these mandated product take back, there also exists voluntary take back strategy (Widmer et al., 2005) which is generally the case observed in developing countries like China and India. Here, there are no laws that mandate compliance and therefore no penalties for not meeting the EPR goals. Increased public awareness and governments' attention to the problems emanating from e-waste have prompted few manufacturers from developing countries to establish individual take-back schemes for specific products as a part of their corporate social responsibility and green image.

Take back policy requires financial instruments in the form of disposal (or recovery) fees either at the time of disposal or at the time of purchase (advance recycling fees or advance disposal fees). For instance, the Japanese model argues for both the approaches: advance fees for computers while fees at the point of disposal for home appliances. The Californian and the Taiwanese model on the other hand favors the advance recycling fees invariably for all the products, which typically are used to fund the state controlled recycling system (Lee et al., 2010; Atasu and Van Wassenhove, 2012). Understandably, advance disposal or recovery fees have the advantage of being visible to all the stakeholders which influences better and reasonable future planning at the downstream end. Additionally, fees charged at the point of disposal might lead to an indifferent disposer who in all likelihood may be tempted to illegally dump the used products or perpetually store them. Contrarily, the European WEEE directives are implemented through the manufacturer operated take back systems (Dempsey et al., 2010; Atasu and Van Wassenhove., 2012).

A major issue for planners in the implementation of any form of EPR is in deciding which type of producer responsibility is optimal for the producers: individual or collective. From the long term perspective of EPR, the producers favoring the individual take-back, ideally will attempt to internalize the recycling cost into the product price, which could provide the required incentive for producers to adopt better product design features to facilitate better recovery, recycling and avoid the inclusion of hazardous substances in the manufacturing stage. A good number of producers engage in collective systems to take advantage of the economies of scale and reduce costs. Such an arrangement while allows producers to delegate most take-back-related activities to third-party treatment providers, leave them with very little scope and incentive to make substantive future investments to address the long term objectives of EPR. The argument over the cost efficiency of the two schemes remains debatable and inconclusive till date. Producers that favor individual scheme, argue that it is an ideal platform for producers to invest in environment friendly products which in the long run will reap economic benefits from reduced recovery costs. In stark contrast, certain industrial alliances and some national collective systems (Atasu and Subramanian, 2012) in countries such as Sweden, Netherlands, Belgium and Norway have supported collective take back scheme based on the argument that a collective system is the simplest and most cost-effective way to collect and recycle e-waste.

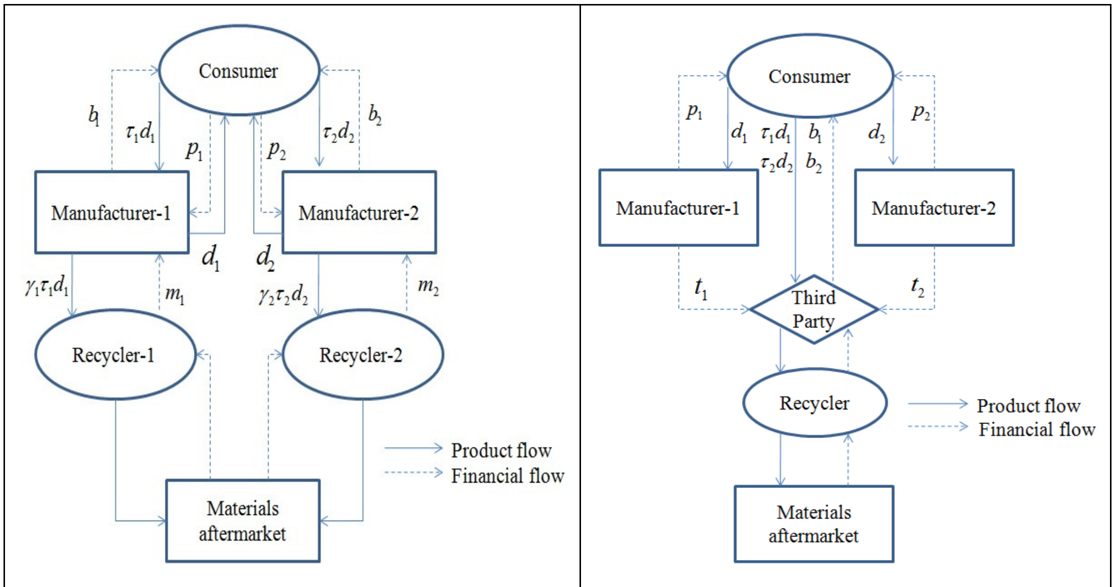
The recent e-waste guidelines issued by the MoEF, Government of India forms the benchmark through which producers need to develop appropriate take-back schemes for their products. The proposed “e-waste (Management and Handling) Rules, 2010” clearly stipulates the producer responsibility for the proper collection of e-waste through appropriate take-back system on the same lines as the European EPR directive. The producers, as per the new guidelines, are expected to voluntarily set up collection centers/ take back system either individually or collectively. Currently in India, there is an established informal sector which collects e-waste. To avoid this, producers need to explore appropriate take-back schemes so that e-waste goes to the right channel. Customers need to be given incentives to return their end-of-life (EOL) e-products back to the collection centers. This could be done by enforcing a buy-back policy. Once a product reaches the end of its useful life, the producers would buy it back from the consumers at a price higher than that of the informal sector, thereby cutting off the supply to this sector and ensuring that e-waste goes to the right channel. This added cost for the manufacturer would be offset by increasing the selling price of new products.

By take-back schemes, the study refers to collection decisions while most literature in this area (Toyasaki et al., 2009) use an integrated approach between the manufacturer and the recycler to develop a framework for analyzing and optimizing take back schemes. Since no laws exist which mandate the responsibility for the collection and recycling of the end-of-life products in India, it is too early to speculate the extended bargaining role of recyclers in the current framework. The manufacturers though not mandated, need to or at least seem to evolve a take-back policy as expected from the latest draft guidelines. Bereft of collection and recycling targets, it becomes imperative to identify the right take back policy from the manufacturers' point of view. Juxtaposing the experiences from the developed world will not suffice given that there exist serious shortcomings in the existing regulatory framework, and also the price sensitive Indian consumer not overtly willing to pay for recycling the e-waste.

The purpose of this study is to report on research undertaken to model and investigate whether the current end-of-life product take back theories and practices can be applied to developing countries like India. To this effect, the study investigates and build upon the existing baseline European take back schemes for waste electrical and electronic equipment (WEEE) recycling: Individual and Collective take-back scheme. This is done to achieve and complement the newly set producer responsibility laws in India.

4.2 Mathematical Model

In this section, the framework used to represent the industrial structure, the modeling assumptions and the profit function of the manufacturer are formulated. Firstly, for the sake of ease of analysis, the two-manufacturer case was investigated. Our primary objective is to analyze the profit function of the manufacturer vis-à-vis the choice of the take-back scheme: individual or collective take-back. The model further allows us to investigate competition amongst manufacturers. Fig. 4.1 shows the schematic representation of both take-back schemes. In both cases, it was assumed that the manufacturers compete against each other through the market positioning of their new product prices. In the case of the individual take-back scheme, the manufacturer is by choice interested in institutionalizing collection networks for sourcing end-of-life (EOL) returns and allocating the same to the recyclers. The competition amongst recyclers is by nature an indirect one, which in our case is through the manufacturers.



(a) Individual take back scheme | (b) Collective take back scheme

Fig. 4.1: Schematic representation of two take back schemes

On the other hand, in the case of the collective take-back scheme as in where a consortium of manufacturers sub-contract their WEEE collection activity to a third party such as a Producer Responsibility Organization (PRO) or a retailer (who sells products of both manufacturer's), which in turn is responsible for collecting WEEE from the consumers and selling the same to contracted recyclers. In either of the cases, the manufacturers compete in the market through appropriate positioning of their original product prices. This will allow us to examine the performance measures: the manufacturer's profit and the new product selling price; since the manufacturer has the flexibility to opt either for an individual take-back or a collective take-back scheme. Henceforth, using the superscript s to denote the take back scheme where $s = i$ for individual take back scheme and $s = c$ for collective take back scheme. We use the subscript j, $j = 1,2$ to denote the two manufacturers. The selling price of new product for manufacturer j in the scheme s will be denoted by p_j^s. The demand model that was used is a linear model having substitution effects (Toyasaki et al., 2011). The demand (d) of manufacturer j can be stated as

$$d_j(p_1^s, p_2^s) = \alpha_j - p_j^s + \beta p_{3-j}^s, \quad j = 1,2; \quad s = i, c \qquad (1)$$

where, α_j is the market share of manufacturer j and β is the cross elasticity of demand. It was also assumed that the products sold by competing manufacturers are comparable substitutes, so $\beta > 0$, and that the concerned manufacturer's own-price effect will be stronger than the cross-price effect, implying $\beta < 1$. Only EOL reverse flows of products for potential recycling have been considered here. The fraction of total products of manufacturer j collected at the end of the period is denoted by τ_j, $j = 1,2$ and $0 < \tau_j \leq 1$. The buyback price in both the schemes is denoted as b. In the case of collective take-back, the manufacturer pays a certain fee (t) per collected unit to the third party contracted for EOL product collection, which can be expressed as a certain fraction over the buy-back rate $t = \frac{b}{v}, 0 < v < 1$. In both the schemes, the buy-back price is taken to be a certain fraction (k) of the selling price of a new product which results in $b = kp$, $0 < k < 1$. For the ease of comparison, the unit cost of production for each manufacturer is assumed to be c in both the schemes. Note that this c is different from the superscript c. In the collective scheme, letting m_j denote the cost per unit the recycler pays to obtain the collected items from the manufacturer j. Note that unlike Europe, in India the recycler would buy the collected items. Here, the recycler is assumed to buy a certain fraction (γ) of the collected items from the manufacturer and $0 < \gamma \leq 1$. Additionally, the government sets a penalty that the manufacturer would have to incur in case they do not meet the set collection target. Thus, this penalty will be some function (say f) of the collection rate, τ_j which is subtracted from the profit function of manufacturer j. Since the penalty is designed to decrease with the increase in collection, f is assumed to be a decreasing function in τ_j.

Manufacturer $j's$ optimization problem for the individual take-back scheme can be expressed as

$$max_{p_j}\, \pi_j^i = (\alpha - p_j + \beta p_{3-j})(p_j - c) - b_j\tau_j(\alpha - p_j + \beta p_{3-j}) + \gamma m_j \tau_j(\alpha - p_j + \beta p_{3-j}) - f(\tau_j) \tag{2}$$

Equation (2) gives the j^{th} manufacturer's profit function resulting from selling new products at unit selling price (p_j) less the unit production cost (c), cost incurred in the collection of used products from the consumers, the revenue earned from selling collected EOL products to the recycler and the associated penalties resulting from not fulfilling the mandated collection targets. Introducing $b_j = kp_j$ into the manufacturer $1's$ profit function results in:

$$\pi_1^i = (\alpha - p_1 + \beta p_2)(p_1 - c - \tau_1 k p_1 + \tau_1 \gamma m_1) - f(\tau_1) \quad (3)$$

For the collective take-back scheme (superscript c), manufacturer $j's$ optimization problem is analogous to the individual scheme except that the manufacturer does not physically transact any EOL collection or management cost, while contracting the same to a PRO for a unit price of t_j resulting in

$$\pi_j^c = \left(\alpha - p_j + \beta p_{3-j}\right)\left(p_j - c\right) - \tau_j t_j \left(\alpha - p_j + \beta p_{3-j}\right) - f(\tau_j) \quad (4)$$

$Eq.(4)$ gives the j^{th} manufacturer's profit function resulting from selling new products at unit selling price (p_j) less the unit production cost (c), cost borne by the manufacturer which is paid to the PRO with whom the manufacturer has an exclusive contract for the collection and disposal of products put into the market by him and the associated penalties resulting from not fulfilling the mandated collection targets. Introducing $b_j = kp_j$ and $t_j = b_j/v$ into manufacturer $1's$ profit function, where the unit collection and disposal cost (t_j) paid by the manufacturer to the PRO is a fraction of the price paid that he would have paid to the consumer in the individual scheme, and can be expressed as:

$$\pi_1^c = (\alpha - p_1 + \beta p_2)\left(p_1(1 - \tfrac{k\tau_1}{v}) - c\right) - f(\tau_1) \quad (5)$$

Here, the PRO is responsible for collecting used products from the consumer, while the inability to meet the collection targets is penalized to the manufacturer.

4.2.1 Equilibrium prices

In this section, the reaction functions of the manufacturers for both the take-back schemes are derived and the Nash equilibrium prices computed from the derived profit functions. For the individual take back scheme, the reaction functions are derived by differentiating Eq. (3).

$$\frac{\partial \pi_1^i}{\partial p_1} = (\alpha - p_1 + \beta p_2)(1 - k\tau_1) - (p_1(1 - k\tau_1) - c + \tau_1 \gamma m_1) - f(\tau_1) = 0 \quad (6)$$

Solving Eq. (6) results in $2p_1 = \alpha + \beta p_2 + \frac{c - \tau_1 \gamma m_1}{1 - k\tau_1}$ which gives the reaction function of manufacturer 1 as,

$$p_1^{i*}(p_2) = 1/2\left[\alpha + \beta p_2 + \frac{c - \tau_1 \gamma m_1}{1 - k\tau_1}\right] \quad (7)$$

$Eq.(7)$ states that for a given manufacturer 2's price (p_2^i), the manufacturer 1 reacts by selecting price $p_1^{i*}(p_2)$.

Similarly, setting ${\partial \pi_2^i}/{\partial p_2} = 0$ the reaction function of manufacturer 2 was found to be,

$$p_2^{i*}(p_1) = 1/2\left[\alpha + \beta p_1 + \frac{c-\tau_2\gamma m_2}{1-k\tau_2}\right] \tag{8}$$

Solving these expressions simultaneously for Nash equilibrium, the optimal prices are found to be $2p_1^{i*} = (\alpha + \frac{c-\tau_1\gamma m_1}{1-k\tau_1}) + \frac{\beta}{2}(\alpha + \beta p_1 + \frac{c-\tau_2\gamma m_2}{1-k\tau_2})$ which on further simplification results in,

$$p_1^{i*} = \left[(2+\beta)\alpha + 2\left(\frac{c-\tau_1\gamma m_1}{1-k\tau_1}\right) + \beta\left(\frac{c-\tau_2\gamma m_2}{1-k\tau_2}\right)\right]\frac{1}{(4-\beta^2)} \tag{9}$$

and,
$$p_2^{i*} = \left[(2+\beta)\alpha + 2\left(\frac{c-\tau_2\gamma m_2}{1-k\tau_2}\right) + \beta\left(\frac{c-\tau_1\gamma m_1}{1-k\tau_1}\right)\right]\frac{1}{(4-\beta^2)} \tag{10}$$

For collective take-back scheme, the reaction functions are derived in the same way from $\frac{\partial \pi_1^c}{\partial p_1} = (\alpha - p_1 + \beta p_2)\left(1 - \frac{k\tau_1}{v}\right) - \left(p_1(1 - \frac{k\tau_1}{v}) - c + \tau_1\gamma m_1\right) = 0$, and ${\partial \pi_2^c}/{\partial p_2} = 0$

which on solving gives the reaction functions of manufacturer-1 and -2 as

$$p_1^{c*}(p_2) = {}^1\!/_2\left[\alpha + \beta p_2 + \frac{c}{1-\frac{k\tau_1}{v}}\right] \tag{11}$$

$$p_2^{c*}(p_1) = {}^1\!/_2\left[\alpha + \beta p_1\frac{k\tau_1}{v} + \frac{c}{1-\frac{k\tau_2}{v}}\right] \tag{12}$$

Solving these optimal prices simultaneously for Nash equilibrium results in $2p_1^* = (\alpha + \frac{c}{1-\frac{k\tau_1}{v}}) + \frac{\beta}{2}(\alpha + \beta p_1 + \frac{c}{1-\frac{k\tau_2}{v}})$ which on simplifying gives

$$p_1^{c*} = \left[(2+\beta)\alpha + \frac{2c}{1-\frac{k\tau_1}{v}} + \frac{\beta c}{1-\frac{k\tau_2}{v}}\right]\frac{1}{(4-\beta^2)} \tag{13}$$

and
$$p_2^{c*} = \left[(2+\beta)\alpha + \frac{2c}{1-\frac{k\tau_2}{v}} + \frac{\beta c}{1-\frac{k\tau_1}{v}}\right]\frac{1}{(4-\beta^2)} \tag{14}$$

4.3 Analysis

Next an attempt is made to study how the equilibrium price and the manufacturer profit vary with respect to variation in the different variables, for both the schemes. Since our principal motivation is to compare the two schemes, it can be assumed that the market share of both the manufacturer's is the same. i.e. $\alpha_1 = \alpha_2 = \alpha$. It was also assumed that all EOL products collected, in both schemes, are given to recycler i.e. $\gamma = 1$. The sensitivity analysis is carried out wherever it was analytically tractable, and the rest were conducted numerically, by observing the following guidelines:

$A1$: $c > m_1, m_2$ holds always, indicating that the collection cost (m_j) is always a fraction of the unit production cost, c.

$A2$: $c - \gamma m_j \geq 0$ and $c - \gamma m_j \tau_j > 0$ follows from $0 < \gamma \leq 1$, $0 < \tau \leq 1$ and $A1$.

$A3$: The sign of $ck - \gamma m_j$ varies with the choice of k.

$A4$: $1 - \tau_j k > 0$ holds true always since $0 < \tau_j \leq 1$ and $0 < k < 1$.

$A5$: The expressions $4 - \beta^2 > 0$ and $1 - \beta > 0$ are always true since $0 < \beta < 1$.

$A6$: For the purpose of numerical simulation, the values of the variables were choosen to be $\alpha = 65000$ (fixed), $c = 60000$ (fixed), $0.2 \leq \beta \leq 0.8$, $\gamma = 1$, $0.05 \leq k \leq 0.2$, $0.8 \leq v \leq 0.95$, $8000 \leq (m_1, m_2) \leq 12000$, $0.2 \leq (\tau_1, \tau_2) \leq 0.6$.

$A7$: $1 - \frac{k\tau_j}{v} > 0$ as from $v > k$, so $\frac{k}{v} < 1$. Given that $\tau_j < 1$, which translate to $\frac{k\tau_j}{v} < 1$. Therefore, $1 - \frac{k\tau_j}{v} > 0$

4.3.1 Sensitivity analysis

To investigate as to how key operating variables and market conditions affect product prices and manufacturer profits under the two take-back schemes, the sensitivity of the investigated parameters towards the equilibrium prices and profits are derived analytically in Table 4.1. Here, the sign '+' and '−' represents increase and decrease in the equilibrium, given a respectively marginal increase in the parameters. For those parameters which are not tractable analytically, their sensitivity were found numerically.

The table below shows the partial derivatives of the manufacturer 1's equilibrium prices and profits with respect to different parameters. In computing the derivatives, it is noted that $0 \leq \beta \leq 1$ from $(A1)$ and $(A2)$. Also it is reasonable to assume that the term, $c - m_j\tau_j > 0$ from $(A3)$.

The following derivatives are analytically computed for the individual take-back scheme:

Table 4.1: Partial derivatives

Par	Individual take-back scheme		Collective take-back scheme		Difference (individual-collective)	
	Price	Profit	Price	Profit	Price	Profit
$\boldsymbol{\alpha}$	+	+	+	+	0	+
$\boldsymbol{\beta}$	+	+	+	+	−	+
$\boldsymbol{c}$	+	−	+	−	−	−
$\boldsymbol{\tau_1}$	−	+	+	−	−	+
$\boldsymbol{\tau_2}$	−	−	+	+	−	−
$\boldsymbol{v}$	NA	NA	−	+	NA	NA
$\boldsymbol{k}$	+	−	+	−	+	+
$\boldsymbol{m_1}$	−	+	NA	NA	NA	NA
$\boldsymbol{m_2}$	−	+	NA	NA	NA	NA
$\boldsymbol{\gamma}$	−	+	NA	NA	NA	NA

Proof:

A: ***For Individual take-back scheme***

$$\frac{\partial p_1^{*i}}{\partial \alpha} = \frac{1}{2-\beta} > 0 \; (A5)$$

$$\frac{\partial p_1^{*i}}{\partial \beta} = \frac{1}{(4-\beta^2)^2}\left[(4-\beta^2)\left(\alpha + \frac{c-\gamma m_2\tau_2}{1-\tau_2 k}\right) + 2\beta\left(\frac{2(c-\gamma m_1\tau_1)}{1-\tau_1 k} + \alpha(2+\beta) + \frac{\beta(c-\gamma m_2\tau_2)}{1-\tau_2 k}\right)\right] > 0 \; (A2;\ A4)$$

$$\frac{\partial p_1^{*i}}{\partial c} = \frac{1}{4-\beta^2}\left(\frac{2}{1-\tau_1 k} + \frac{\beta}{1-\tau_2 k}\right) > 0 \; (A4;\ A5)$$

$$\frac{\partial p_1^{*i}}{\partial \tau_1} = \frac{2(ck-\gamma m_1)}{(4-\beta)^2(1-\tau_1 k)^2}$$

$$\frac{\partial p_1^{*i}}{\partial \tau_2} = \frac{\beta(ck - \gamma m_2)}{(4-\beta)^2(1-\tau_2 k)^2}$$

$$\frac{\partial p_1^{*i}}{\partial k} = \frac{1}{(4-\beta^2)}\left[\frac{2\tau_1(c-\gamma m_1\tau_1)}{(1-\tau_1 k)^2} + \frac{\beta\tau_2(c-\gamma m_2\tau_2)}{(1-\tau_2 k)^2}\right] > 0 \ (A2;\ A4;\ A5)$$

$$\frac{\partial p_1^{*i}}{\partial \gamma} = \frac{-1}{(4-\beta^2)}\left[\frac{2\tau_1 m_1}{(1-\tau_1 k)} + \frac{\beta\tau_2 m_2}{(1-\tau_2 k)}\right] < 0 \ (A4;\ A5)$$

$$\frac{\partial p_1^{*i}}{\partial m_1} = \frac{-1}{(4-\beta^2)}\left[\frac{2\tau_1\gamma}{(1-\tau_1 k)}\right] < 0 \ \ (A4;\ A5)$$

$$\frac{\partial p_1^{*i}}{\partial m_2} = \frac{-1}{(4-\beta^2)}\left[\frac{\beta\tau_2\gamma}{(1-\tau_2 k)}\right] < 0 \ \ (A4;\ A5)$$

B: ***For Collective take-back scheme***

$$\frac{\partial p_1^{*c}}{\partial \alpha} = \frac{1}{2-\beta} > 0 \ (A5)$$

$$\frac{\partial p_1^{*c}}{\partial \beta} = \frac{1}{(4-\beta^2)^2}\left[(4-\beta^2)\left\{\alpha + \frac{c}{1-{k\tau_2}/{v}}\right\} + 2\beta\left\{(2+\beta)\alpha + \frac{2c}{1-{k\tau_1}/{v}} + \frac{\beta c}{1-{k\tau_2}/{v}}\right\}\right] > 0 \ (A5;\ A7)$$

$$\frac{\partial p_1^{*c}}{\partial c} = \frac{1}{(4-\beta^2)}\left[\frac{2}{1-{k\tau_1}/{v}} + \frac{\beta}{1-{k\tau_2}/{v}}\right] > 0 \ (A5;\ A7)$$

$$\frac{\partial p_1^{*c}}{\partial \tau_1} = \frac{2c}{(4-\beta^2)(1-{k\tau_1}/{v})^2}\left(\frac{k}{v}\right) > 0 \ (A5;\ A7)$$

$$\frac{\partial p_1^{*c}}{\partial \tau_2} = \frac{\beta c}{(4-\beta^2)\left(1-{k\tau_2}/{v}\right)^2}\left(\frac{k}{v}\right) > 0 \ (A5;\ A7)$$

$$\frac{\partial p_1^{*c}}{\partial v} = \frac{-ck}{(4-\beta^2)v^2}\left\{\frac{2\tau_1}{(1-{k\tau_1}/{v})^2} + \frac{\beta\tau_2}{(1-{k\tau_2}/{v})^2}\right\} < 0 \ (A5;\ A7)$$

$$\frac{\partial p_1^{*c}}{\partial k} = \frac{c}{(4-\beta^2)v}\left\{\frac{2\tau_1}{(1-{k\tau_1}/{v})^2} + \frac{\beta\tau_2}{(1-{k\tau_2}/{v})^2}\right\} > 0 \ (A5;\ A7)$$

It is pretty clear that any increase in the market size α shifts the demand upwards, which allows the manufacturers to increase prices and recover more profits invariably in both the schemes. Intuitively, it can be established that with the increase in production cost, the equilibrium prices will increase while the equilibrium profit shall decrease. Similarly, when the degree of substitutability factor β for products increases, the demand curve shifts up, allowing the manufacturers to charge higher prices and therefore generating more profits. The effect of the collection rate for the case of individual collection scheme cannot be ascertained analytically, but have to be confirmed numerically.

4.3.2 Sensitivity analysis results

The sensitive analysis discussed in previous section were simulated through numerical experiments. The data used in our numerical experiments have been obtained from the investigation carried out by Toyasaki et al., (2011). In all the cases that are investigated numerically, each parameter in question was varied within their prescribed range while keeping the others fixed at their baseline values given in $A6$. Therefore, for the case when $k \geq m_1\gamma/c$, as the collection rate (τ_1) increases, the equilibrium price (p_1^*) offered by manufacturer-1 will increase in the individual collection scheme, and the same trend can be consistently observed for the assumed data in the collective scheme.

In the same way, for the stated data, increase in the collection cost (from increase in the value of k) results directly in the increase in the equilibrium prices and a drop in the profits to the manufacturer. The manufacturer, who opts for the individual scheme, earns an income from selling the collected used products to the recycling market, therefore allowing the possibility of reducing the new product prices in the future, which in the long run would result in improving profit margins from increased economics of scale, which our numerical study conclusively proves. The expressions for difference in equilibrium prices and profits for individual versus collective scheme are not tractable analytically, therefore are examined numerically.

The results that are obtained from the numerical runs are consistent. Likewise, the impact of different variables on the manufacturers profit was not analytically tractable, so they were investigated numerically.

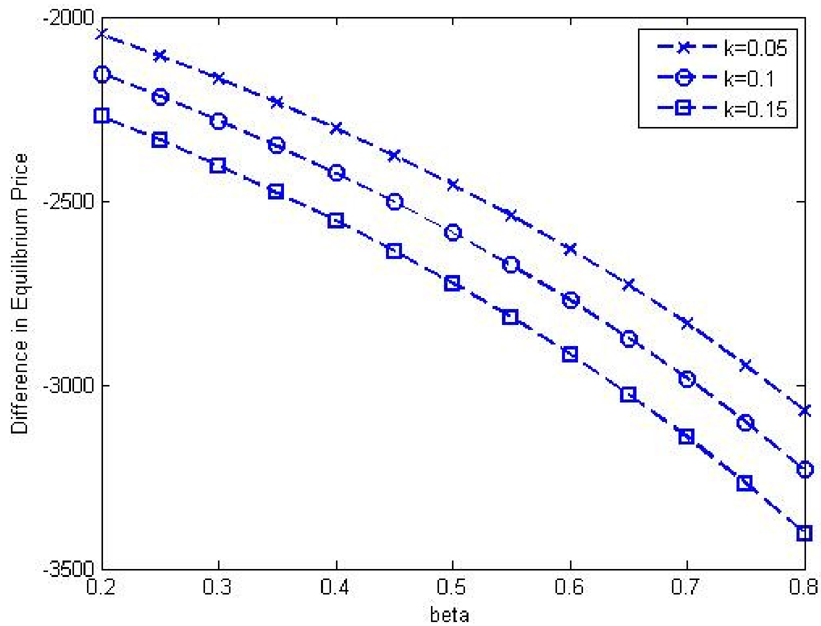


Fig. 4.2: Difference in equilibrium prices ($p_1^{i*} - p_1^{c*}$) Vs β

Figure 4.2 shows the variation of difference in equilibrium price for manufacturer 1 between individual and collective take-back schemes. The graphs are plotted for three different values of k (=0.05, 0.1, 0.15). From $Fig.$ 4.2, it was observed that as the degree of substitutability of products (β) increases the difference in equilibrium prices reduce, and approaches zero as β approaches 1. Also, for very low values of β, the difference in equilibrium prices becomes very high. This is expected, because at low values of β, the manufacturer's products have relatively independent demands, and therefore, new product prices will be comparatively higher in the individual take back scheme over that of the collective scheme, which is what explains the high price difference at low values of β. On the other hand, at high values of β, the market competition becomes very high, resulting in lower price difference between the two take back schemes. In general, it can be observed that the equilibrium prices for new products are always higher for the collective case. Understandably, with increase in the buy-back cost (from increase in k), the difference in equilibrium values further decreases, which implies that new product prices are significantly impacted more for the collective case whenever the buy-back prices are raised.

Figure 4.3 shows the difference in equilibrium profit in respect of the two schemes for manufacturer 1, plotted against the cross elasticity of demand (β), for 3 different values of k (=0.05, 0.1, 0.15) with all other variables having standard values. From $Fig.$ 4.3, it was observed that as the degree of substitutability of products (β) increases, the difference in equilibrium profits increase steadily upto $\beta = 0.7$, after which there is a decline. As the cross elasticity of demand increases (β approaches 1), the demand for products of competing manufacturers is affected by not only their own price, but also by the price quoted by the competitors. This translates to higher profits in the individual collection scheme upto $\beta = 0.7$, following which, a decline is observed on account of cross-price effect. Also observed is the fact that the difference in equilibrium profits are more pronounced when the buy-back prices increase.

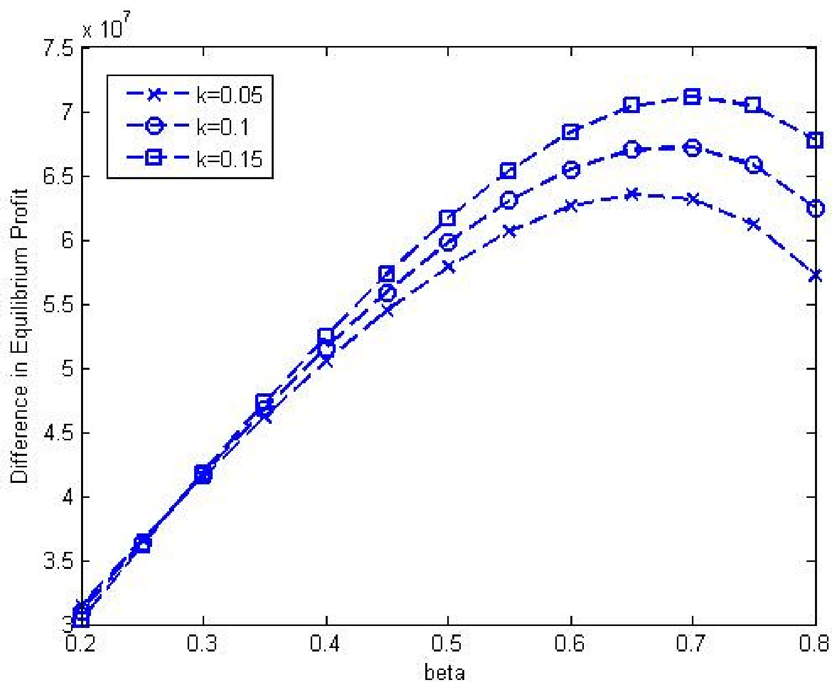


Fig. 4.3: Difference in equilibrium profits ($\pi_1^{i*} - \pi_1^{c*}$) Vs β

The plot for difference in equilibrium prices and equilibrium profits for different values of buy-back price fraction k are shown in $Fig.$ 4.4 and $Fig.$ 4.5, respectively. From $Fig.$ 4.4, it was observed that for any value of k, the price difference consistently remains negative, demonstrating clearly that new product prices in the collective scheme are always higher than those observed in the individual collection scheme. There was a steady decrease in the price difference with increase in the buy-back price. Contrarily, with the increase in buy-back price, the profit difference ($Fig.$ 4.5) marginally increases in the range. However, the profit difference consistently remains positive, for all values of k, reinforcing the fact that the profits are comparably higher in the individual collection scheme over the collective scheme.

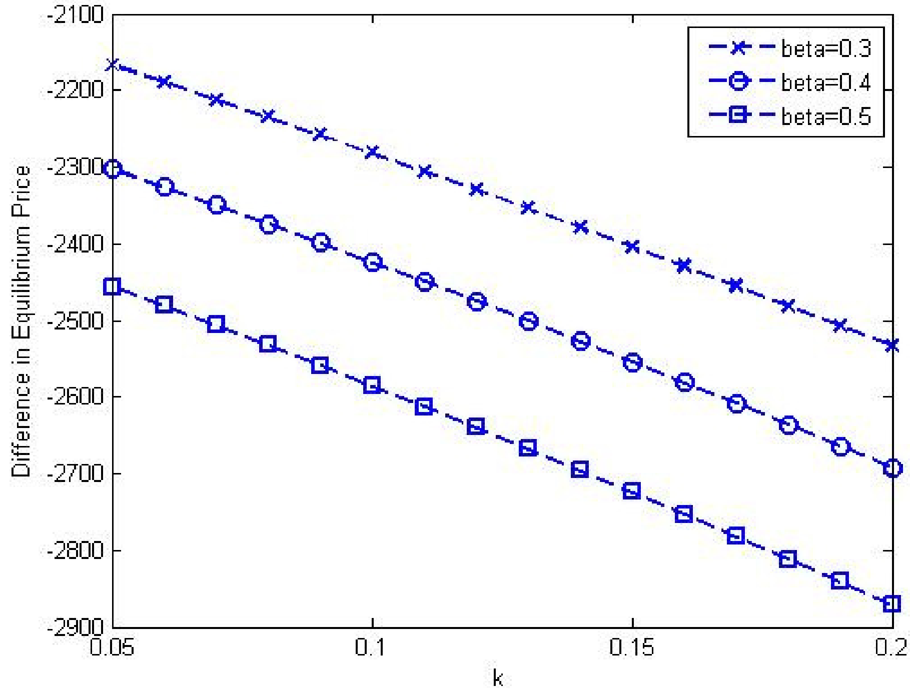


Fig. 4.4: Difference in equilibrium prices ($p_1^{i*} - p_1^{c*}$) Vs k

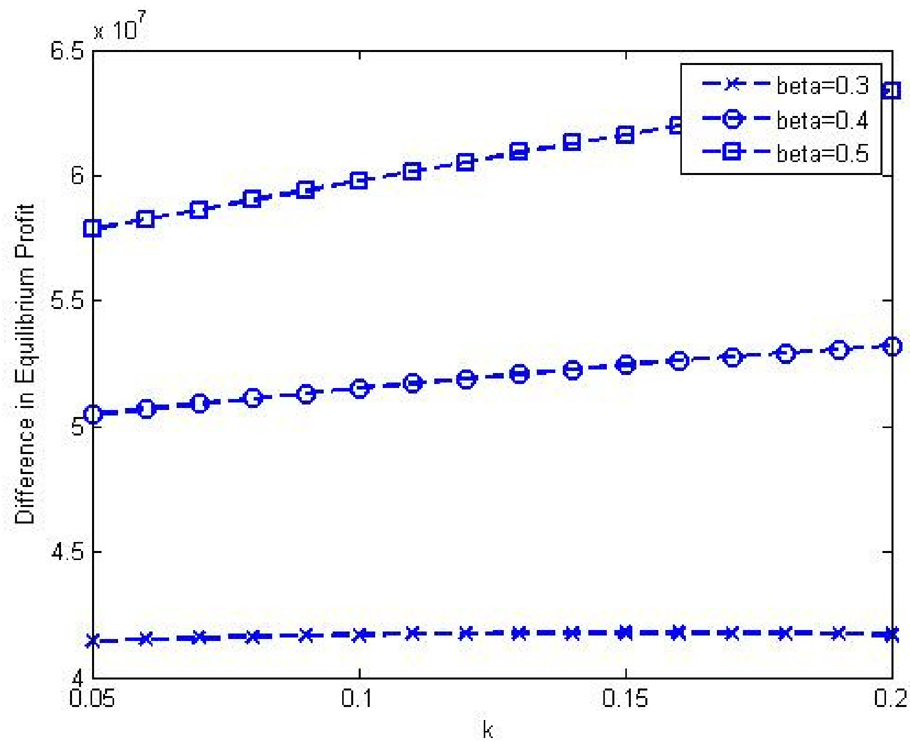


Fig. 4.5: Difference in equilibrium profits ($\pi_1^{i*} - \pi_1^{c*}$) Vs k

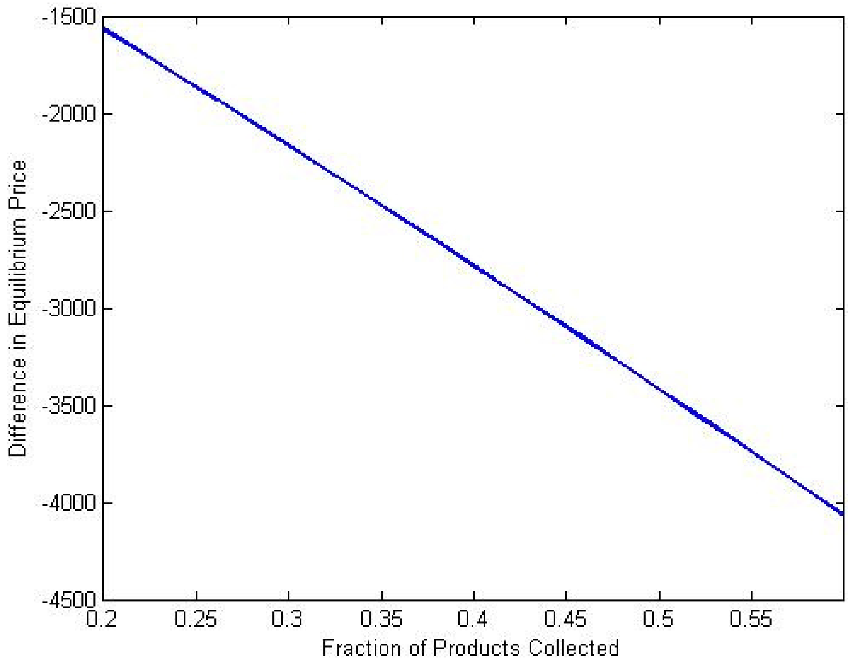


Fig. 4.6: Difference in equilibrium prices ($p_1^{i*} - p_1^{c*}$) Vs τ

The equilibrium price and profit of manufacturer 1 have been plotted against the fraction of products collected of manufacturer 1 (τ_1), with all other variables having standard values in $Fig.$ 4.6 and $Fig.$ 4.7, respectively.

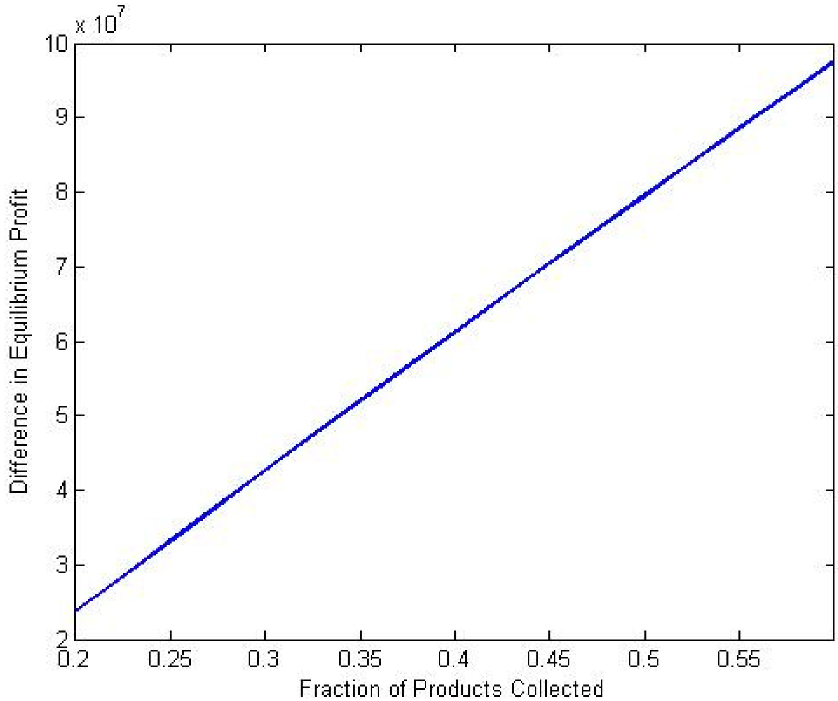


Fig. 4.7: Difference in equilibrium profits ($\pi_1^{i*} - \pi_1^{c*}$) Vs τ

It was also observed from the plots that as the fraction of products collected by manufacturer 1 increases, the absolute values of both the price and profit difference increase. Here too, for the given data range, the prices are always higher in the collective scheme and profits are higher in the individual collection scheme.

4.4 Conclusions

For a peculiar nature of market for recycling in India, where consumers expect economic benefits while disposing e-waste, the EPR model practiced in the developed countries is likely to fail because it imposes cost to consumers. The objective of this chapter was to gain insight into the impact of such market conditions into an EPR model. Here an analytical framework is proposed and developed to compare the two different modes of collection of EOL products. The analysis reveals key insights which have significant ramification for policymaking in the future, especially in deciding which take back practice is best suited to the Indian scenario. Results showcase win-win outcomes for both the consumers and the manufacturers. The equilibrium price is always higher in the collective case, and the equilibrium profit is always higher in the individual case. Higher product prices translate to lower demand, lowering the profit margins for manufacturers that favor collective take back scheme. Thus, the individual case is a win-win situation (with respect to consumers and manufacturers). Since the work deals only with take back schemes vis-a-vis the interaction between the consumer and manufacturer, the model does not include costs incurred by the manufacturer during the interaction with the recyclers. In the collective case, due to different make of the products, the collected products need to be segregated before they can recycled. This added cost in not present in the individual case. These results principally contradict the findings of several authors who have attempted to model different take back schemes in the context of developed countries, but their focus was on allocation of collected end-of-life products to recyclers and does not go into the details of the respective take-back schemes. Another notable difference is that the proposed model explicitly incorporated the idea of making a payment to the consumers in the process of collecting used products from them, which is a reality in the Indian context.

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Chapter 5

An Investigation into Attitudes, Behavior and Willingness of Residents towards e-waste Recycling in India

5.1 Introduction

The WEEE management in developed nations is guided by the concept of extended producer responsibility (EPR) which states that producers are responsible for managing WEEE generated by their products. The primary aims of any EPR framework are: waste prevention and reduction; increased use of recycled materials in production; reduced natural resource consumption; internalisation of environmental costs into product prices; and, energy recovery when incineration is considered appropriate (Fraige et al., 2012). In the developed economies like EU, Japan, and US which principally follow extended producer responsibility, there already exists a mature financing model with countries having their own unique set of stakeholder responsibilities and guidelines. For instance, in Japan the consumers are accountable for financing recycling through a visible fee levied upfront by the producers over and above the product price. On the other hand, several EU nations have mandatorily passed the burden of e-waste recycling on to the producers, who indirectly levy an invisible fee from the consumers tagged into the product price, while consumers retain the obligation of returning e-waste to designated collection centers. In contrast, a co-operative framework is practiced in the US, where the responsibilities are shared by the producers, government and the consumers.

The European EPR models have a well-structured system of visible and invisible fees for the recycling of WEEE, while for India in contrast; the consumers expect and demand money in exchange for their discards. Recently, on account of societal pressures and anticipated government legislation towards safe disposition of WEEE, formal recycling practices are increasingly being advocated. Additionally, the presence of limited landfill space combined with an increased cost of disposal in landfill has renewed focus on recycling by all manufacturers. Certainly critical issues like enforcement of the proposed e-waste rules, monitoring compliance and invoking penalties are additional milestones, which are to be adequately captured while framing laws in the near future. Kahhat et al.

(2008) argue that designing a sustainable WEEE management system should start with a clear understanding of the culture within which the dynamics of material flow takes place in the country. In contrast to the formal e-waste recycling practices found in developed countries, the informal recycling sector is currently the de-facto practice in India, where harmful techniques in de-soldering circuit boards to recover valuable metals are very common. Open burning of e-waste to recover precious metals and dumping of non-valuable fractions is widely prevalent resulting in significant environmental and health impacts (Herat and Agamuthu, 2012).

Despite the evidence of severe environmental and health impacts, recycling and recovery operations in India have generated a huge informal employment sector. Part of the problem in implementing EPR in India is the challenge of how to handle this informal sector. Certainly, the informal collectors have realized very high collection efficiency and have become a competitor to the formal sector in gaining access to e-waste. To mitigate the issue of lack of raw materials for processing to the organizing recycling sector, the Ministry of Environment and Forests has initiated action by granting permission to one recycling company to import e-waste from developed nations.

5.2 Behavior of Individuals in e-waste Recycling

The behavior of consumers is one of the major pillars in the design of any e-waste management system, more so for countries like India and China where e-waste is presumed to be of some monetary value. For designing effective policies addressing e-waste recycling, it is vitally essential to understand the issues concerning consumers' willingness to adopt such policies. Though there have been several studies in the past which explore the critical factors affecting willingness to participate and pay for recycling in developed countries, little is known about consumer behavior towards recycling of e-waste in the context of a developing country. Wang et al. (2011) argue that in the absence of mature EPR financing policies, juxtaposing contemporary recycling behavior prevalent in developed nations to analyze the developing nations like India and China, will be erroneous. The authors state that the principal impending barriers in advancing the knowledge gained from developed economies are low income and awareness levels together with a lower enthusiasm of residents to participate. Understanding the determinants of an individual's willingness to participate in recycling (Collins et al., 2006) is crucial to getting people to move off from zero participation in recycling and to the success of meeting any national environmental policy targets.

To comprehend this, an attempt was made by conducting a cross-sectional survey of consumer recycling behavior in a university setting. The prevailing Indian demographic profile can be judged from key indices such as: (1) approximately 65% of the population are in the age bracket of 15-64 years with the median age of males and females as 25.6 and 26.9 years, respectively; (2) urban population constitute 30% of the total population; and (3) mean household annual income in 2004-05 (Desai et al., 2010) for rural (urban) India is Rs 36, 755 (Rs 75, 266). The geographic spread of income patterns are quite familiar where high income is observed in the north-west, west coast and the north east. The percentage share of highest income deciles is approximately 45% (Vanneman and Dubey, 2010). Gurauskienė (2008) reported that basic variables like: consumer attitude, motivation, knowledge and behavior are very important considerations while empowering consumers to participate in the e-waste management system. They argue that consumers should ideally be in a position to understand their responsibility in a transparent industrial ecology system understanding the life cycle of products, materials and their impact on carbon footprint reduction and improved social value. In the light of new EPR rules and guidelines framed in India, it has become all the more important to understand the issue of consumer willingness to pay for the recycling of e-waste. To this end, this study critically examines the underlying issue of customer's willingness to participate in recycling activity in India. Research on the contextual pro-environmental WEEE disposal behavior in India is hardly available. Infact the requirement of a large cross-country data set for any insightful comparison remains a major concern.

5.2.1 Factors affecting individuals' participation in recycling

There have been several studies in the past that aim at elucidating the relationship between consumer pro-environmental participation and different socio-demographic characteristics. For instance, Aadland and Caplan (1999) report that age, education level, gender, and income level are positively correlated with curbside recycling. Others argue that younger women who are: less educated (Sterner and Bartelings, 1999), highly educated members of an environmental organization and living in large households (Aadland and Caplan, 2003), and/or living in cities (Caplan et al., 2002) are more likely to be involved in green recycling programs. In a recent study related to recycling participation in Turkey (Budak and Oguz, 2008), the authors find home ownership and household size as important factors that influence household's decision to participate. Similar investigation in Nigeria (Momoh and Oladebeye, 2010) clearly spell out that residential geographical location has no bearing on willingness to participate. Martin et al., (2006) argue recycling participation tends to be higher among more affluent and older people, but lower among less affluent and younger households. Similar arguments are espoused by Caplan et al., (2002) for the city of Ogden, who state that mid-to high-income household respondents are more likely to participate in green recycling programs. By contrast, Garces et al., (2002) state that older subjects having lower incomes are more likely to participate in selective collection programs. Yet there are few studies which report that age (Tiller et al., 1997; Do Valle et al., 2004; Momoh and Oladebeye, 2010), sex and education level (Momoh and Oladebeye, 2010) and household size (Martin et al., 2006) are not significant in assessing willingness to participate in recycling. Contrarily, a positive association between higher education and recycling has been identified (Samdahl and Robertson, 1989; Scott and Willits, 1994).

Despite the contradictory findings, demographic characteristics influence willingness to pay for environment friendly products. However, most authors (Laroche et al., 2001) agree that demographics are less important than knowledge, values and attitudes in explaining ecologically friendly behavior. Others (Vining and Ebreo 1990; Lake et al., 1996) state that higher socio-economic status has a positive influence on recycling behavior. For instance, Tiller et al., (1997) report that rural household's income positively affects, but has no effect on a suburban household's willingness to participate in recycling. Yet there have been also researches which have found contradictory results (McGuire, 1984; Oskamp et al., 1991; Garces et al., 2002).

Regardless of these inconsistent findings as in the case of developed countries, the impact of socio-economic-demographic variables on the variation in conservation behaviors for developing countries needs further investigation. Guerin et al., (2001) argue that despite the overwhelming bulk of research having used what they call as the individualistic approach in the study of conservation behaviors, the explanation potential of this theoretical approach has now reached its limits given the contradictory findings it has generated. Therefore, several authors have investigated the effect of different situational factors to participation in a variety of conservation behaviors. Corral-Verdugo (1996) investigated predictors like convenience, information, availability of conditions for recycling amongst others. Other situational factors like convenient access to recycling programs (Berger, 1997; Mee et al., 2004) and possession of a bin (Guagnano et al., 1995) has a significant effect on recycling behavior.

Guagnano (2001) show the contrast between self-interested behavior and altruistic behavior and their impact on pro-environmental behavior. Several studies espouse the point that pro-environmental behaviors may not always be best guided by self interest behavior since they also might be implicitly influenced by moral norms, particularly in the event when individuals feel that their action is seen as having consequences for others. This behavior involves a tradeoff between self-interest and altruism. In this context, Guagnano (2001) investigated 'green consumerism' around the issue of recycling where households get voluntarily involved in segregating solid waste. Bruvoll et al., (2002) stated that household recycling effort which though remains a voluntary activity, involves a cost to society since sorting at source requires significant extra time (opportunity cost of time in terms of foregone leisure) and energy. Such green consumers strongly believe that current environmental conditions are deteriorating and represent serious problems facing the society. An alternative conjecture (Berglund, 2006) could be that willingness to participate in segregation at source stems from potential financial benefits derived from disallowing others in the segregation process. Therefore, variables like environmental knowledge, past environment friendly behavior and perceived psychological consequences of environment friendly behavior (Connor et al., 2000; Albarracin and Wyer, 2000; Abdul-Muhmin, 2007) are positively correlated to environmental concern.

However, it is now fairly consistent in the academic literature of environmental psychology that supports the argument that environmental concern (Minton and Rose, 1997; Ohtomo and Hirose, 2007) is an attitude separate from its subsequent intentions and behaviors. Perrin and Barton (2001) made the point that environmental concern is the primary reason for household participation, with convenience being the next in importance. Yet there have been studies (McCarty and Shrum, 1994) which emphasize the reverse: that perception of inconvenience of recycling had a greater influence on individuals followed by environmental concern. While Garces et al., (2002) puts the argument that individual participation in recycling programs increases with increase in the environmental awareness levels of individuals, and the degree of participation decreases with increase in recycling inconvenience. In addition, socio-psychological construct like environmental values and beliefs (Barr et al., 2003), which depicts an individual's orientation towards the environment, is also important in shaping their environmental action. This is also corroborated by Collins et al., (2006), who in their study of household participation in recycling activity have reported that respondent's involved in charitable work in support of the environment, were significantly more likely to recycle. Individualistic and collectivistic behavior shapes our environmental beliefs. Laroche et al., (2001) puts forth the argument that collectivism which implies cooperation, helpfulness, and considerations of the group relative to the individual motivations is conducive to environmental friendliness.

Additionally, Martin et al., (2006) explicitly show that recycling participation is critically linked to economic benefits especially for low income groups who may not be able to offset the cost of participation and waste disposal. Several attempts have been made in the past to outline the significant factors that influence recycling behavior and environmental participation, where today exists a voluminous literature providing the practitioner with a wide array of data, but generally shrouded in dense academic language. Barr et al., (2003) caution that it is understandably rare that an academic investigation of environmental behavior can be exactly translated into a practical framework that can have concrete policy implications. Moreover, national contextual-level variables like GDP, environmental conditions (Gelissen, 2007) and Engel's coefficient (Wang et al., 2011) do influence an individual's willingness to pay for the environment.

The issue of household participation in WEEE recycling schemes in developed nations is widely explored. Darby and Obara (2005) investigated the attitudes of consumers towards the disposal of small WEEE in the UK. Nixon and Saphores (2006) identified the significant factors which explain the willingness to recycle e-waste in the state of California. The authors find that gender, education, convenience, and environmental beliefs but not income or political affiliation are key factors explaining the willingness to drop off e-waste at recycling centers. The same authors (Saphores et al., 2007) identified that on an average most respondents are willing to support a 1% advance recycling fee (ARF) and prefer drop-off recycling to curbside recycling (Nixon et al., 2009). Saphores et al., (2012) argue from their analysis of US households that moral norms followed by recycling convenience, priori knowledge of toxicity of e-waste, recycling experience, gender and marital status are principal determinants that stimulate willingness to recycle amongst residents. Additionally, the authors also observed that socio-demographic variables like education, age and ethnicity play a minor role. Interestingly, knowledge of e-waste laws and income are not statistically significant. Song et al. (2012) showed that the Macau respondents' age, education level and income are the significant factors affecting the residents' willingness to participate and pay for e-waste recycling schemes. The prevailing modes of consumer disposal in Macau are reported to be the retailer collection model followed by sale to recyclers. Although there exists a plethora of empirical studies in the past decade to identify the determinants of household participation in WEEE recycling for developed nations, limited research was found in the context of developing countries. From this perspective, both Nnorom et al. (2009) and Wang et al. (2011) concretely address the issue of willingness to participate in recycling. To this end, the primary aim of this study is to lay the preliminary groundwork to ascertain the significant factors that influence household decision to participate in WEEE recycling in India.

5.3 Methodology

The methodology followed for this study was to collect data through survey in a university environment and based on the survey data, a model was developed to explore the attitude, behavior and willingness of individuals to participate in e-waste recycling.

5.3.1 Data collection

The study was conducted in a university wide setting through an online survey. An e-mail survey traditionally elicits very low response rates and could be skewed with bias towards one point of view. To address this lacuna, the survey was administered beginning with a brief introduction to the subject of interest, scope of the survey and finally briefed about the national cause the survey would fulfill. The primary intent was to gather information about ownership of electrical and electronic (EEE) products, household e-waste disposal practices, the residents' attitudes towards collection and financing for e-waste recycling and residents' willingness to participate in recycling schemes and reasons for non-participation.

The e-mail survey comprised of four sections namely: (1) demographic and socio-economic information; (2) explicit information on e-waste awareness, laws and product possession; (3) specific facts characterizing respondent's pro-environmental behavior, situational factors and economic benefits; and (4) typical e-waste disposal behavior, collection method and financing model. The university which is among the top ten national level technical universities in India was chosen for the survey, a setting ideal for the study since the subjects under investigation are believed to come from different strata of society and from different nook and corner of the country giving us the flexibility of stratified sampling for investigating the role of regional disparities in the survey responses.

5.3.2 Modeling willingness to participate in e-waste recycling

This section investigates the effect of socio-demographic characteristics (gender, age, education, geographical region, urban-rural nativity and household size), socio-economic characteristics (household income, Engl's coefficient and residential type), e-waste awareness level, knowledge of e-waste rules and regulations, recycling habit, environmental concern, environmental affiliation, access to recycling and economic benefits on willingness to participate in e-waste recycling. Engel's law is based on the observation that there is a limit to the amount that any person can possibly eat so that from a certain level of income onwards demand for food increases by less than income and its coefficient is measured from the sample household by computing the share of food expenditure from the total expenditure. *Recycling habit* of respondents are measured by past experience of whether participated in recycling or not. *Environmental concern* was determined from the respondents concern about the deteriorating environment around them. *Convenience of recycling facilities* was evaluated from the respondents access to e-waste collection center or recovery/recycling facility around their residential area. The importance of households sensitivity towards acquiring financial gain from the disposal of their e-waste was evaluated from the variable '*Economic benefit*'. .A regression model was developed to investigate the significant factors affecting the residents' willingness to pay for recycling. Here the respondents are required to show their willingness to participate in e-waste recycling by choosing either "Yes" (coded as "1") or "No" (coded as "0").

Since the dependent variable is dichotomous in nature, taking a value 1 or 0, therefore the most commonly used approaches to estimate such models are the logistic regression model and the probit regression model. The primary requirement here is the need for a probability model that captures two basic features: (1) as the value of X (predictor) increases, the conditional mean $P = E(Y = 1|X)$ increases but never steps outside the 0-1 interval, and (2) the relationship between P and X is non-linear, that is P asymptotically approaches 0 or 1 as X approaches 0 or 1 respectively. The logistic regression was used in this work, which allows for estimating the probability that an event will occur or not, by predicting a dichotomous outcome from a set of independent variables as per the following representation:

$$P_i = E(y_i = 1|X_i) = \frac{1}{1+exp\,(-Z_i)} \tag{1}$$

$$Z_i = \beta_0 + \sum_{j=1}^{n} \beta_j x_{ij} + \epsilon_i = \beta_0 + \langle \beta^T . X_i \rangle + \epsilon_i \tag{2}$$

where, Z_i is the latent and continuous measure of respondent i ($i = 1, \dots, N$) willingness to participate in e-waste recycling; X_i is an $(n \times 1)$ column vector grouping the explanatory variables (x_{ij}) for the i^{th} respondent; β_0 and the vector β are unknown parameters to be estimated; and, ϵ_i is the random error term representing unobserved attributes that affect choices.

Taking natural log of $Eq. 1$, gives the logit transformation L_i as,

$$L_i = ln[\text{Odds of participation}] = \ln\left[\frac{P_i}{1-P_i}\right] = Z_i = \beta_0 + \sum_{j=1}^{n} \beta_j x_{ij} \tag{3}$$

This logit transformation in Eq.(3) is identical to a simple linear regression model. But given that the response is a binary value, the probability distribution of P_i in the sample will follow a binomial distribution. So traditional linear regression theory cannot be used here, instead the unknown parameters are estimated using the method of maximum likelihood. To estimate the unknown parameters using the maximum likelihood estimation, we need to first construct the maximum likelihood function. Therefore, given the probability of willingness to participate in e-waste recycling for a respondent with $y_i = 1$ as P_i, then the probability of not willing to participate can be expressed as $(1 - P_i)$. Now in a sample, for those pairs (X_i, y_i) for which $y_i = 1$, the contribution to the likelihood function is ${P_i}^{y_i}$ and for those pairs for which $y_i = 0$, the contribution to the likelihood function is $(1 - P_i)^{1-y_i}$. Therefore, the convenient way to express the likelihood function of the i^{th} respondent is ${P_i}^{y_i}(1 - P_i)^{1-y_i}$. Since the observations of different respondents' are independent, the total likelihood function becomes

$$l(\beta) = \prod_{i=1}^{N} {P_i}^{y_i}(1 - P_i)^{1-y_i} \tag{4}$$

Taking the negative log likelihood of Eq.(4), gives

$$L(\beta) = -\sum_{i=1}^{N}\{y_i log\, P_i + (1 - y_i)\log\,(1 - P_i)\} \tag{5}$$

Finding the gradient of $Eq. 4$ w.r.t β_j, results in

$$\frac{\partial L}{\partial \beta_j} = -\sum_{i=1}^{N}\left\{y_i \frac{\partial log\, P_i}{\partial \beta_j} + (1 - y_i)\frac{\partial \log\,(1-P_i)}{\partial \beta_j}\right\} \tag{6}$$

It is easy to verify that the following terms reduce to $\frac{\partial log\, P_i}{\partial \beta_j} = x_{ij}(1 - P_i)$ and $\frac{\partial \log\,(1-P_i)}{\partial \beta_j} = -P_i x_{ij}$. Therefore, we have $\frac{\partial L}{\partial \beta_j} = \sum_{i=1}^{N}(P_i - y_i)x_{ij}$ which is the dot product of j^{th} column of matrix A and the vector $(P_i - y_i)$. This leads to $\left(\frac{\partial L}{\partial \beta_1} \cdots \frac{\partial L}{\partial \beta_j} \cdots \frac{\partial L}{\partial \beta_n}\right) = (P_i - y_i)^T \cdot A$. Taking the transpose of the gradient, results in

$$\begin{pmatrix} \frac{\partial L}{\partial \beta_1} \\ \vdots \\ \frac{\partial L}{\partial \beta_n} \end{pmatrix} = A^T \cdot (P_i - y_i) = \nabla_\beta L \tag{7}$$

where,
$$A = \begin{pmatrix} x_{11} & \cdots & x_{1j} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots & & \vdots \\ \cdot & & x_{ij} & & \cdot \\ \vdots & & \vdots & \ddots & \vdots \\ x_{N1} & \cdots & \cdots & \cdots & x_{Nn} \end{pmatrix} \tag{8}$$

Given that P_i is a non-linear function of $\beta's$, it is not possible to identify directly the critical points by setting $Eq. 5$ to zero. In such a scenario, iterative are used to solve the system of non-linear equations given in Eq.(7). For instance, using the Newton's method, we have $\beta_{t+1} = \beta_t - \frac{g}{H}$, where $g\ (gradient) = A^T \cdot (P_i - y_i)$ is known and the Hessian $H = \nabla_\beta^2 L$, which are required to be computed. Given that, $\frac{\partial^2 L}{\partial \beta_j \partial \beta_k} = \sum_{i=1}^{N} x_{ij}\frac{\partial P_i}{\partial \beta_k} = \sum_{i=1}^{N} x_{ij}x_{ik}P_i(1 - P_i)$ and noticing that this corresponds to the quadratic form $A_j^T B A_k$, where $A_j \, and \, A_k$ are the j^{th} and k^{th} column of A (which represents the survey responses for the j^{th} and k^{th} question, respectively. Relating this analogy to the entire generic model, results in $H = \nabla_\beta^2 L = A^T BA$. The diagonal entries of B is

$$B = \begin{pmatrix} P_i(1-P_i) & 0 & \cdots & 0 \\ 0 & P_i(1-P_i) & & \vdots \\ \vdots & & P_i(1-P_i) & 0 \\ 0 & \cdots & 0 & P_i(1-P_i) \end{pmatrix} \tag{9}$$

Finally, using $Eqs. 5, 6 \, and \, 7$, the recursive equation to solve for unknown parameters is,

$$\beta_{t+1} = \beta_t - (A^T BA)^{-1} A^T \cdot (P_i - y_i) \tag{10}$$

Recalling that $0 \le P_i \le 1$, therefore, the eigenvalues of the matrix $A^T BA$ will be non-negative which means positive semi-definite. In other words, L is convex but not strictly convex.

5.3.2.1 Marginal effects in logit

The marginal effects for a logit determines how a marginal change in one regressor changes the distribution of the outcome variable, i.e., all the outcome probabilities. The marginal effects, $\frac{\partial \Pr(y=1|x)}{\partial x_j}$ for a continuous predictor variable can be computed from:

$$\frac{\partial \Pr(y=1|x)}{\partial x_j} = \frac{\partial F(x_j,\beta)}{\partial x_j} = \frac{\partial F(x_j,\beta)}{\partial x_j\beta} \times \frac{\partial x_j\beta}{\partial x_j} = F(x_j,\beta)'\beta_j = f(x_j,\beta)\beta_j \tag{11}$$

where, F and f are the CDF and PDF of the logistic distribution, respectively. $Eq. (11)$ can be simplified to:

$$\frac{\partial \Pr(y=1|x)}{\partial x_j} = f(x_j,\beta)\beta_j = \frac{e^{Z_i}}{(1+e^{Z_i})^2}\beta_j = \frac{e^{Z_i}}{1+e^{Z_i}}\left(\frac{1+e^{Z_i}-e^{Z_i}}{1+e^{Z_i}}\right)\beta_j$$

$$= \Pr(y_i = 1|X) \, . \, Pr(y_i = 0|X). \beta_j = \frac{1}{1+e^{-Z_i}} \cdot \frac{1}{1+e^{Z_i}} \cdot \beta_j \tag{12}$$

Similarly, the marginal effect for discrete predictor variables can be expressed as:

$$\text{Marginal effect of } x_j = \Pr\left(y = 1 \middle| X, x_j(2) = 1\right) - \Pr\left(y = 1 \middle| X, x_j(1) = 0\right) \tag{13}$$

Here, the difference in predicted probabilities at discrete change in the given independent variable is carried out holding all other independent variables constant at their reference points.

5.3.2.2 Sample size issues for logistic distribution

Peduzzi et al. (1996) propose that for a single term main effects model having discrete covariates, the relevant quantity to check for sample adequacy is the computation of events per parameter. This is done by computing the frequency of the least frequent outcome, $m = \min\,(n_1 = number\ of\ \Pr(Y=1), n_0 = number\ of\ \Pr(Y=0)\,)$ in the sample. So the model should contain no more than $p + 1 \leq \min(n_1, n_0)\,/10$ number of parameters. The authors further argue that this rule of 10 should be taken only as a guideline and a final determination should be made based on the overall context of the problem. The rule of 10 assumes that the discrete covariates have a balanced distribution. Under settings where the distribution of covariates are weighed heavily to one value, the guideline is that the minimum frequency be 10, in the contingency table of outcome. The authors argue that further research is needed to determine if 10 is too stringent a requirement.

5.4 Results and Discussion

5.4.1 Socio-demographic-economic characteristic of the respondents

A total of 148 complete responses were received from the online survey. For a population of size 8000 (which is the total university population strength), a sample size of 150 indicates a 90% confidence with an error of 6.7%. Also, from the contingency table (see $Table$ 5.4), the assessment was made that the sample size is adequate for logistic regression. $Table$ 5.1 gives the descriptive statistics of key variables of the respondents. The respondents of the survey were predominantly male and fall into the bracket of 20-29 years. Our survey data comes close to the Indian median age of 25.6 for females and 26.9 for males. On an average, each sample household had 3.94 members. According to the National Family Health Survey (2005) estimates, the mean Indian household size was 4.8 persons per household. The average educational level of the sample was between bachelor and higher education. Similarly, the sample average income level indicates that majority of the respondents fall in the bracket of lower middle class and upper middle class, but predominantly more closer to upper middle class. Engl's coefficient for households living in village and small towns, cities and metros are respectively 3.8%, 4.3% and 4.6%. The coefficient behaves differently for rural and urban households, with the latter exhibiting markedly lower value. This is to be expected, as urban dwellers generally pay more than rural residents for housing, transport and other essential non-food goods and services.

Table 5.1: Descriptive statistics for key variables entering the logit (sample size N=148)

Variables	**Scale**	**Mean**	**SD**
Dependent Variable			
Recycling participation	0 = participate in recycling, 1= not participate in recycling	0.50	0.502
Independent variable			
Gender (x_1)	0 = female, 1= male	0.84	0.370
Education level (x_2)	1 = secondary, 2 = college, 3 = masters/PhD	2.41	0.736
Geographical location (x_3)	1=east, 2= west, 3= north, 4= south	2.71	0.964
Place (x_4)	1 =village, 2 = city, 3 = metro	2.13	0.673
Age (x_5)	1 = less than 20 years, 2 = 20-29 years, 3 = 30-39 years, 4 = 40-49 years, 5 = 50 years and above,	1.80	0.690
Household size (x_6)	1 = one, 2 =two, 3 = three, 4 = four, 5 = five and above	3.94	0.835
Monthly household income in INR (x_7)	1 = less than 14K, 2 = 14K – 28K, 3 = 28K – 1.4 lakh, 4 = more than 1.4 lakh,	2.95	0.823
Type of dwelling (x_8)	1 = rented house in a locality/village, 2 = rented house in apartment building, 3 = own house in a locality/village, 4 = own house in an apartment, 5 = owns more than one house	3.19	1.203
Engel's coefficient (x_9)	Actual continuous value	0.424	0.1798
E-waste awareness level (x_{10})	1 = low , 2 = medium, 3 = high	1.97	0.521
Laws and regulations (x_{11})	0 = unaware, 1= clearly aware	0.09	0.284
Recycling habit (x_{12})	0 = used to recycling, 1 = not participated before	0.49	0.502
Concern about deteriorating environment (x_{13})	0 = not my concern, 1= concerned	0.98	0.141
Affiliation with environmental organization (x_{14})	0 = not affiliated, 1 = affiliated	0.09	0.294
Access to e-waste collection facility (x_{15})	0 = access, 1 = no access	0.17	0.376
Economic benefits (x_{16})	0 = no, 1 = yes	0.50	0.502

About 15% of the respondents were found to be not aware about the issues and problems concerning e-waste, while the remaining 73% and 12% respectively had a brief to a very high understanding of the problem. Interestingly, despite the high awareness level of the respondents, overwhelming majority of the respondents (92%) were not aware about the rules and regulations concerning e-waste. Also a greater part of the respondents (83%) reported no formal access to recycling facilities. Infact, for the year 2005, according to the estimate by Mckinsey (2007) and KPMG and IMRB (2006), about 3% of the total 208 million households in India have an annual salary exceeding Rs 0.215 Million. This corresponds to the total number of upper middle class and rich households in the country.

5.4.2 The usage and disposal of EEE products

The survey data are analyzed for the ownership, usage patterns and disposal methods adopted by the sample in the following sections.

5.4.2.1 Ownership of EEE products

The survey results for the penetration rate of electrical and electronic products (EEE) in a typical Indian household are shown in Table 5.2.

Table 5.2: EEE penetration rate

Item	Penetration rate	
	per household	per capita
Mobiles	3.52700	0.93680
Televisions	1.36486	0.36047
Desktops	0.91216	0.24189
Laptops	1.64864	0.43716
Washing Machines	0.85135	0.23040
Air Conditioners	1.12162	0.28547

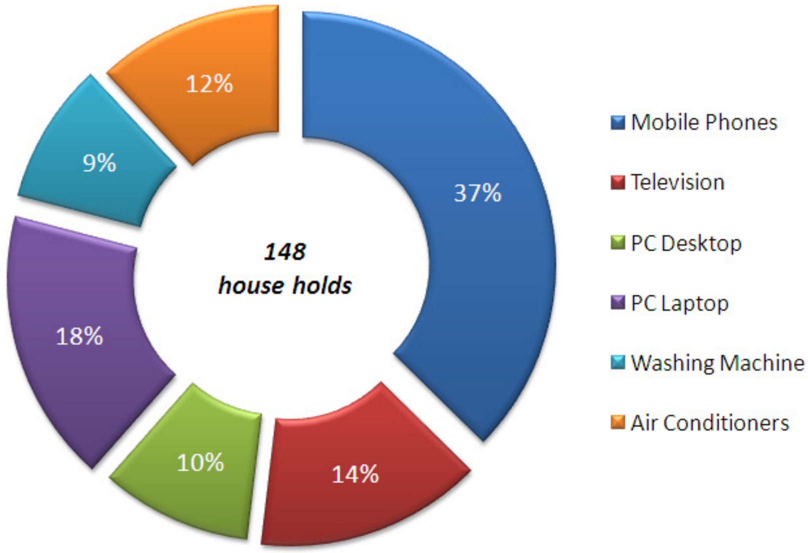

Fig. 5.1: Product category wise

It is observed from *Table* 5.2 that of all the appliances investigated, the penetration rate of mobiles per household (3.527) is the highest translating to about one mobile per person. Interestingly, the numbers of laptop PCs in the sample household exceed the number of desktop PCs by a factor of 2.8, indicating the popularity of laptops amongst the educated youth.

Similarly, the number of washing machines and air-conditioners in the sample are expectedly higher than the national figures, given that our respondents were highly educated and come from higher socio-economic strata. The product category wise distribution of the total number of appliances in 148 households shown in *Fig.* 5.1 clearly indicates that significant percentage (37%) of the total appliances in usage are mobile phones followed by laptop PCs (18%).

5.4.2.2 Discard methods of WEEE

The flow of e-waste at the national level is far from clear in India. Though there have been studies documenting the disposal patterns of consumers at regional levels, little is known about the disposal patterns of educated youth at the country level, who are seemingly the major stakeholders that drive the sales of EEE in India. This can be verified from the fact that, the household EEE usage figures of our sample are higher than the national average.

The disposal behavior of households for individual WEEE are shown in $Fig. 5.2$. The most preferred disposal method is “sold in second hand market/ exchange for new products” illustrating the fact that individuals look for some form of financial benefit from their used appliances. The other notable attribute was that on an average, households view “donation and passing on to friends, relatives etc” as preferred choice over “selling to scrap dealer”, clearly indicating that households would either like to maximize the returns from selling or prefer donating over selling for a pittance. A further investigation into the most important consideration while disposing (see $Fig. 5.3$) shows that “best exchange offer” followed by “best price” are arguably the prime considerations in making up their choice.

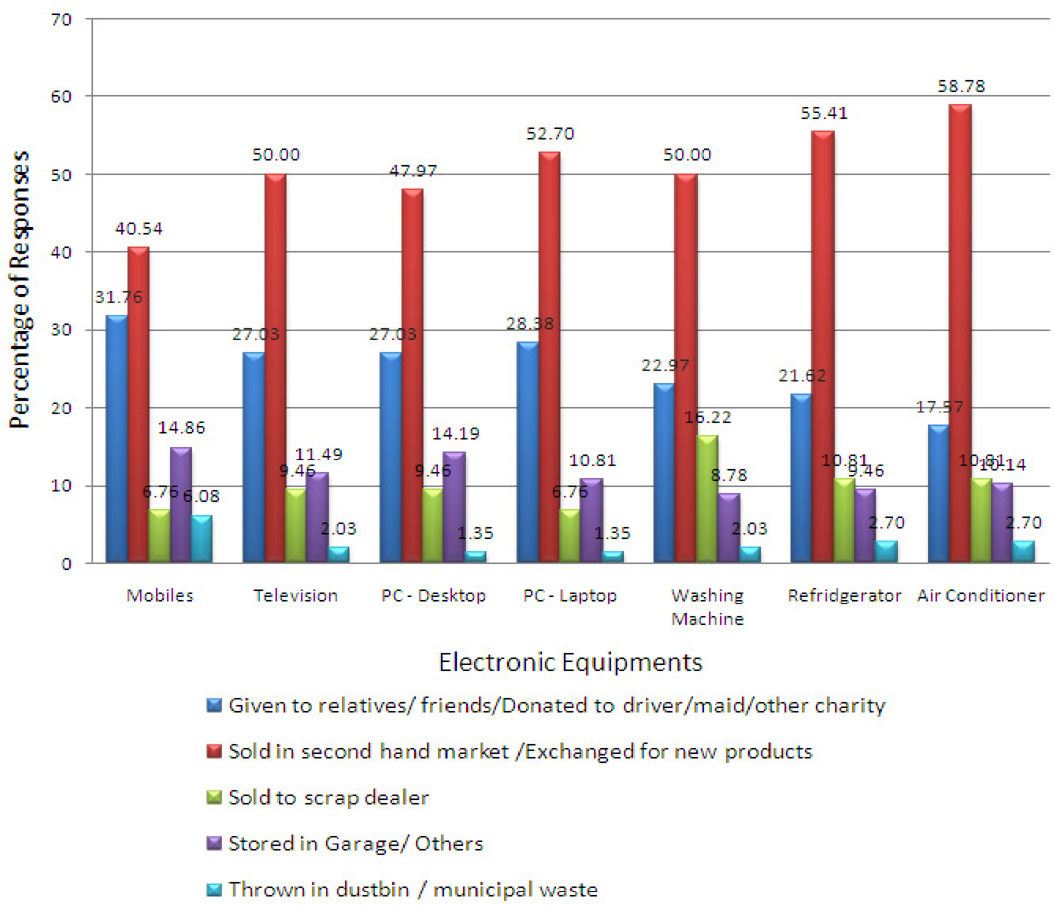

Fig. 5.2: Disposal behavior of households: methods of disposal

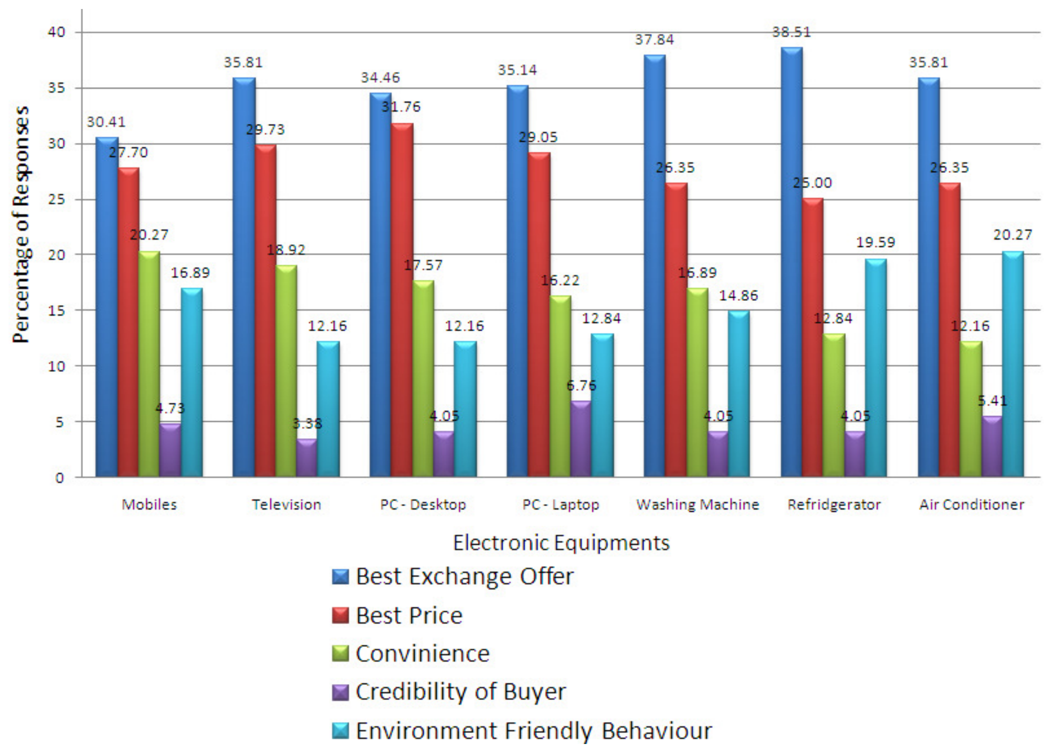

Fig. 5.3: Important considerations during disposal

5.4.3 Residents attitude on collection and financing for recycling

A major issue in planning a take back program is deciding the way in which the costs of recovery and recycling are passed on to customers. There are primarily four basic policy alternatives that are often proposed for effective financial management of e-waste. Some states like California in the US, Switzerland in EU have adopted ARFs to tackle the growing menace of e-waste. ARFs are front-end financing systems that charge consumers a fee at the point of sale, which is then used to finance e-waste recovery and recycling programs (Nixon and Sophores, 2007). The success of implementing ARF (which is denoted as "pay in advance") depends on two strategies: making the fee transparent/visible to the producer/customer and reducing cross-subsidization where the ARF collected for one category of products is used to sponsor recycling of another category of products.

The Japanese Electric Household Appliance Recycle Law which is hereafter referred to as "pay afterward", contrarily puts the onus of funding the establishment and operation of e-waste treatment facilities on the producers' during the production process while consumers pay recycling fees at the time of disposal. Alternatively, the "deposit/refund" system (Bhule et al., 2004) imposes an upfront deposit for potential future recycling of purchased goods and are rewarded with most (or all) of their initial deposit when they participate in returning the used product. Incorporating deposit/refund schemes in the take back program motivates and stimulates consumer participation in e-waste collection and boosting recycling rates. The other alternative is the "monthly recycling fee", widely prevalent in the management of municipal solid waste and waste water in cities.

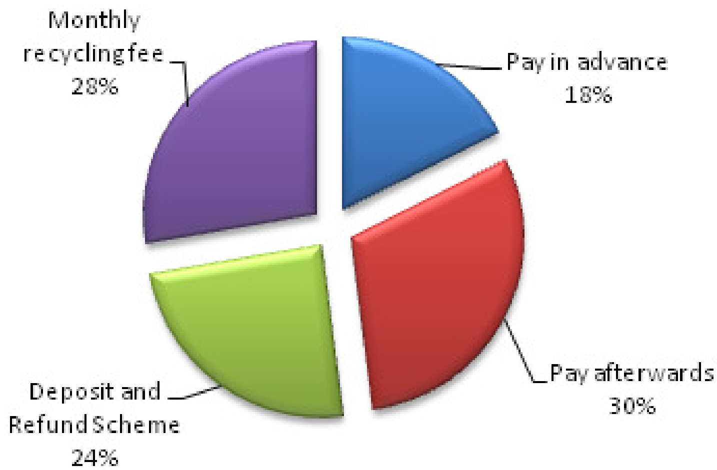

Fig. 5.4: Modes of payment for e-waste recycling

It can be observed from $Fig.$ 5.4 that "pay afterwards" was the favored payment mode (30%) amongst the respondents. The results for the "deposit/refund" and "monthly recycling fee" are roughly the same, while the least preferred remains the "pay in advance" scheme. The respondents also expressed their opinion on the choice of collection method as can be seen from $Fig.$ 5.5.

Apparently, the respondents show overwhelming support (34%) for "retailer collection with discount in exchange for new products" as against the alternative "retailer collection for buy-back" (17%). Interestingly, respondents are roughly equally favored to the idea of "telephonic reservation system to collect e-waste" (22%) and "permanent collection space in your city" (19%).

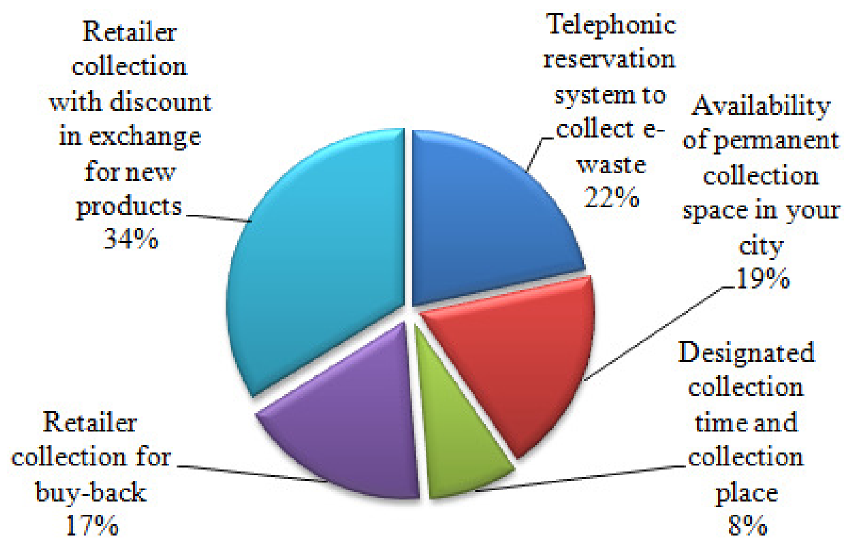

Fig. 5.5: e-waste collection preferences

5.4.4 Willingness to participate in recycling

The step wise logistic regression procedure was performed using the commercial SPSS v17.0 software. The advantage of using SPSS software is the availability of extensive model fit tests, which are used to assess the robustness of results. The total sound judgment of the intercept only norm model was found to be 76.4%, and with the introduction of predictors, the overall predictive capacity of the model is increased to 83.8% (see *Table* 5.3).

Table 5.3: Predicted and observed response classification

Actual Observed	**Predicted**			
	Participate	**Do not participate**	**Total**	**% correct**
Participate	108	5	113	95.6
Do not participate	19	16	35	45.7
Total	127	21	148	83.8

Sensitivity = 108/127 = 85%; Specificity = 16/21 = 76.2 %

Of the 113 respondents who voted for "participate", the logistic model predicted that 108 would "participate" and 5 would "not participate" yielding a prediction rate of 95.6%. Of the 35 respondents who voted for "not participate", the model predicted that 16 would "not participate" and 19 would "participate" yielding a successful prediction rate of 45.7%. Thus the model tells us more about why respondents would support the measure over why they would oppose the measure. Since the distribution of the covariates are weighed more towards the event occurring rather than the non-occurrence of the event, and also by observing the frequency in each decile of the contingency table, an assessment was made that the sample size is adequate for logistic regression. For the purpose of predicting the outcome of each respondent, the cut value adopted was 0.50, which means that classification was made (see $Table$ 5.3) based on the assumption that Pr(respondent will participate)$\geq$ $cut\ value$.

A more complete description of the computed classification accuracy for different cut values can be ascertained from the area under the Receiver Operating Characteristic (ROC) curve. The ROC curve is constructed by plotting sensitivity (probability of detecting true signal) over all the cut points versus (1- specificity) which is the probability of detecting false signal. For instance, for a cut value of 0.5, as observed from $Table$ 5.3, the probability of detecting participation (true signal) and not detecting non-participation in e-waste recycling by the regression model is 85% and 23.8%, respectively.

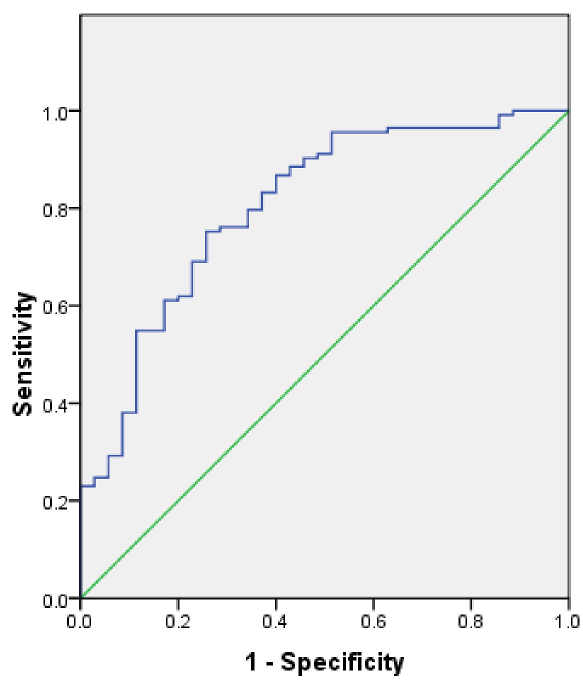

Fig. 5.6: ROC curve

Table 5.4: Observed and estimated expected frequency

Decile	Not willing to participate		Willing to participate		Total
	Observed	Expected	Observed	Expected	
1	11	10.414	4	4.586	15
2	8	7.064	7	7.936	15
3	3	5.180	12	9.820	15
4	4	4.090	11	10.910	15
5	3	2.991	12	12.009	15
6	2	2.120	13	12.880	15
7	1	1.385	14	13.615	15
8	2	0.932	13	14.068	15
9	1	0.627	14	14.373	15
10	0	0.196	13	12.804	13

The area under the ROC curve (see $Fig.$ 5.6) for all the cut points is 0.805 (> 0.5), suggests that the regression model was successfully able to discriminate the likelihood that a respondent who is willing to participate in recycling was given a higher probability than a respondent who is not willing to participate. As a general rule, the scenario when ROC = 0.5, indicates no discrimination (i.e., we might as well flip a coin) which is the default threshold in SPSS. The goodness of fit of the regression model was assessed using the Hosmer and Lemeshow test from the SPSS output.

The contingency table (see $Table$ 5.4) where the predicted probabilities (computed from $Eq.$ 1) for the 148 respondents are sorted and segregated into 10 categories or deciles. The first decile groups predicted probabilities closer to not willing to participate ($Y = 0$) in recycling, while the last decile groups the actual probabilities closer to "willingness to participate" ($Y = 1$). The groupings are then used to compute the frequency in each decile. For instance, the observed frequency (see $Table$ 5.4) in the "willing to participate" for the fifth decile is 12, which is obtained from the sum of the observed outcomes for the 15 subjects in this decile. Similarly, the corresponding estimated expected frequency for this decile is 12.009. Greater the difference between the frequency of expected and predicted outcomes in each decile, the less predictive capacity exists in the logistic regression estimates.

The Hosmer and Lemeshow Test (Hosmer and Lemeshow, 2000), which tests the null hypothesis that the Pearson chi-square distributions of frequency in the observed and expected probabilities are significantly different, was reported. In other words, to have a good fit, the chi-square statistic from Hosmer and Lemeshow Test should not be statistically significant, which is to say that the null hypothesis should be rejected. For our logistic regression fit, the model chi-square (χ^2) is 3.606 with 8 (=10-2) degrees of freedom is not significant at p-value of 0.891. The null hypothesis is rejected which indicates that the observed responses and expected outcomes from the regression model are not significantly different and that the overall model fit is good. The logistic regression model fit estimates from SPSS are shown in Table 5.5.

Table 5.5: Model estimation results

Variables	**B**	**S.E.**	**Wald**	**df**	**Sig.**	**Exp(B)**
Household income(1)	2.084	1.128	3.412	1	0.065**	8.037
Household income(2)	2.176	1.050	4.298	1	0.038*	8.813
Recycling habit	0.962	0.519	3.441	1	0.064**	2.617
Economic benefits	-0.891	0.491	3.296	1	0.069**	0.410
Constant	-4.538	1.701	2.822	1	0.093**	0.011

* and ** denote significance at 5% and 10% level

-2 log likelihood = 125.363; Cox & Snell R^2 = 0.219; Nagelkerke R^2 = 0.329

Since the standard errors of Beta (β) coefficients are all less than 2.0, multicollinearity amongst the independent variables was not observed. It is observed that the only explanatory variable significant at the 5% level is "Income Level (2)" which in our case refers to the "upper middle class". Those that are significant at 10% level are "Place", "Recycling habit" and "Economic benefits". The estimated co-efficient for all the significant explanatory variables are positive except "Economic benefits". It is clearly evident that the significance of the variables “Recycling habit” and “Economic benefits” corroborates the result of Wang et al., (2011). Amongst the explanatory variables entering the logit, only “Income level” was taken to be categorical (with the first category taken as the reference) while retaining the remaining as covariates. Since income is a categorical variable, a one unit increase in the explanatory variable from x_7 to $(x_7 + 1)$, the odds of willingness to participate changes from $(e^{\beta_0} \cdots e^{\beta_7 x_7} \cdots e^{\beta_{16} x_{16}})$ to $(e^{\beta_0} \cdots e^{\beta_7 (x_7+1)} \cdots e^{\beta_{16} x_{16}})$. In other words, the odds ratio (OR) of willingness to participate is e^{β_7}. From *Table 5*.5 it was observed that the odds of willingness to participate in recycling of e-waste increases, when the income level changes from lower class (defined by us as ‘1’ and since being the reference is by default taken as "0" by SPSS) to upper middle class (defined by us as ‘3’ and coded as '2' by SPSS). Alternatively, this could be interpreted as that the odds of willingness to participate are 8.813 times higher for upper middle class than they are for the low income respondent (the reference category). In this case, since the probability of Wald statistic $(\chi^2(1, N = 148) = 4.298, p < 0.038)$ was less than or equal to the 5% significance level, the null hypothesis that the B coefficient corresponding to “Income level (2)” is equal to zero is rejected.

The results can be verified from the fact that the fitted model logit for households having a low level of income (where $x_7(2) = 0; x_7(3) = 0$ and others zero) is $L(P_{low}) = \{-4.538\}$, and similarly for households coming from the upper middle class (where $x_7(3) = 1$ and others zero) is $L(P_{high}) = \{-4.538 + 2.176\}$. Taking the difference and remembering that the logit is the log of the odds, gives $L(P_{high}) - L(P_{low}) = \log{(odds_{high} - odds_{low})}$, which reduces to $\frac{odds_{high}}{odds_{low}} = e^{2.176} = 8.813$. Similar trend is observed at 10% significance level when the income level changes from lower class (reference category) to lower middle class (defined by us as ‘2’ and coded by SPSS as '1'). The significance of income from the survey is in close agreement with the study by Nnorom et al., (2009) on the issue of willingness to pay for green phones in Nigeria. However, our study contradicts Wang et al., (2011), who state that income has no visible effect on willingness to participate in recycling.

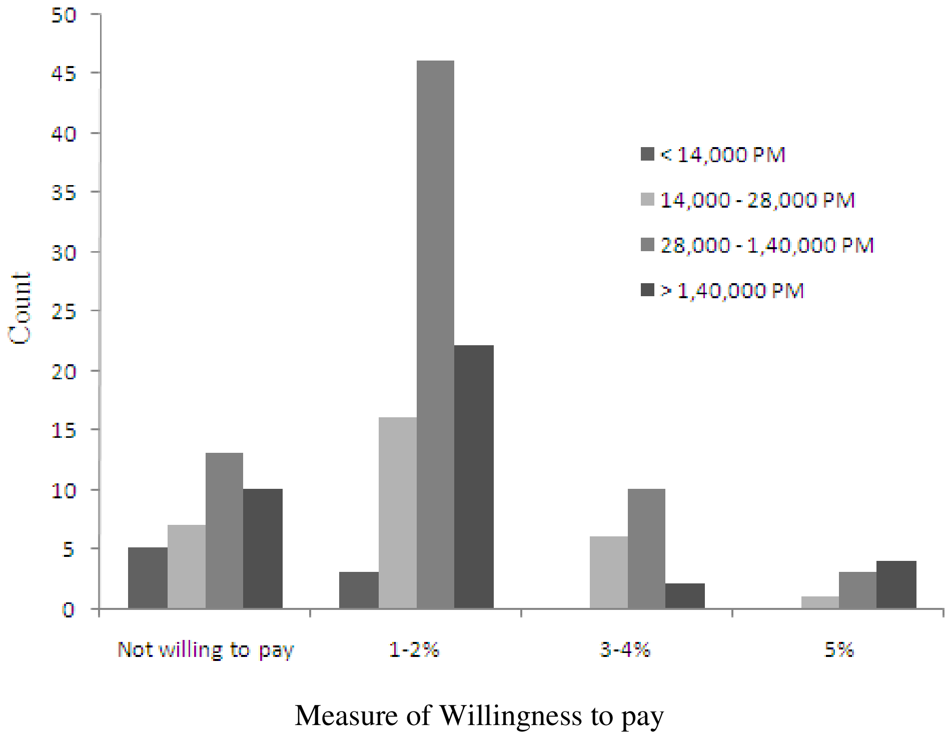

Fig. 5.7: Count of willingness to pay income-wise

A further breakdown of survey responses as observed from $Fig.$ 5.7 show that roughly about 59% of the respondents (majority constitute middle class) are willing to pay a modest recycling fee in the range of 1-2% of the product market price. An equally large percentage (23.6%) is not willing to pay any form of recycling fee. Following this, the respondents who are not willing to voluntarily pay were requested to submit their reason explaining their decision. Incidentally, 38% of this population feared that the cost of living will increase, 28% stated their inability to contribute on account of lack of time, 27% argue that the current laws and regulations do not mandate and a smaller proportion (7%) believe that it is the responsibility of the state to pay for the recycling of e-waste (see $Fig.$ 5.8).

The rest of the variables have few disparities with each other. The significance of the variable 'Place' could be explained from the view that people living in cities and metros have higher odds of participating in e-waste recycling schemes than those from villages. A similar argument suggests that when recycling habit is instilled on households having no such prior habits (reference category), will result in increase in the odds of participating in recycling by a factor of 2.6. The Indian household live in close knit communities, which raises the possibility of involving the communities in inculcating household recycling habits, which in the long run might bolster voluntary participation in future recycling schemes.

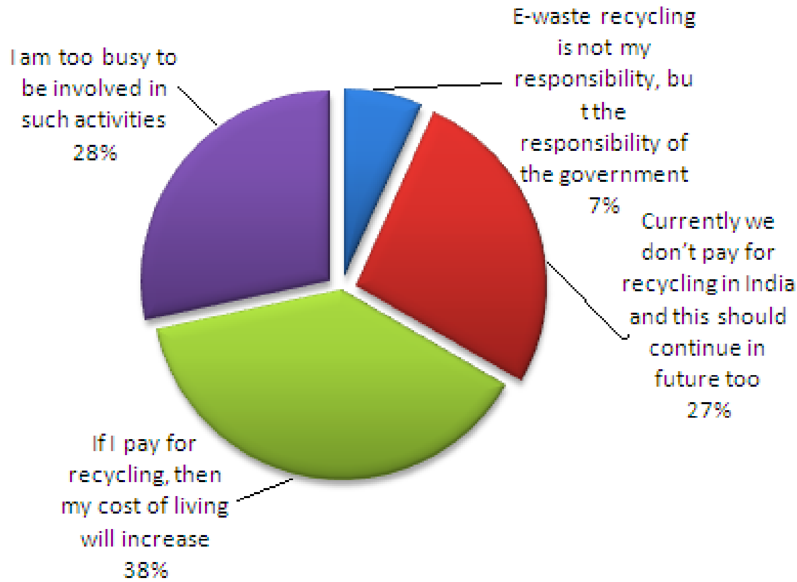

Fig. 5.8: Reasons for not willing to pay

Equivalently, recycling habit can be cultivated by disseminating and projecting the idea of environmental protection, resource conservation and sorting household waste at home to young impressionist minds right from the primary school level. The value of $EXP(B) or\ e^{\beta}$ for the variable 'Economic benefits' was 0.410 (see $Table$ 5.5), which implies a decrease in the odds of 59% (0.410-1.000=−0.59). This is to say that for each unit increase in 'Economic benefit', the subjects were 59% less likely to participate in any future recycling schemes.

Table 5.6: Predicted probabilities of willingness to participate for households living in cities

Household's level of income	**Economic Benefits***		**Recycling habit****	
	Yes=1	**No=0**	**Yes=1**	**No=0**
Low Income	0.066	0.148	0.148	0.062
Lower middle class	0.364	0.582	0.418	0.348
Upper middle class	0.385	0.604	0.604	0.369

* Recycling Habit=1; **Economic benefit=0

In India, household consider it a privilege to explore economic benefits when they dispose off their e-waste. Physically, this signifies that when market externalities (informal collection by kabbadiwalas, repair shops and scrap merchants) offer economic incentives during collection of e-waste as against no forthcoming incentives (reference category) from the formal sector, the study reveals a doubling (i.e., $\frac{1}{0.410} = 2.44$) of the odds that the respondents would not be willing to participate in formal recycling.

$Table$ 5.6 shows the predicted probabilities of willingness to participate in recycling for different groups of urban household characteristics. From $Table$ 5.6, it is quite evident that the relative risk of participating in recycling activities for a lower income household used to recycling when there are no economic benefits as compared to when economic benefits exist, is 2.24 ($= 0.148/0.066$). Similarly, the risk drops to roughly about 1.5 for the middle income group. Also observed is the fact that, the lower income urban households face the highest relative risk of participating in recycling activities who observe recycling over those who have no experience of recycling.

Table 5.7: Marginal effect of predicted probability

Predictors	**Marginal effect**	
	Discrete Marginal effect	**Instantaneous Marginal effect**
Household income(1)	0.4560328242	0.484535524
Household income(2)	0.4839253211	0.478174777
Recycling habit	0.1780626913	0.134810067
Economic benefits	-0.2172945789	-0.219112009

In the current case (see $Table$ 5.7), the marginal effect of two hypothetical rural individuals, having no prior experience of recycling and who is not interested in any form of economic benefits for disposing off his/her e-waste were computed. For the proposed hypothetical case, the predicted probabilities of willingness to participate is 0.4839 greater for the individual coming from a higher income household than for one coming from a traditional lower income household. Similarly, there is a visible increase in the predicted probabilities of willingness to participate when the hypothetical individual is initiated to the habit of recycling or is not disposed towards monetary gains from trading with e-waste.

Table 5.8: Model estimation results with interaction effects

Variables	B	S.E.	Wald	df	Sig.	Exp(B)
Household income(1)	1.557	1.192	1.706	1	0.191	4.745
Household income(2)	2.586	1.490	3.014	1	0.083**	13.277
Recycling habit	0.965	0.531	3.299	1	0.069**	2.623
Economic benefits	-1.154	1.096	1.109	1	0.292	0.315
Constant	-4.886	3.478	1.974	1	0.160	0.008
Economic benefits X Household income(2)	1.554	1.213	1.643	1	0.200	4.733
Economic benefits X Education(2)	-6.386	0.877	0.530	1	0.467	0.528

* and ** denote significance at 5% and 10% level

-2 log likelihood = 121.090; Cox & Snell R^2 = 0.241; Nagelkerke R^2 = 0.362

From the model summary of the interaction effect model (see $Table$ 5.8), it was observed that the value of $-2Log(likelihood)$ to be 121.090. With just the main effects it was 125.363. The difference is only 4.273. This is approximately χ^2 with 2 degree of freedom (the degrees of freedom is the number of extra parameters in the more complex model), so certainly not significant. Though the interaction terms are not significant, one can draw certain general trends from the new model. From the $Table$ 5.8, one can interpret that despite e-waste trade under the expectation of economic benefit gaining ground, the odds of household willingness to participate in recycling welcomingly increases with increase in their income status. In stark contrast, for the case of higher educated individuals (masters/PhD), the allure of economic benefits results in a decrease in the odds of participation. From an academic point of view, our study suggests that in a level playing field when there exists no allure of economic benefits, the odds of participation in recycling increases more for higher educated individuals than for less educated individuals. Although both gender and the dummy variable "Gender×Economic Benefit" were not found significant, one observes the interesting trend that the odds of participation for both males and females decreases when the individuals look for some form of economic benefit from their e-waste transaction.

Residents in India have historically benefited financially from selling their waste to hawkers, scrap dealers and second hand market. The thriving repair business and second hand market are market conditions that are realities in China and India. This relationship naturally evolved over the years in the absence of any formal channel, implying that any future take back policy implementing EPR will not be successful in isolation so long as competition from these non-formal channels exists. Formal recyclers are liable to comply with pollution control measures and environmental standards, which the informal sector apparently flouts thereby allowing them to buy e-waste at higher prices than what the formal sector can afford. Wang et al., (2011) also report similar results as they argue for a country wide regulation requiring consumers to compulsorily contribute to the recycling fund by making a payment which shall finance e-waste recycling. But this would entail depriving the only source of livelihood to hundreds of thousands of those engaged in the existing informal chain.

So long as this informal channel is not reined in, the ‘pay afterward’ scheme which is the preferred financing model for the respondents in our sample invariably might become ineffective because consumers can sell obsolete goods to such channels for financial gain. Given the reluctance of the state to participate in the business of managing e-waste, which it considers as an additional burden, ‘monthly recycling fee’ scheme may not be the viable alternative. The only plausible alternative which complements the respondents’ perception of getting economic benefits from the disposal of used EEE goods is the ‘deposit-refund’ scheme. Uwasu et al. (2012) argue that to achieve a certain level of waste reduction, the "pay afterwards" scheme involves the highest fees. The authors also report that the "deposit/refund" scheme is comparatively cheaper than the "pay afterwards" scheme, especially when the consumers are less sensitive to product prices than to recycling fees. Moreover, incorporating deposit/refund schemes in the take back program motivates and stimulates consumer participation in e-waste collection and boosting recycling rates. Presumably, our study clearly underscores the behavior of a composite individual who has an inclination to be financially rewarded from his e-waste recycling activity, is least disposed towards paying a recycling fee affront ("pay before") and who in the event of legislation would be willing be pay a modest fee. Future legislation in favor of an EPR take-back policy should be structured in line with the regional aspirations and be sensitive to the potential behavior of the residents towards such policies.

5.5 Policy Perspective

This study uncovers a peculiar nature of market for recycling in India. As most of the e-waste materials in India are being collected by informal scrap collectors at a monetary exchange rate much higher than any formal recycler can competitively match, Extended Producer Responsibility (EPR) model of e-waste recycling is likely to fail because it imposes cost to consumers. However, as India becomes urbanized rapidly, the people's mindset will change in future so that they will gradually participate (as the results show). More environmental awareness and habit formation will also help. The results show that competition from informal scrap dealers is the most crucial hindrance to moving towards a formal re-cycling model in India. What should government do now as informal recycling is environmentally more costly (larger social cost and more economic benefit for individual)? Clearly market mechanism fails here due to externality. This is not an easy task for policy makers to choose either side as livelihood of large section of poor people depends on this informal sector. One possible way would be to giving informal sector some economic incentive to collaborate with the formal sector. This low-cost informal network can be channelized by manufacturers in their future collection program.

5.6 Conclusions

The growing concern for developing effective e-waste management triggered, though albeit late, the e-waste handling rules which came into effect from May, 2012. The rules lack clarity, they are not mandatory while remaining silent on several important issues like monitoring, enforcement, funding and the role of the informal sector. The results and arguments put forth in this research will immensely benefit in the understanding and drafting of appropriate legislative measures in the future. The respondents of the survey are the group of people from a case university. This group of people are expected to be well educated, as a result, might be more concerned about e-waste recycling than ordinary citizens. Our study being the first, limited, attempt at analyzing this problem in the Indian context and therefore the conclusions may not hold for all of India and for all actors. However, it lays the groundwork for future studies with more complexity to be undertaken at a broader national level to test the robustness of the estimates presented in this research. The study contributes to knowledge by suggesting that to mitigate issues in the existing e-waste management practices, sound management of e-waste through EPR incorporating the WEEE directives is central. A national mandatory program that at least puts collection responsibility on the producers will scale up the incentive for formalization of recycling in India. Selective evidence from our study clearly indicates that residents are principally averse to making payment in advance for e-waste recycling. Seemingly, even in the alternate scheme, which is the "pay afterwards" scheme, there is every likelihood that leakages in the system might percolate through illegal disposal to avoid paying the fees. Concurrently, the study also reports that economic benefits are vital to participation in e-waste recycling activities. Although further research is needed, in light of the limited findings, the findings from the study justifiably argues for the appropriateness of deposit-refund financing model for the management of e-waste in India, a policy that will moderate the people’s expectation for financial gain from disposing their e-goods. In the event of EPR becoming a policy instrument in India, the possibility of realizing increased returns through the dealer/retailer channel needs further exploration. Supposedly, our study substantiates this, given that majority of the respondents’ prefer for “best exchange offer” as a criterion for disposing off their e-waste. Illegal imports of WEEE have the potential to undermine future EPR legislation. Illegal imports together with the informal downstream processes are existing market anomalies that needs to be addressed since they represent major dysfunctions of the current EPR legislation.

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Chapter 6

Third Party WEEE Remanufacturing

6.1 Introduction to third party remanufacturing

An attempt was made to develop a two period model for a single firm with single product setting (no competition) in the first period and potential competition in the second period. The study builds on the two-period models proposed by Majumder and Groenevelt (2001), Ferguson and Toktay (2005) and Ferrer and Swaminathan (2006). The mathematical framework was adopted from Webster and Mitra (2007) and Chiang et al. (2003) and solutions independently arrived using a two stage game theoretic model. In period-1, the manufacturer (M) sells the new product. These products are taken back and remanufactured by the remanufacturer (R). This is followed by the manufacturer selling the new product and remanufacturer selling refurbished product in period-2. Therefore, in second period competition is between the new products and the remanufactured products. For simplicity, the length of the period is assumed as equal to the useful life of the product. Further, it was assumed that the manufacturer has to collect the product under the take-back law and the product is remanufactured once. Here, period-2 was analyzed using Game theory (Stackelberg competition). In Stackelberg competition, the leader (M) is aware of the follower's (R) optimal response and makes the first move accordingly. The follower (R) responds this with its corresponding optimal response which is analyzed using backward induction. The objective is therefore to investigate how the competition from remanufactured units affects the pricing decision of the OEMs (M). The market is conceptualized for a single product which is either sold as new or sold with the labeling as remanufactured. This labeling affects the consumers utility and purchasing attitude. Any consumer buys the product only if the net utility exceeds the quoted price. At the end of period-1, the product has reached its end-of-life status, which under the requirement of take-back law have to be collected by the manufacturer who then sells it to the remanufacturer. The remanufacturer remanufactures the products and sells in the market in period-2. The manufacturer and the remanufacturer compete in the market in the period-2. Products that cannot be remanufactured are disposed and the disposal costs are borne by the manufacturer. Such $2-$period actions are repeated over time with the manufacturer introducing the next generation products at the start of period-3 and competing with the remanufacturer in period-4.

6.1.1 Nash equilibrium

A strategy game is a model of interacting decision makers. Here each player has a set of possible actions. The model captures the interaction between the players by allowing each player to be affected not only by his/her actions but also by the actions of all players. More precisely, a strategic game is defined as:

Definition 6.1: A strategic game (with ordinal preferences) consists of

- a set of players
- for each player, there is a unique set of actions (or pure strategies)
- for each player, preferences over the set of action profile (pay-off or utility function)

In a strategic game, it is frequently convenient to specify the player's preferences through a pay-off function. Here the payoff's have only ordinal significance. For example, if a player's payoffs to the action profiles a, b and c are 1, 2 and 10, then the only conclusion that can be made is that the player prefers c to b and b to a; the numbers do not imply that the preferences between c and b is stronger than her preference between a and b. Time is completely absent from the model. The idea is that each player chooses her action once and for all, while all the players choose their actions simultaneously, in the sense that no player is informed, when he chooses his action and of the action chosen by any other player. Each player chooses the best available action and this best available action depends in general, on the other player's actions. Therefore, each player must form a belief about the other player's actions and such belief is derived from his/her past experience playing the game, and that this experience is sufficiently extensive that he/she knows how his/her opponents will behave. This philosophy is embodied in the following definition:

Definition 6.2: A Nash (1950) equilibrium is an action profile a^* with the property that no player 'i' can do better by choosing an action different from a_i^* given that every other player 'j' adheres to a_j^*.

This concept can be understood by considering a game involving two players (pure strategy), each of whom has two available actions, which we call A and B. If the players choose different actions, they each get a payoff of 0. If they both choose A, they each get 2, and if they both choose B, they each get 1. The coordination game can be represented as follows: when player-1 chooses a row, the player-2 chooses a column, and the resulting pay-offs are listed in parenthesis, with the first component corresponding to player-1's payoff. This is shown in Table 6.1.

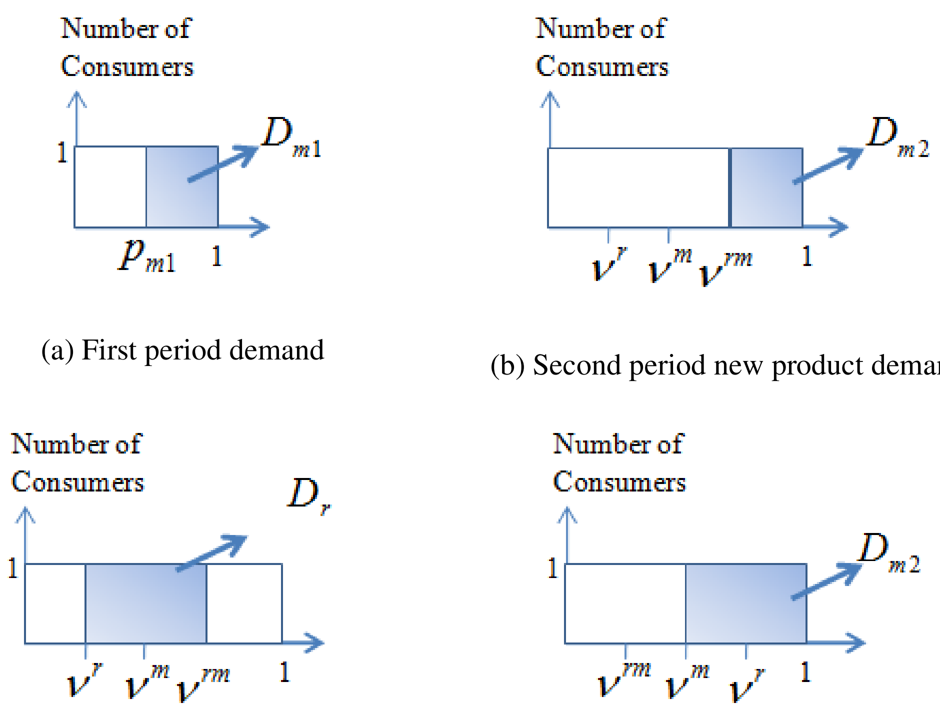
Table 6.1: Pay-off matrix

		Player-2	
		A	B
Player-1	Strategy A	$(2, 2)$	$(0, 0)$
	Strategy B	$(0, 0)$	$(1, 1)$

The action profile (B|B) is an equilibrium, since a unilateral deviation to A by any one player would result in a lower payoff for the deviating player. Similarly, the action profile (A|A) is also an equilibrium. Sometimes, Nash equilibrium solutions can sometimes correspond to outcomes that are inefficient, in the sense that there exist alternative outcomes that are both feasible and preferred by all players. This is the case, for instance, with the equilibrium (B|B) in the coordination game above. Following this, Nash (1951) generalized the concept of the solution of two-person zero-sum game to the set of equilibrium points which is simply the set of all pairs of opposing “good strategies”.

6.2 Mathematical Framework for Modeling Competition between Manufacturer and Remanufacturer

Consumer may buy the product either from the manufacturer or the remanufacturer. To model the difference in consumer preferences, the consumer willingness to pay (or sometimes called the perceived valuation, (v) was assumed to be uniformly distributed in the interval [0, 1] having a density of 1 within the consumer population, which means that the total demand is 1 if all consumers purchase the product. In other words, each consumer uses at most one unit. The total population of consumers (market size) is normalized to unity. Further it was assumed that each consumer's willingness to pay for a remanufactured product is a fraction of their willingness to pay for the new product. This means that if the customer valuation for new goods be v; then the customer valuation for remanufactured goods will be θv where $\theta \in (0, 1)$. In other words, θ is a measure of the acceptability of products from the remanufacturer. Equivalently, 1-θ represents the customer product differentiation or the gap in quality that exist in the two channels. Note that if θ=0, the remanufacturer is eliminated from the market since consumers are unwilling to pay for a remanufactured product. Similarly when θ=1, consumers perceive both the new and remanufactured product as identical and are willing to pay equivalent price for both the products. We assume a 2−period model, where the prices for new products in the first and second period are p_{m1} and p_{m2}, respectively.



(a) First period demand

(b) Second period new product demand

(c) Second period remanufactured product demand

(d) Second period new product demand

Fig. 6.1: Relationship between indifference points

6.2.1 Demand functions

For period-1, the demand function (D_{m1}) is represented by the consumer surplus $1 - p_{m1}$ (see Fig. 1a). In period-2, consumers have the choice of buying either from the manufacturer or the remanufacturer. All consumers whose valuation satisfies $v - p_{m2} > \Theta v - p_r$ would consider buying from the manufacturer. This reduces to $v > \frac{p_{m2} - p_r}{1-\Theta}$ or $v > v^{rm}$ (see Fig. 1b). Alternatively, for $v < v^{rm}$, the consumer prefers the remanufacturer. The consumer whose valuation v equals v^{rm}, is indifferent between the two choices. The marginal consumer whose valuation v^m equals p_{m2} is indifferent to buying from the manufacturer or not at all. Similarly, the marginal consumer whose valuation v^r equals $p_r/_\Theta$ is also indifferent to buying from the remanufacturer or not at all. This is to suggest that for the cases where $v > v^m$ and $v > v^r$, the consumer would consider buying from the manufacturer and remanufacturer, respectively. Alternatively, if $v < v^m$ and $v < v^r$, the manufacturer and the remanufacturer respectively will be priced out of the market. For the case where $v^m < v^r$, it is straightforward to express the demand function (D_{m2}) equal to $1 - p_{m2}$. Now let us consider the relation between the three indifference points v^r, v^m and v^{rm}. To realize this, two different cases were considered.

Case (i): If $v^m \geq v^r$, which means $p_{m2} \geq p_r/_\Theta$

Multiplying both the sides of the expression with $(-\Theta)$, results in $-\Theta p_{m2} \leq -p_r$. Subtracting the resulting expression from p_{m2}, leads to $p_{m2} \leq \frac{p_{m2} - p_r}{1-\Theta}$. Comparing the two expressions results in $p_r/_\Theta \leq p_{m2} \leq \frac{p_{m2} - p_r}{1-\Theta}$ for $v^r \leq v^m \leq v^{rm}$ (see Fig. 6.1b). Therefore, the demand function of the manufacturer (D_{m2}) will be equal to $1 - \min\{v^{rm}, 1\}$. Similarly the demand function of the remanufacturer (D_r) will be equal to $\min\{v^{rm}, 1\} - v^r$ (see Fig.6.1c). The resulting demand functions are:

$$D_{m2} = \begin{cases} 1 - v^{rm}, & for \;\; v^{rm} \leq 1 \\ 0 & otherwise \end{cases} \tag{1}$$

$$D_r = \begin{cases} v^{rm} - v^r, & for \;\; v^{rm} \leq 1 \\ 1 - v^r & otherwise \end{cases} \tag{2}$$

For $v^{rm} \leq 1$, the following results $\frac{p_{m2} - p_r}{1-\Theta} \leq 1$ which reduces to $p_{m2} \leq p_r + 1 - \Theta$.

Equivalently, for $v^{rm} \geq 1,\ p_{m2} \geq p_r + 1 - \Theta$. The expression $v^{rm} - v^r$ can be further simplified to $\frac{\Theta p_{m2} - p_r}{\Theta(1-\Theta)}$.

Case (ii): If $v^m \leq v^r$, which means $p_{m2} \leq {}^{p_r}/_{\Theta}$

Multiplying both sides of the inequality by $(-\Theta)$ and adding p_{m2}, results in $p_{m2} \geq \frac{p_{m2}-p_r}{1-\Theta}$. Combining both the expressions, gives $\frac{p_{m2}-p_r}{1-\Theta} \leq p_{m2} \leq {}^{p_r}/_{\Theta}$ or $v^{rm} \leq v^m \leq v^r$ (see Fig. 1d). The resulting demand functions are:

$$D_{m2} = 1 - v^m = 1 - p_{m2} \text{ and } D_r = 0 \tag{3}$$

Aggregating both the cases, the demand functions in period-2 can be expressed as:

$$D_{m2} = \begin{cases} 1 - p_{m2} & if\ p_{m2} \leq {}^{p_r}/_{\Theta} \\ 1 - \frac{p_{m2}-p_r}{1-\Theta} & if\ {}^{p_r}/_{\Theta} \leq p_{m2} \leq p_r + 1 - \Theta \\ 0 & if\ p_{m2} \geq p_r + 1 - \Theta \end{cases} \tag{4}$$

$$D_r = \begin{cases} 1 - {}^{p_r}/_{\Theta} & if\ p_r \leq p_{m2} - (1-\Theta) \\ \frac{\Theta p_{m2}-p_r}{\Theta(1-\Theta)} & if\ p_{m2} - (1-\Theta) \leq p_r \leq \Theta p_{m2} \\ 0 & if\ p_r \geq \Theta p_{m2} \end{cases} \tag{5}$$

6.2.2 Profit functions

Given the demand function of the manufacturer in period-1, the corresponding profits it would earn equal

$$\pi_{m1} = (1 - p_{m1})(p_{m1} - c) \tag{6a}$$

Here c represents the unit cost of production. The first segment of the demand functions from Eqs. (4) and (5) occurs when all demand goes to the manufacturer and remanufacturer, respectively. The second segment on the other hand represents the case where both players exist in the market. The third segment occurs when demand for both is zero. It is obvious from the second segments of Eqs. (4) and (5), that as p_r increases, the demand in the manufacturer channel increases and as p_{m2} increases, the demand in the remanufacturer channel also increases. This is the classic case of substitution effect of prices of one channel with the demand of the other channel.

The corresponding profit function of the manufacturer and the remanufacturer in period-2 can be expressed as:

$$\pi_{m2} = D_{m2}(p_{m2} - c) - c_d(\gamma D_{m1} - D_r) \quad (6b)$$

$$\pi_r = D_r(p_r - c_r) \quad (7)$$

Eq. (6b) states that the manufacturer is solely responsible for the proper disposal of those returned units which cannot be sold as a remanufactured product. Here, c_r c_d and γ respectively, represents the unit remanufacturing cost, unit cost of disposal and the fraction of products sold in period-1 that are returned after its useful life. So the total profit function of the manufacturer in both the periods is:

$$\pi_m = (1 - p_{m1})(p_{m1} - c) + (1 - \frac{p_{m2}-p_r}{1-\theta})(p_{m2} - c) - c_d[\gamma(1 - p_{m1}) - \frac{\theta p_{m2}-p_r}{\theta(1-\theta)}] \quad (8)$$

Subject to the condition $p_r/_\theta \leq p_{m2} \leq p_r + 1 - \theta$. This condition is denoted as $C1$

The following assumptions are made:

- $\boldsymbol{A1}$: Whenever manufacturer (M) can choose multiple prices that result in the same profit for M, he selects the lowest price.
- $\boldsymbol{A2}$: Whenever remanufacturer (R) can choose multiple prices that result in the same profit for R, he selects the lowest price
- $\boldsymbol{A3}$**:** $c_r \leq \theta$. This is necessary to ensure that there is an incentive to remanufacture; and $c + c_d < 1$. This is to maintain the low cost structure of the model
- $\boldsymbol{A4}$: R will set his price such that Demand $\leq$ Supply i.e., $D_r \leq \gamma(1 - p_{m1})$. The assumption $A4$: $\frac{\theta p_{m2}-p_r}{\theta(1-\theta)} \leq \gamma(1 - p_{m1})$ can be further reduced to the inequality $p_r \geq \theta[p_{m2} - \gamma(1-\theta)(1-p_{m1})]$ and will be widely used in the remainder of the analysis. Let us denote this condition as $C2$. Notice that $C2$ should always hold true.

6.2.3 Reaction functions

Reaction of manufacturer and remanufacturer are defined by reaction function and are developed next.

6.2.3.1 The manufacturer's reaction function

The manufacturer has control over only one variable to maximize his profit, the selling price of new product p_{m2}. Setting the first derivative of the manufacturer's profit function for the case where both the players exist in the market (Eq. 8) equal to 0, gives

$$\frac{\partial \pi_m}{\partial p_{m2}} = \left(1 - \frac{2p_{m2} - p_r - c}{1-\theta}\right) + \frac{c_d}{1-\theta} = 0 \quad (9)$$

It follows that

$$p_{m2}^* = \frac{1-\theta+c+c_d+p_r}{2} \quad (10)$$

and the second order derivative of π_m is:

$$\frac{\partial^2 \pi_m}{\partial {p_{m2}}^2} = -\frac{1}{1-\theta} - \frac{1}{1-\theta} = -\frac{2}{1-\theta} < 0 \quad (11)$$

Clearly, π_m is a concave function with the maximum value at p_{m2}^*. But condition $C1$ and $C2$ need to hold true for this value of p_{m2}^*. For $C1$ to hold for the case where both players exist in the market, the optimal selling price of the manufacturer in period-2 should satisfy, ${p_r}/{\Theta} \leq p_{m2}^* \leq p_r + 1 - \Theta$, which results in the two expressions: $p_r < \frac{\theta(1-\theta+c+c_d)}{2-\theta}$ and $p_r > c + c_d - (1 - \Theta)$. Therefore, the optimal reaction price p_{m2}^* in the region is defined by

$$c + c_d - (1 - \Theta) < p_r < \frac{\theta(1-\theta+c+c_d)}{2-\theta} \quad (12)$$

For the sake of convenience, let us denote the left hand limit of p_r as $'A'$ and the right hand limit as $'B'$. Similarly for $C2$ to hold

${p_r}/{\Theta} \geq \frac{1-\Theta+c+c_d+p_r}{2} - \gamma(1-\theta)(1-p_{m1})$ which reduces to

$$p_r \geq \frac{\Theta[c+c_d+(1-\Theta)\{1-2\gamma(1-p_{m1})\}]}{2-\Theta} \quad (13)$$

Note that Eqs. (12) and (13) needs to hold. Let us denote the RHS of Eq. (13) as $'C'$. Also since the term of Eq. (13), $\{1 - 2\gamma(1 - p_{m1})\} < 1$, $C \leq B$ always hold. Therefore, the domain of the reaction function becomes $\max\{A, C\} < p_r < B$.

This leaves the scope to investigate the case where the manufacturer is priced out of the market. The primary objective here is to determine the optimal p_{m2}^* for which the consumer declines any purchase from the manufacturer. The remanufacturer can then appropriately choose an action by setting his corresponding p_r. For this scenario, $p_{m2}^* \geq p_r + 1 - \theta$ was found from Eq. (4). Further from assumption $A1$, setting $p_{m2}^* = p_r + 1 - \theta$ and subsequently, applying $C2$: ${p_r}/{\Theta} \geq p_r + 1 - \theta - \gamma(1-\theta)(1-p_{m1})$ results in

$p_r \geq \Theta(1-\gamma(1-p_{m1}))$. The third scenario wherein the remanufacturer is priced out need not be considered for further analysis and therefore the action of the manufacturer is not required.

Summarizing, the price functions can be expressed as:

$$P_{m2}^{*} = \begin{cases} \dfrac{1-\theta+c+c_d+p_r}{2}, & \max\{A,C\} \leq p_r \leq B \\ p_r+1-\theta, & \theta(1-\gamma(1-p_{m1})) \leq p_r \leq A \end{cases} \tag{14}$$

The manufacturer's reactions functions to the remanufacturer's prices are illustrated in Table 6.2 below.

Table 6.2: Manufacturer's response to price competition

Remanufacturer's action	**Manufacturer's reaction**	**Remarks**
Case I: $A > C$		
$p_r = \Theta(1-\gamma(1-p_{m1}))$	$p_{m2}^{*} = 1-\gamma\theta(1-p_{m1})$	Only remanufacturer exists in the market.
$\Theta(1-\gamma(1-p_{m1})) < p_r < c+c_d-(1-\Theta) = A$	$p_{m2}^{*} = p_r+1-\theta$	Only remanufacturer exists in the market.
$p_r = c+c_d-(1-\Theta)$	$p_{m2}^{*} = c+c_d$	Only remanufacturer exists in the market.
$c+c_d-(1-\Theta) < p_r < \dfrac{\theta(1-\theta+c+c_d)}{2-\theta} = B$	$p_{m2}^{*} = \frac{1-\theta+c+c_d+p_r}{2}$	Both exist in the market.
$p_r = \frac{\theta(1-\theta+c+c_d)}{2-\theta}$	$p_{m2}^{*} = \frac{c+c_d+(1-\Theta)}{2-\theta}$	Only manufacturer exists in the market.
Case II: $A < C$		
$p_r = \frac{\Theta[c+c_d+(1-\Theta)\{1-2\gamma(1-p_{m1})\}]}{2-\Theta} = C$	$p_{m2}^{*} = \frac{c+c_d+(1-\Theta)(1-\gamma(1-p_{m1}))}{2-\theta}$	Only remanufacturer exists in the market.
$C < p_r < \frac{\theta(1-\theta+c+c_d)}{2-\theta}$	$p_{m2}^{*} = \frac{1-\theta+c+c_d+p_r}{2}$	Both exist in the market.
$p_r = \frac{\theta(1-\theta+c+c_d)}{2-\theta}$	$p_{m2}^{*} = \frac{c+c_d+(1-\Theta)}{2-\theta}$	Only manufacturer exists in the market.

For the Case I, where $\Theta(1-\gamma(1-p_{m1})) \leq p_r \leq A$, the consumer valuation for both the goods can be expressed as $v^r \geq v^m$, which means that the manufacturer responds by hiking the price of his goods in order to back-off from the market. When $p_r \in (A,B)$, both the manufacturer's and remanufacturer's compete in the market for sales. However, in the case when $p_r = B$, the manufacturer prices out the remanufacturer from the market. Similarly, for the Case II, in the instance of $p_r \in \left(C,\ \frac{\theta(1-\theta+c+c_d)}{2-\theta}\right)$, both the players compete in the market. As in when $p_r = \frac{\theta(1-\theta+c+c_d)}{2-\theta}$, the manufacturer sets a price such that the remanufacturer is forced out of the market.

6.2.3.2 The remanufacturer's reaction function

The remanufacturer only makes decisions concerning the remanufactured product. Setting the first derivative of the remanufacturer's profit function corresponding to the duopoly case (Eq. (7)) for period-2 equal to zero, results in

$$\frac{\partial \pi_r}{\partial p_r} = \frac{\theta p_{m2}+c_r}{\theta(1-\theta)} - \frac{2p_r}{\theta(1-\theta)} = 0 \tag{15}$$

It follows that

$$p_r^* = \frac{\theta p_{m2}+c_r}{2} \tag{16}$$

And the second order derivative of π_r is:

$$\frac{\partial^2 \pi_r}{\partial {p_r}^2} = -\frac{2}{1-\theta} < 0 \tag{17}$$

Given that p_r^* needs to hold for condition $C1$, we have ${p_r^*}/{\Theta} \leq p_{m2} \leq p_r^* + 1 - \Theta$ which results in two inequalities $p_{m2} \geq \frac{c_r}{\Theta}$ and $p_{m2} \leq \frac{c_r+2(1-\theta)}{2-\Theta}$. Combining them gives

$$\frac{c_r}{\theta} \leq p_{m2} \leq \frac{c_r+2(1-\theta)}{2-\theta} \tag{18}$$

Similarly, for condition $C2$ to hold, which is ${\theta p_{m2} + c_r}/{2\theta} \geq p_{m2} - \gamma(1-\theta)(1-p_{m1})$ gives

$$p_{m2} \leq \frac{c_r}{\theta} + 2\gamma(1-\theta)(1-p_{m1}) \tag{19}$$

Denoting the left and right limit terms of Eq. (18) as $'D'$ and $'E'$ and the RHS term of Eq. (19) as $'F'$, it was observed that $D \leq F$ is always true which leads us to the domain $D \leq p_{m2} \leq \min\{E, F\}$. If however condition $C2$ does not hold i.e. demand of remanufactured goods exceeds their supply, then $p_r^* \leq \theta(p_{m2} - \gamma(1-\theta)(1-p_{m1}))$. In such a situation, one can set $p_r^* = \theta(p_{m2} - \gamma(1-\theta)(1-p_{m1}))$. The value of p_r^* should hold for $C1$ i.e., ${p_r^*}/{\Theta} \leq p_{m2} \leq p_r^* + 1 - \Theta$ which results in two inequalities

$\gamma(1-\theta)(1-p_{m1}) \geq 0$ and $p_{m2} \leq 1 - \gamma\theta(1-p_{m1})$

The other scenario where the remanufacturer is priced out of the market will only be possible when $\frac{p_r^*}{\theta} \geq p_{m2}$ and which is where condition $C1$ does not hold. Using assumption $A2$, the inequality can be transformed to $\frac{p_r^*}{\theta} = p_{m2}$. Now combining these expressions, the reaction functions of the remanufacturer can be expressed as:

$$For \;\; E \geq F, p_r^* = \begin{cases} \theta p_{m2}, & if \; p_{m2} \leq D \\ \frac{\theta p_{m2}+c_r}{2}, & if \; D \leq p_{m2} \leq F \\ \theta(p_{m2} - \gamma(1-\theta)(1-p_{m1})), & if \; F \leq p_{m2} \leq 1 - \gamma\theta(1-p_{m1}) \end{cases} \quad (20)$$

$$For \;\; E \leq F, \; p_r^* = \begin{cases} \theta p_{m2}, & if \; p_{m2} \leq D \\ \frac{\theta p_{m2}+c_r}{2}, & if \; D \leq p_{m2} \leq E \end{cases} \quad (21)$$

Table 6.3: Remanufacturer's response to price competition

Manufacturer's action	**Remanufacturer's reaction**	**Remarks**
Case III: $E \geq F$		
$0 \leq p_{m2} < \frac{c_r}{\theta} (= D)$	$p_r^* = \theta p_{m2}$	Only manufacturer exists in the market.
$p_{m2} = \frac{c_r}{\theta}$	$p_r^* = \theta p_{m2} = c_r$	Only manufacturer exists in the market.
$D < p_{m2} < \frac{c_r}{\theta} + 2\gamma(1-\theta)(1-p_{m1}) = F$	$p_r^* = \frac{\theta p_{m2}+c_r}{2}$	Both exist in the market.
$p_{m2} = F$	$p_r^* = c_r + \gamma\theta(1-\theta)(1-p_{m1})$	Both exist in the market.
$F \leq p_{m2} < 1 - \gamma\theta(1-p_{m1})$	$p_r^* = \theta(p_{m2} - \gamma(1-\theta)(1-p_{m1}))$	Both exist in the market.
$p_{m2} = 1 - \gamma\theta(1-p_{m1})$	$p_r^* = \Theta\big(1 - \gamma(1-p_{m1})\big)$	Only remanufacturer exists in the market.
Case IV: $E \leq F$		
$p_{m2} < D$	$p_r^* = \theta p_{m2}$	Only manufacturer exists in the market.
$p_{m2} = D$	$p_r^* = \theta p_{m2} = c_r$	Only manufacturer exists in the market.
$D < p_{m2} < \frac{c_r+2(1-\theta)}{2-\theta} = E$	$p_r^* = \frac{\theta p_{m2}+c_r}{2}$	Both exist in the market.
$p_{m2} = E$	$p_r^* = \frac{c_r+\theta(1-\theta)}{2-\theta}$	Only remanufacturer exists in the market.

For the Case III, where $0 \leq p_{m2} \leq D$, the consumer valuation for both the goods can be expressed as $v^r \leq v^m$, which means that the remanufacturer no longer can compete in the market. When $p_{m2} \epsilon (D, F)$, both the manufacturer's and remanufacturer's compete in the market for sales and where the demand for remanufactured goods are less than the total supply. Similarly, when $\mathrm{p_{m2}} \epsilon\, [\mathrm{F}, 1 - \gamma\theta(1 - p_{m1}))$, both the manufacturer's and remanufacturer's compete in the market for sales and where the demand for remanufactured goods are exactly equal to the total supply. In the event $p_{m2} = 1 - \gamma\theta(1 - p_{m1})$, the remanufacturer reacts with a price setting that eliminates the competition from the manufacturer's. Similar conclusions can be made for Case IV.

6.3 Determining Nash Equilibrium from the Competition

For determining the equilibrium conditions, the study utilizes the reaction functions p_r^* and p_{m2}^* and solve them simultaneously. Recall that the inverse function of p_{m2} which is $(p_{m2}^*)^{-1}$ gives p_r as a function of p_{m2}^*. It does not matter whether one finds the inverse function of p_r^* or p_{m2}^* for analysis, the selection is based solely on the ease of calculation of the inverse function, which in this case are

$$If\ C \geq A,\ (p_{m2}^*)^{-1} = 2p_{m2} - c - c_d - (1-\theta),\ C \leq p_r \leq B \tag{22}$$

$$\text{If } C \leq A,\ (p_{m2}^*)^{-1} = \begin{cases} 2p_{m2} - c - c_d - (1-\theta), & if\ A \leq p_r \leq B \\ p_{m2} - (1-\theta), & if\ \Theta(1-\gamma(1-p_{m1})) \leq p_r \leq A \end{cases} \tag{23}$$

Now the limits of p_r have to be changed in terms of p_{m2}. To achieve this, one can substitute the values of p_r (i.e $(p_{m2}^*)^{-1}$) into the limits. So the expression $A \leq p_r \leq B$, which is the same as $c + c_d - (1-\Theta) \leq p_r(or\ \ (p_{m2}^*)^{-1}) \leq \frac{\theta(1-\theta+c+c_d)}{2-\theta}$ can be reduced to $p_{m2} \geq c + c_d$ and $p_{m2} \leq \frac{c+c_d+1-\theta}{2-\theta}$. Similarly, the inequality $C \leq p_r(or\ \ (p_{m2}^*)^{-1}) \leq B$ reduces to $p_{m2} \geq \frac{c+c_d+(1-\theta)(1-\gamma(1-p_{m1}))}{2-\theta}$ and $p_{m2} \leq \frac{c+c_d+1-\theta}{2-\theta}$. Replicating the same for the third segment of Eq. (22) which is $\Theta(1-\gamma(1-p_{m1})) \leq p_r(or\ \ (p_{m2}^*)^{-1}) \leq A$ results in $p_{m2} \geq 1 - \gamma\Theta(1-p_{m1})$ and $p_{m2} \leq c + c_d$. Combining all the expressions, results in

$$If\ C \geq A,\quad (p_{m2}^*)^{-1} = 2p_{m2} - c - c_d - (1-\theta) \quad for\ \frac{c+c_d+(1-\theta)(1-\gamma(1-p_{m1}))}{2-\theta} \leq p_{m2} \leq \frac{c+c_d+1-\theta}{2-\theta} \tag{24}$$

$$If\ C \leq A, (p_{m2}^*)^{-1} = \begin{cases} 2p_{m2} - c - c_d - (1-\theta), & for\ c + c_d \leq p_{m2} \leq \frac{c+c_d+1-\theta}{2-\theta} \\ p_{m2} - (1-\theta), & for\ 1 - \gamma\Theta(1-p_{m1}) \leq p_{m2} \leq c + c_d \end{cases} \tag{25}$$

Now, one can algebraically manipulate to retransform the cases $C \geq A$ and $C \leq A$ into variable of interest, which in this case is p_{m1}.

For $C \geq A$ (or $C \leq A$), $\frac{\theta[c+c_d+(1-\theta)\{1-2\gamma(1-p_{m1})\}]}{2-\theta} \geq (\leq) c + c_d - (1-\theta)$ holds which on further simplifying results in

$$p_{m1} \geq (\leq) 1 - \frac{1-(c+c_d)}{\gamma\theta} = X(say). \tag{26}$$

Repeating the same argument for the case $E \geq F$ (or $E \leq F$), results in $\frac{c_r+2(1-\theta)}{2-\theta} \geq (\leq) \frac{c_r}{\theta} + 2\gamma(1-\theta)(1-p_{m1})$, leading to

$$p_{m1} \geq (\leq) 1 - \frac{1-{c_r}/{\theta}}{\gamma(2-\theta)} = Y(say). \tag{27}$$

Comparing the two cases $X \geq Y$(or $X \leq Y$) i.e $1 - \frac{1-(c+c_d)}{\gamma\theta} \geq (\leq) 1 - \frac{1-{c_r}/{\theta}}{\gamma(2-\theta)}$, it was observed that

$$c_r \geq (\leq)(2-\theta)(c+c_d) - 2(1-\theta) = c_2 \tag{28}$$

Using these rearranged terms, Eq. (20) and Eq. (23) are simultaneously solved. Now the cases of interest are investigated, which in this case are $X \geq Y\ and\ X \leq Y$ and their individual sub cases are summarized in Table 6.4.

Table 6.4: Cases of interest

Main case	**Sub case**	**Equations to compare**
$X \leq Y$ $(p_{m1} \leq X / p_{m1} \geq X)$	$p_{m1} \epsilon [0, X]$	$Eqs. (21), (25)$
	$p_{m1} \epsilon [X, Y]$	$Eqs. (21), (24)$
	$p_{m1} \epsilon [Y, 1]$	$Eqs. (20), (24)$
$X \geq Y$ $(p_{m1} \leq Y / p_{m1} \geq Y)$	$p_{m1} \epsilon [0, Y]$	$Eqs. (21), (25)$
	$p_{m1} \epsilon [Y, X]$	$Eqs. (20), (25)$
	$p_{m1} \epsilon [X, 1]$	$Eqs. (20), (24)$

Noticing that many of the values of the functions are the same in different ranges, the necessary values to be compared are $\left(\theta p_{m2}, \frac{\theta p_{m2}+c_r}{2}, \theta(p_{m2} - \gamma(1-\theta)(1-p_{m1}))\right)$ with $\left(2p_{m2} - c - c_d - (1-\theta), p_{m2} - (1-\theta)\right)$ which results in six comparisons.

6.4 Model Incorporating Green consumer to the Baseline Model

The primary objective of this section is to develop necessary guidelines for remanufacturing decisions. Similar to previous sections, in this section profitability conditions for remanufacturing are identified; both for the manufacturer and the remanufacturer. Understandably, the assumptions that were made for the analysis are: (i) The remanufactured product is typically a low-cost alternative to a new product, (ii) Remanufactured products have lower valuation from the regular consumer segment, (iii) Remanufactured products are labeled with a green certification, and therefore, has a green image because it reduces the quantity of waste generated and reuses old material, and provides high value to a relatively small (albeit increasing) green consumer segment, (iv) Remanufactured product has the same functionality as a new product, and (v) Remanufacturing supply is bounded by the number of returns from previous sales. In particular, the focus is on the demand side aspects of the problem and to address direct competition between manufacturer and remanufacturer together with the existence of the green segment. It can be fairly assumed that in the near future that the existence of a green consumer segment will become a marketing opportunity for remanufacturers. Therefore, an assumption is made about the existence of a green consumer market segment, which consists of consumers who do not discount the value of the remanufactured product. This means that for such consumers, whenever there exists a choice between new and remanufactured goods, they will always prefer the remanufactured goods.

6.4.1 Demand functions

The demand and profit functions for period-1 can be expressed as:

$$D_{m1} = (1 - p_{m1}) \tag{29}$$

$$\Pi_{m1} = (1 - p_{m1})(p_{m1} - c) \tag{30}$$

Similarly, the demand functions for period-2 can be expressed as:

$$D_{m2}^{p} = \begin{cases} (1-\beta)(1-p_{m2}) & when \quad P_{m2} \le P_r/\theta \\ (1-\beta)(1-\frac{p_{m2}-p_r}{1-\theta}) & when \quad P_r/\theta \le P_{m2} \le P_r + 1 - \theta \\ 0 & when \quad P_{m2} \ge P_r + 1 - \theta \end{cases} \tag{31}$$

and for green consumer

$$D_r^p = \begin{cases} 0 & if \quad P_{m2} \geq P_r + 1 - \theta \\ (1-\beta)\dfrac{\theta_{pm2} - p_r}{\theta(1-\theta)} & if \quad P_r/\theta \leq P_{m2} \leq P_r + 1 - \theta \\ (1-\beta)(1-\dfrac{p_r}{\theta}) & if \quad P_{m2} \leq P_r/\theta \end{cases} \tag{32}$$

Eq.(31) and Eq.(32) indicate that there are two types of consumers: primary and green consumers. When the primary consumers values the new product υ, the remanufactured product is valued as $\theta\upsilon$. The green consumers on the other hand, value both the new and remanufactured products the same. With this representation, the green segment not only represents consumers who are environmentally conscious but also who care only for the functionality of the product and not for its newness. The green consumers' proportion in the market is $\beta(<1)$. It is noted that in period-2, in addition to primary consumers, there is a demand for remanufactured goods from the green consumer segment, as well. Therefore, the demand function of green consumers can be stated as:

$$\begin{aligned} D_r^G &= \beta(1 - p_r) \\ D_{m2}^G &= 0 \end{aligned} \tag{33}$$

The total demand for remanufactured and new products reduces to, respectively, $D_r = D_r^p + D_G^p$ and $D_{m2} = D_{m2}^P + D_{m2}^G$. Note that green consumers prefer not to buy the manufactured product in period-2, hence, $D_{m2}^G = 0$. The case where the manufacturer is priced out of the market (see Eq. (4)) for $p_{m2} \geq p_r + 1 - \theta$, is of no significance and is not be considered for further analysis. This leaves two scenarios, where $p_{m2} \leq p_r/\theta$, denoted as case-1 and $\dfrac{p_r}{\theta} \leq p_{m2} \leq p_r + 1 - \theta$, denoted as case-2. In case-1, where all primary consumers purchase from the manufacturer, and the demand for remanufactured products come only from the green consumer segment. The corresponding demand and profit functions are expressed as:

$$D_r = \beta(1 - p_r) \tag{34}$$

$$D_{m2} = (1-\beta)(1 - p_{m2}) \tag{35}$$

$$\Pi_{m2}(p_{m2} \mid p_r) = (1-\beta)(1-p_{m2})(p_{m2} - c) - c_d[\gamma(1-p_{m1}) - \beta(1-p_r)] \tag{36}$$

$$\Pi_r(p_r \mid p_{m2}) = \beta(1-p_r)(p_r - c_r) \tag{37}$$

Similarly, for case-2, where there exists direct competition for new and remanufactured products from the primary consumers, in addition to the presence of green consumers, the demand and profit functions are expressed as:

$$D_r = \beta(1-p_r) + (1-\beta)\frac{\theta_{pm2} - p_r}{\theta(1-\theta)} \tag{38}$$

$$D_{m2} = (1-\beta)(1-\frac{p_{m2} - p_r}{1-\theta}) \tag{39}$$

$$\Pi_{m2}(p_{m2} \mid p_r) = (1-\beta)(1-\frac{p_{m2} - p_r}{1-\theta})(p_{m2} - c) - c_d[\gamma(1-p_{m1}) - \beta(1-p_r) - (1-\beta)\frac{\theta\, p_{m2} - p_r}{\theta(1-\theta)}] \tag{40}$$

$$\Pi_r(p_r \mid p_{m2}) = [\beta(1-p_r) + (1-\beta)\frac{\theta_{pm2} - p_r}{\theta(1-\theta)}](p_r - c_r) \tag{41}$$

It is realized that remanufacturing activity is bounded by the number of products returned. Therefore, the assumption that Demand $\leq$ Supply holds. Using this assumption for case-1, the equation $\gamma(1-p_{m1}) \geq \beta(1-p_r)$ is obtained, which gives $p_r \geq 1 - \frac{\gamma}{\beta}(1-p_{m1})$.

For case-2, the same assumption gives the expression $p_r[\beta\theta(1-\theta) + K] \geq \theta(1-\theta)(\beta - \gamma(1-p_{m1}) + K\theta p_{m2}$, where $K = {(1-\beta)}/{(1-\theta)}$. The reaction functions in case-1, wherein all primary consumers prefer new products from the manufacturer can be constructed by setting the profit function of the manufacturer in period-2 to zero:

$$\frac{\partial \Pi_{m2}}{\partial p_{m2}} = (1-\beta)(1-p_{m2}) - (1-\beta)(p_{m2} - c) = 0 \tag{42}$$

The solution of which is

$$p_{m2}^* = \frac{1+c}{2} \tag{43}$$

The profit function is easily observed to be concave with the maximum value at p_{m2}^*, as

$$\frac{\partial^2 \Pi_{m2}}{\partial p_{m2}^2} = (1-\beta)(-1) + (1-\beta)(-1) = -2(1-\beta) < 0 \tag{44}$$

In a similar way, it was observed that the remanufacturer has absolute control over his prices. Hence, the reaction function of the remanufacturer can be found by setting its derivative to zero, which is

$$\frac{\partial \Pi_r}{\partial p_r} = \beta(1-p_r) + \beta(p_r - c_r)(-1) = 0 \tag{45}$$

The solution of Eq. (45) gives the reaction price as

$$p_r^* = \frac{1+c_r}{2} \tag{46}$$

Taking the second derivative, Eq. (47), it is clearly evident that the reaction function is also concave with maximum value of the remanufacturer's reaction function to be at p_r^*.

$$\frac{\partial^2 \Pi_r}{\partial p_r^2} = -2\beta < 0 \tag{47}$$

Similarly, the reaction function of the manufacturer for case-2 is found by setting

$$\frac{\partial \Pi_{m2}}{\partial p_{m2}} = (1-\beta)(1 - \frac{p_{m2} - p_r}{1-\theta}) + (1-\beta)\frac{(p_{m2} - c)}{1-\theta}(-1) + c_d \frac{1-\beta}{1-\theta} = 0 \tag{48}$$

which gives

$$p_{m2}^* = \frac{p_r + (1-\theta) + c + c_d}{2} \tag{49}$$

The second derivative, Eq.(50), indicates a concave profit function,

$$\frac{\partial^2 \Pi_{m2}}{\partial p_{m2}^2} = -2(\frac{1-\beta}{1-\theta}) < 0 \tag{50}$$

For the remanufacturer, in case-2, the reactions function of the remanufacturer is obtained by setting

$$\frac{\partial \Pi_r}{\partial p_r} = [\beta(1-p_r) + (1-\beta)\frac{\theta p_{m2} - p_r}{\theta(1-\theta)}] + (p_r - c_r)[-\beta - \frac{1-\beta}{\theta(1-\theta)}] = 0 \tag{51}$$

whose solution is

$$p_r^* = \left[\frac{1-\beta}{\theta(1-\theta)}(\theta p_{m2} + c_r) + \beta(1+c_r)\right]\left[2\beta + \frac{2(1-\beta)}{\theta(1-\theta)}\right]^{-1} \tag{52}$$

Having identified the reaction functions, the prices for the border conditions checked. Given that the case-2 refers to $\frac{p_r}{\theta} \leq p_{m2} \leq p_r + 1 - \theta$ which together with Eq. (49), reduces to

$$c + c_d - (1-\theta) \leq p_r \leq \frac{\theta(c + c_d + 1 - \theta)}{2-\theta} \tag{53}$$

Earlier it was assumed that the left hand limit of p_r as A and the right hand limit as B. Therefore, $A \leq p_r \leq B$, where A and B are independent of p_{m1}. Introducing p^*_{m2} into condition *C2* (i.e., demand $\leq$ supply), it was observed from Eq.(13) that $p_r \geq C$ and therefore the domain of the reaction function becomes $\max\{A, C\} < p_r < B$. Now if, $p^*_{m2} > p_r + 1 - \theta$ then as per our assumption *A1*, one can set $p^*_{m2} = p_r + 1 - \theta$ and applying this on the inequality demand$\leq$supply, results in: $p_r \geq D$ where D is dependent of p_{m1}. This is when the manufacturer is priced out of the market. Similarly, if $p^*_{m2} < \frac{p_r}{\theta}$, setting $p^*_{m2} < \frac{p_r}{\theta}$ and applying demand < supply; results in: $p_r \geq E$ where,

$$E = 1 - \frac{\gamma}{\beta}(1 - p_{m1}) \tag{54}$$

Combining the above results, we get the optimal reaction function shown in Table 6.5.

Table 6.5: Optimal manufacturer reaction functions in green consumer model

Price	$A \leq C \leq B$		$C \leq A \leq B$	
	Expression	Condition	Expression	Condition
$p^*_{m2} =$	$\frac{p_r + c + c_d + 1 - \theta}{2}$	$C \leq p_r \leq B$	$\frac{p_r + c + c_d + 1 - \theta}{2}$	$A \leq p_r \leq B$
	$p_r + 1 - \theta$	$D \leq p_r < A$	$p_r + 1 - \theta$	$Max(C, D) \leq p_r \leq A$
	$\frac{p_r}{\theta}$	$p_r \geq \max(B, E)$	$\frac{p_r}{\theta}$	$p_r \geq Max(B, E)$

The optimal reaction functions of the remanufacturer in case-2 can now be computed. The condition in terms of the manufacturer's price in period-2 was found to be $\frac{p_r}{\theta} \leq p_{m2} \leq p_r + 1 - \theta$ is. A little bit of arithmetic brings us to the condition in terms of the remanufacturer's price.

$$p_{m2} - 1 + \theta \leq p^*_r \leq \theta p_{m2} \tag{55}$$

Putting the expression for P_r^* from Eq.(52) in the above inequality, results in:

$$p_{m2} - 1 + \theta \leq \frac{\frac{1-\beta}{1-\theta}(\theta p_{m2} + c_r) + \beta(1 + c_r)}{2\beta + \frac{2(1-\beta)}{\theta(1-\theta)}} \leq \theta p_{m2} \tag{56}$$

Solving the inequality given in Eq.(56), it was observed that:

$$\frac{Kc_r + \beta(1 + c_r)}{\theta(2\beta + K(\frac{2}{\theta} - 1))} \leq p_{m2} \leq \beta + c_r(\frac{1-\theta\beta}{1-\theta}) + 2\beta(1-\theta) + \frac{2(1-\beta)}{\theta} \tag{57}$$

where, $K = \frac{1-\beta}{1-\theta}$ .This inequality can be written simply as $L \leq p_{m2} \leq N$. Now, putting the expressions in order to satisfy demand < supply, results in

$$p_r^*[\beta\theta(1-\theta) + K] \geq \theta(1-\theta)\{\beta - \gamma(1 - p_{m1})\} + K\theta p_{m2} \tag{58}$$

Since p_r^* can be expressed in terms of p_{m2}, Eq.(58) can be rewritten as

$$P_{m2} \leq M \tag{59}$$

Combining this with the previous result, $L \leq p_{m2} \leq \min(M, N)$ arises. Now to investigate the scenario where, $p_r^* \geq \theta p_{m2}$, wherein the remanufacturer is priced out of the market, the assumption that was made earlier, allows to choose the minimum value i.e. $p_r^* = \theta p_{m2}$. Using this value and applying demand < supply, results in:

$$\theta p_{m2}[\beta\theta(1-\theta) + K] \geq \theta(1-\theta)(\beta - \gamma(1 - p_{m1})) + K\theta p_{m2} \tag{60}$$

Rearranging the terms of Eq. (60), gives

$$p_{m2} \leq \frac{\gamma(1 - p_{m1})}{\beta\theta}(= P) \tag{61}$$

The other case which is explored is when $p_r^* \leq p_{m2} - 1 + \theta$. Using the equality and applying Demand $\leq$ Supply into the equation for case-1 derived earlier, results in;

$$p_{m2} - 1 + \theta \geq 1 - \frac{\gamma}{\beta}(1 - p_{m1}) \tag{62}$$

Eq. (62) can be reduced to

$$p_{m2} \leq 2-\theta-\frac{\gamma}{\beta}(1-p_{m1})(=Q) \tag{63}$$

The final optimal reaction functions of the remanufacturer is shown in Table 6.6.

Table 6.6: Optimal remanufacturer reaction functions in green consumer model

Price	$L \leq N \leq M$		$L \leq M \leq N$	
	Expression	Condition	Expression	Condition
$p_r^* =$	θp_{m2}	$p_{m2} \leq \min(L, P)$	θp_{m2}	$p_{m2} \leq \min(L, P)$
	$\dfrac{\frac{1-\beta}{1-\theta}(\theta p_{m2}+c_r)+\beta(1+c_r)}{2\beta+\frac{2(1-\beta)}{\theta(1-\theta)}}$	$L \leq p_{m2} \leq N$	$\dfrac{\frac{1-\beta}{1-\theta}(\theta P_{m2}+c_r)+\beta(1+c_r)}{2\beta+\frac{2(1-\beta)}{\theta(1-\theta)}}$	$L \leq p_{m2} \leq M$
	$p_{m2}-1+\theta$	$N \leq p_{m2} \leq Q$	$p_{m2}-1+\theta$	$M \leq p_{m2} \leq Q$

6.5 The Nash Equilibrium

6.5.1 Model without green consumer segment

The Nash equilibrium for the second period pricing game is found by solving the following cases.

Case (6.5.1i): Solving, $\theta p_{m2} = 2p_{m2} - c - c_d - (1-\theta)$, gives $p_{m2}^* = \frac{c+c_d+1-\theta}{2-\theta}$ and $p_r^* = \theta p_{m2}^*$.

Since, $p_r^* = \theta p_{m2}^*$ holds for $p_{m2} \leq D$, which gives $\frac{c+c_d+1-\theta}{2-\theta} \leq \frac{c_r}{\theta}$. This reduces to:

$$c_r \geq \frac{\theta(c+c_d+1-\theta)}{2-\theta}(= c_1\ say) \tag{64}$$

Also note that $p_{m1}\epsilon[0,1]$. Coming to $(p_{m2}^*)^{-1} = 2p_{m2} - c - c_d - (1-\theta)$, it was observed that the upper limit for p_{m2} is $\frac{c+c_d+1-\theta}{2-\theta}$ which clearly holds. Therefore, it is not required to check the lower limit. Also $p_{m1}\epsilon[0,1]$ holds as the case is in both $C \leq A$ and $C \geq A$. In summary, the manufacturer is a monopolist so long as $c_r \geq c_1$ regardless of the first period price.

Case (6.5.1ii): Solving, $\theta p_{m2} = p_{m2} - (1-\theta)$, results in $p_{m2}^* = 1$ and $p_r^* = \theta p_{m2}^*$

Since here too, $p_r^* = \theta p_{m2}^*$, $c_r \geq \frac{\theta(c+c_d+1-\theta)}{2-\theta}$ and $p_{m1} \epsilon [0,1]$.

Note that $C \leq A$ holds for $(p_{m2}^*)^{-1} = p_{m2} - (1-\theta)$. Also the term $C \leq A$ results in $p_{m1} \leq 1 - \frac{1-(c+c_d)}{\gamma\theta}$. Earlier it was found that $p_{m2} - (1-\theta)$ remains valid for $1 - \gamma\square(1-p_{m1}) \leq p_{m2} \leq c + c_d$. This necessarily means that $1 - \gamma\square(1 - \mathrm{p}_{\mathrm{m1}}) \leq 1 \leq \mathrm{c} + \mathrm{c}_{\mathrm{d}}$, which is not true from A3. Therefore, this scenario is not feasible.

Case (6.5.1iii): Solving, $\frac{\theta p_{m2}+c_r}{2} = 2p_{m2} - c - c_d - (1-\theta)$, gives $p_{m2}^* = \frac{2(c+c_d+1-\theta)+c_r}{4-\theta}$ and $p_r^* = (\theta p_{m2}^* + c_r)/2$ This is the case where both manufacturer and remanufacturer are in the market.

$p_r^* = \frac{\theta p_{m2}^*+c_r}{2}$ holds for both $E \geq F$ and $E \leq F$. For $E \geq F$ which gives $p_{m1} \geq Y$ and $D \leq p_{m2} \leq F$, resulting in

$$p_{m1} \geq 1 - \frac{1 - {c_r}/{\theta}}{\gamma(2-\theta)} = c_4 \tag{65}$$

$$p_{m1} \leq 1 - \frac{(c+c_d+1-\theta)+c_r\left(1-\frac{2}{\theta}\right)}{\gamma(1-\theta)(4-\theta)} = c_3 \tag{66}$$

From the left hand limit of the inequality $D \leq p_{m2} \leq F$, the result $c_r \leq c_1$ follows.

For the latter case $E \leq F$ and $D \leq p_{m2} \leq E$, the results are

$$p_{m1} \leq 1 - \frac{1 - {c_r}/{\theta}}{\gamma(2-\theta)} = c_4 \tag{67}$$

$$\{c_2 = (c+c_d)(2-\theta) - 2(1-\theta)\} \leq c_r \leq \frac{\theta(c+c_d+1-\theta)}{(2-\theta)} = c_1 \tag{68}$$

Combining all, both firms exist in the market when $c_2 \leq c_r \leq c_1$ given that $p_{m1} \epsilon [0, c_3]$.

Case (6.5.1iv): Solving, $\frac{\theta p_{m2}+c_r}{2} = p_{m2} - (1-\theta)$, gives $p_{m2}^* = \frac{c_r+2(1-\theta)]}{2-\theta}$ and $p_r^* = (\theta p_{m2}^* + c_r)/2$

$p_r^* = \frac{\theta p_{m2}^*+c_r}{2}$ holds for both $E \geq F$ and $E \leq F$. For $E \geq F$ which gives $p_{m1} \geq Y$ and $D \leq p_{m2} \leq F$, resulting in

$$p_{m1} \geq 1 - \frac{1 - {c_r}/{\theta}}{\gamma(2-\theta)} = c_4, \tag{69}$$

$$p_{m1} \leq 1 - \frac{(c+c_d+1-\theta)+c_r\left(1-\frac{2}{\theta}\right)}{\gamma(1-\theta)(4-\theta)} = c_3 \tag{70}$$

From the left hand limit of the inequality $D \leq p_{m2} \leq F$, the result $c_r \leq c_1$ follows. For the latter case $E \leq F$ and $D \leq p_{m2} \leq E$, the results are

$$p_{m1} \leq 1 - \frac{1-{c_r}/{\theta}}{\gamma(2-\theta)} = c_4, \tag{71}$$

$$\{c_2 = (c + c_d)(2-\theta) - 2(1-\theta)\} \leq c_r \leq \frac{\theta(c+c_d+1-\theta)}{(2-\theta)} = c_1 \tag{72}$$

Combining all, both firms exist in the market when $c_2 \leq c_r \leq c_1$ given that $p_{m1} \epsilon [0, c_3]$.

Case (6.5.1v): Solving, $\theta[p_{m2} - \gamma(1-\theta)(1-p_{m1})] = 2p_{m2} - c - c_d - (1-\theta)$, gives $p_{m2}^* = \frac{c+c_d+(1-\theta)(1-\gamma\theta(1-p_{m1}))}{2-\theta}$, and $p_r^* = \theta(p_{m2} - \gamma(1-\theta)(1-p_{m1})) = \frac{\theta[c + c_d + (1-\theta)(1-2\gamma(1-p_{m1}))]}{2-\theta}$

$\theta[p_{m2} - \gamma(1-\theta)(1-p_{m1})]$ holds true for $E \geq F$ and $F \leq p_{m2} \leq 1 - \gamma\theta(1-p_{m1})$. From scenario-3, the condition $p_{m1} \geq c_4$ satisfies $E \geq F$. Also the inequality $\frac{c_r}{\theta} + 2\gamma(1-\theta)(1-p_{m1}) \leq p_{m2}^* \leq 1 - \gamma\theta(1-p_{m1})$, results in $p_{m1} \geq c_3$ and $p_{m1} \geq 1 - \left(\frac{1-(c+c_d)}{\gamma\theta}\right) (= c_5\ say)$ respectively. Equivalently, both results translate to $p_{m1} \geq c_3$. The RHS, $2p_{m2} - c - c_d - (1-\theta)$ applies to the regions $C \geq A$ and$C \leq A$. The region $C \geq A$ where $c_2 < c_r < c_1$ holds, translates to $p_{m1} \geq c_5$ and $C \leq A$ where $c_r \leq c_2$ holds, translates to $p_{m1} \leq c_5$.

Case (6.5.1va): The reaction functions $\theta[p_{m2} - \gamma(1-\theta)(1-p_{m1})]$ and $2p_{m2} - c - c_d - (1-\theta)$ corresponding to the region $C \geq A$, results in the unique Nash equilibrium second period prices p_{m2}^* and p_r^*. Here $F \leq p_{m2}^*$ and is the extension of Scenario-3. It is straightforward to find that this scenario is only possible when $c_2 \leq c_r \leq c_1$ and $p_{m1} \epsilon [c_3, 1]$.

Case (6.5.1vb): The region $C \leq A$ where $c_r \leq c_2$ together with the reaction function $\theta[p_{m2} - \gamma(1-\theta)(1-p_{m1})]$ is the extension of Scenario-3. So here this reflects the case $p_{m2}^* \leq 1 - \gamma\theta(1-p_{m1})$. The equilibrium prices result from $c_r \leq c_2$ and $p_{m1} \epsilon [c_5, 1]$.

Case(6.5.1vi): Solving $\theta(p_{m2} - \gamma(1-\theta)(1-p_{m1})) = p_{m2} - (1-\theta)$, gives $p_{m2}^* = \frac{(1-\theta)[1-\gamma\theta(1-p_{m1})]}{1-\theta}$ and $p_r^* = \theta(p_{m2} - \gamma(1-\theta)(1-p_{m1})) = \frac{\theta[c+c_d+(1-\theta)(1-2\gamma(1-p_{m1}))]}{2-\theta}$

$\theta[p_{m2} - \gamma(1-\theta)(1-p_{m1})]$ holds true for $E \geq F$. As observed from Scenario-3, the condition $p_{m1} \geq c_4$ satisfies $E \geq F$.

The term in RHS, $p_{m2} - (1-\theta)$ as observed from Scenario-4 holds for $c_r \leq c_2$. Note that from Scenario-2, $p_{m1} \leq c_5$ holds. Therefore, the equilibrium prices holds for $c_r \leq c_2$ and $p_{m1} \epsilon [c_4, c_5]$.

6.5.2 Model with green consumer segment

For finding the Nash equilibrium, all four reaction functions found can be used. But in the interest of discussion, the study focuses on the case where both players exist in the market. This is the case represented by Eq.(57) and Eq.(59) with the corresponding $(P_{m2}^*)^{-1}$. To do so, the inverse price function i.e. $(P_{m2}^*)^{-1}$ have to be found.

$$\textit{If } C \geq A,\ (p_{m2}^*)^{-1} = 2p_{m2} - c - c_d - 1 + \theta;\ C \leq p_r \leq B \tag{73}$$

$$\textit{If } C \leq A,\ (p_{m2}^*)^{-1} = \begin{cases} 2p_{m2} - c - c_d - 1 + \theta; & A \leq p_r \leq B \\ p_{m2} - 1 + \theta; & \theta(1-\gamma(1-p_{m1})) \leq p_r \leq A \end{cases} \tag{74}$$

The condition $A \leq P_r \leq B$ can be written as:

$$c + c_d - 1 + \theta \leq p_r \leq \frac{\theta(c + c_d + 1 - \theta)}{2 - \theta} \tag{75}$$

The inequalities when solved individually, give:

$$c + c_d \leq p_{m2} \leq \frac{c + c_d + 1 - \theta}{2 - \theta} \tag{76}$$

Similarly, the limits of the condition $C \leq p_r \leq B$ can be simplified by solving the expression $C \leq P_r$ stated as

$$\frac{\theta(1-\theta) + \beta - \gamma(1 - P_{m1}) + K\theta(1 + \frac{c}{2})}{\beta\theta(1-\theta) + K} \leq 2P_{m2} - c - c_d - 1 + \theta \tag{77}$$

which results in

$$p_{m2} \geq \frac{1}{2}\left[\frac{\theta(1-\theta) + \beta - \gamma(1 - p_{m1}) + K\theta\left(1 + \frac{c}{2}\right)}{\beta\theta(1-\theta) + K} + c + c_d + 1 - \theta\right] \tag{78}$$

Now the other limit $p_r \leq B$ can be expressed as

$$p_{m2} \leq \frac{c + c_d + 1 - \theta}{2 - \theta} \tag{79}$$

Algebraically manipulating for the remanufacturer's case, which is the $N \geq (\text{or} \leq) M$ case of Table 6.6, it was imperative to first identify the term "M". The Eq.(58) can be set up as below

$$\left[\frac{K(\theta p_{m2}+c_r)+\beta(1+c_r)}{2\beta+\frac{2K}{\theta}}\right][\beta\theta(1-\theta)+K] \geq \theta(1-\theta)(\beta-\gamma(1-p_{m1}))+K\theta p_{m2} \quad (80)$$

which on further simplification reduces to

$$p_{m2} \leq \frac{\frac{Kc_r+\beta(1+c_r)}{2\beta+\frac{2K}{\theta}}\left(\beta\theta(1-\theta)+K\right)-\theta(1-\theta)\left(\beta-\gamma(1-p_{m1})\right)}{K\theta[J-1]}(=M) \quad (81)$$

where $J=\frac{\beta\theta(1-\theta)+K}{2\beta+\frac{2K}{\theta}}$

Thus, $N \geq (\text{or} \leq) M$ can now be setup as follows:

$$\beta+c_r\left(\frac{1-\theta\beta}{1-\theta}\right)+2\beta(1-\theta)+\frac{2(1-\beta)}{\theta} \geq (\leq) \frac{\frac{Kc_r+\beta(1+c_r)}{2\beta+\frac{2K}{\theta}}\left(\beta\theta(1-\theta)+K\right)-\theta(1-\theta)\left(\beta-\gamma(1-p_{m1})\right)}{K\theta[J-1]} \quad (82)$$

which can be rephrased as $p_{m1} \leq (\geq) Y$

Comparing the values, it is easy solve for the concerned sub-cases as done below:

Case (6.5.2a): Here Eq.(73) which is $(p^*_{m2})^{-1}=2p_{m2}-c-c_d-1+\theta$ are compared with value of p^*_r corresponding to Eq.(52) given by $p^*_r=\left[\frac{1-\beta}{\theta(1-\theta)}(\theta\, p_{m2}+c_r)+\beta(1+c_r)\right]$, $\left[2\beta+\frac{2(1-\beta)}{\theta(1-\theta)}\right]^{-1}$

$$p^*_{m2}=\frac{c_r+\beta(1+c_r)+2(c+c_d+1-\theta)\left(\beta+\frac{K}{\theta}\right)}{4\left(\beta+\frac{K}{\theta}\right)-K\theta} \quad (83)$$

Given the optimal value of p^*_{m2} found in Eq. (83), one can identify the optimal p^*_r using the expression

$$p_r^* = \frac{K(\theta\, p_{m2}^* + c_r) + \beta(1+c_r)}{2\beta + \frac{2K}{\theta}} \tag{84}$$

The corresponding ranges for p_r^* holds for both $N \geq (\leq) M$. For the case $N \leq M$, we have $p_{m1} \geq Y$ which means $p_{m1} \geq c_4^*$. Also note that, $N \leq M$ from Eq.(81) corresponds to $p_{m2} \leq M \Rightarrow p_{m1} \leq c_3^*$. Also, when $N \geq M \Rightarrow L \leq p_{m2} \leq M$. Left hand inequality results in $c_r \leq c_1^*$. In the latter case i.e. $N \geq M$ and $L \leq p_{m2} \leq N$; $p_{m1} \leq c_4^*$ can be obtained and the other equation can be setup as:

$$\frac{Kc_r + \beta(1+c_r)}{\theta(2\beta + K\left(\frac{2}{\theta} - 1\right)} \leq \frac{c_r + \beta(1+c_r) + 2(c_{m2} + c_d + 1 - \theta)\beta + \frac{K}{\theta}}{4\left(\beta + \frac{K}{\theta}\right) - K\theta} \leq \beta + c_r\left(\frac{1-\theta\beta}{1-\theta}\right) + 2\beta(1-\theta) + \frac{2(1-\beta)}{\theta} \tag{85}$$

Eq. (85) can be restated as $c_2^* \leq c_r \leq c_1^*$. Combining the above results both firms exist in the market when $c_2^* \leq c_r \leq c_1^*$ given that $p_{m1} \in [0, c_3^*]$.

6.6 Numerical Study

Having obtained expressions for the optimum price for the manufacturer and the remanufacturer in isolation and in tandem, it is important to understand the behavior of said expressions. How these equilibrium price expressions translate into profit expressions is straightforward. What remains to be seen is how the profit value responds to changes in key parameters. In light of take-back laws for products that have been used for one life cycle, the numerical study carried out provides valuable insights as to what take-back law is suitable and when/why it is feasible for the manufacturer and remanufacturer to collude in the take-back process. To do this, some more notations important for this section are defined.

In the numerical study it is assumed that the unit cost to manufacture and distribute new product (k_m) is the same in both periods. Similarly, it was assumed that the collection/disposal cost (k_d) and the fraction of usable units returned (γ) are the same in both periods. The unit cost to remanufacture and distribute the product is denoted as k_r.

Let k_e denote the optimal mark-up on returns sold to the remanufacturer. Hence, the returns are sold to the remanufacturer at a unit price of $k_d + k_e$.

The various scenarios discussed regarding take-back laws are:

1. No take back law (Scenario-0)
2. Individual take back law (Scenario-1)
3. Collective take back law (Scenario-2).

It must be noted that whenever a take back law is in place, the manufacturer and the remanufacturer incur the collection/disposal cost the end of the second period. Thus, the cost terms c_{m2} and c_r include a γk_d term in Scenarios 1 and 2. It is, thus, implicit that the industry costs are higher in Scenarios 1 and 2 when compared to the scenario 0, where there is no take back law. This can be attributed to the extra γk_d term that appears in cost equations, a burden that the parties will try to shift onto the consumer to maximize profit. Considering all such unit costs, the overall cost equations for the scenarios are:

1. No take back law (Scenario-0):

$$\begin{aligned} c_{m1} &= k_m \\ c_d &= 0 \\ c_{m2} &= k_m \\ c_r &= k_r + k_d \end{aligned} \tag{86}$$

2. Individual take back law (Scenario-1): The manufacturer controls the price (and thus quantity) of goods sold to the remanufacturer.

$$\begin{aligned} c_{m1} &= k_m - \gamma k_e \\ c_d &= k_d + k_e \\ c_{m2} &= k_m + \gamma k_d \\ c_r &= k_r + k_d + k_e + \gamma k_d \end{aligned} \tag{87}$$

3. Collective take back law (Scenario-2): The manufacturer has no control over the price and quantity of returns sold to the remanufacturer; the remanufacturer pays a collection/disposal fee set to the net collection/disposal cost after returned units are sold to the remanufacturer.

$$
\begin{aligned}
c_{m1} &= k_m \\
c_d &= k_d \\
c_{m2} &= k_m + \gamma k_d \\
c_r &= k_r + k_d + \gamma k_d
\end{aligned}
\tag{88}
$$

Using these values for costs, expressions for profits earned by manufacturer and remanufacturer can be obtained in terms of per unit costs. Assigning particular values to these can bring to fore how the expressions respond to changes in parameters. The manufacturer and remanufacturer profits are chosen as feasible measures of interest because with analysis it can be determined when the market and the parties benefit from independent operation or from collusion. It is also the intention here to find reasons why collective take back could be preferred over individual take back or vice-versa

6.6.1 Experimental design

It would be important to recall here that all the values for prices and demands have been normalized to lie between 0 and 1. This shall be put into continuation here in order to choose numerical values for per unit costs. Before listing the assumptions for this analysis study, the notion of a cost structure variable is introduced.

In order to have a sense of relative cost structure, the term $A_m = \dfrac{k_r}{\theta\, k_m}$ is used as a measure of manufacturer's relative competitive advantage. Recall that θ is the valuation ratio of remanufactured product to new product value i.e. a consumer who values new product at v will value remanufactured product at θv. As θ and k_m decrease and as k_r increases, the manufacturer becomes more competitive and the remanufacturer becomes less competitive in the market. The study is, therefore, carried out for different values of A_m, but for simplicity the value of 0.4 has been chosen.

The parameters that will be varied to study the behavior are β and θ, where β is the percentage of green consumers in the market described as a value between 0 and 1. Since the results of this study will be applicable to the extended model that includes green consumers; the choice of β as a varying input is well justified.

The values of β and θ are chosen from a multitude of values between 0 and 1 which renders the even more detailed albeit at the cost of calculation difficulties. It was decided that $\beta \in [0.2, 0.5, 0.8]$ and $\theta \in [0.35, 0.65]$ should suffice for a meaningful analysis. The above ranges give rise to 6 (=3×2) combinations for each scenario. For the three scenarios described above, a sum total of 18 expressions for profit are used to generate the results. Including profit equations for manufacturer and remanufacturer, the overall number of expressions is 36.

Assuming $k_m = 0.2$ and $A_m = 0.4$, the values of k_r and k_d are obtained as shown: $A_m = 0.4 \Rightarrow 5k_r = 0.7k_m \Rightarrow 5k_r = 0.14 \Rightarrow k_r = 0.028$

and, $k_d = \frac{k_d^{\max}}{8} = \frac{k_m - k_r}{8} = 0.0344$

$k_e = 0.2$ is also assumed. In a complete analysis study, it would be logical to assume a range of values for k_d between the extremes of zero and the value that equalizes the production costs of new and remanufactured product, i.e. letting $k_d^{\max} = k_m - k_r$. In order to maintain simplicity, the value of $k_d = \frac{k_d^{\max}}{8}$ has been assumed which gave rise to the value of $k_d = 0.0344$.

Now, it would be useful to look back at expressions that will act as the starting point in our study. Given that the focus of interest lies in finding the expressions for profit for the manufacturer and the remanufacturer as a function of the return rate γ which varies from 0 to 1 in steps of 0.1, we must recognize the need of expressions for p_{m2} and p_r. It is but logical to use the expressions for equilibrium price for both the manufacturer and the remanufacturer. Thus, from Tables 6.5 and 6.6, the expressions are re-written as:

$$p_{m2} = \frac{p_r + c_{m2} + c_d + 1 - \theta}{2} \tag{89}$$

$$p_r = \frac{\frac{1-\beta}{1-\theta}(\theta p_{m2} + c_r) + \beta(1 + c_r)}{2\beta + \frac{2(1-\beta)}{(1-\theta)}} \tag{90}$$

A close scrutiny of Eq. (89) and Eq. (90) brings us to realize that for every combination of β and θ, separate values of p_{m2} and p_r will be obtained. Since, Eq. (40) and Eq. (41) show the expressions for profits of the manufacturer and the remanufacturer, the values of p_{m2} and p_r obtained by inserting values into Eq. (89) and Eq. (90), can be used to calculate the profit expressions. As observed earlier, the unit cost expressions discussed in the take back law scenarios have dependency on the return rate γ, it is obvious that the profit expressions for each combination of β and θ will be a function of γ. This will allow us to generate plots of how the profits vary with changes in the return rate γ.

6.6.2 Scenario-0 (No take back law)

The following results are obtained when assumed values are put into equations of cost terms: $c_{m1} = 0.2$, $c_d = 0$, $c_{m2} = 0.2$ and $c_r = 0.0624$

The next step is to obtain values of p_{m2} and p_r by simultaneously solving Eq. (89) and Eq. (90) using the values obtained above. For the case where $\beta = 0.2$ and $\theta = 0.35$, the values are obtained as $p_{m2} = 0.48$, and $p_r = 0.1107$. Profit was thus obtained as $\Pi_m = 0.247$ and $\Pi_r = 0.1877$.

Solving for other cases in a similar manner, it was found that any dependency on the return rate γ in the profit equations did not exist. Thus, depicting results as a plot of profit vs γ will not useful in this case i.e. when there is no take back law.

6.6.3 Scenario-1 (Individual take back law)

Scenario-1 explores the case when the manufacturer assumes the responsibility of collecting goods for remanufacturing. The manufacturer sells the goods for remanufacturing by marking up the price by k_e from the initial cost of k_d per unit. The following results are obtained:

$$\begin{aligned} c_{m1} &= k_m - \gamma k_e = 0.2 - 0.2\gamma \\ c_d &= k_d + k_e = 0.234 \\ c_{m2} &= k_m + \gamma k_d = 0.2 + 0.034\gamma \\ c_r &= k_r + k_d + k_e + \gamma k_d = 0.262 + 0.034\gamma \end{aligned} \tag{91}$$

Inserting the obtained values into Eq. (89) and Eq. (90) and solving simultaneously for each case gives the following results:

Table 6.7: p_{m2} and p_r values for Scenario-1

Price values	$\beta = 0.2$		$\beta = 0.5$		$\beta = 0.8$	
	p_{m2}	p_r	p_{m2}	p_r	p_{m2}	p_r
$\theta = 0.35$	0.757+ 0.204 γ	0.43+ 0.064 γ	0.666+ 0.0265 γ	0.248+ 0.019 γ	0.7615+0.0265 γ	0.439+0.019 γ
$\theta = 0.65$	0.776+ 0.0665 γ	0.468+0.099 γ	0.6145+0.136 γ	0.445+0.238 γ	0.63+0.028 γ	0.476+0.022 γ

Having obtained the above values, they are inserted into Eq. (40) and Eq. (41) for corresponding combinations of β, θ. The results are tabulated below:

Table 6.8: Profit expressions for Scenario-1

Profit eqns.	$\beta = 0.2$		$\beta = 0.5$		$\beta = 0.8$	
	Π_m	Π_r	Π_m	Π_r	Π_m	Π_r
$\theta = 0.35$	0.368- 0.145 γ- 0.056 γ^2	0.00025 γ^2 - 0.013 γ	0.195- 0.1224 γ+ 0.00046 γ^2	0.37- 0.0131 γ+ 0.00034 γ^2	0.16615- 0.1177 γ- 0.00013 γ^2	0.393- 0.016 γ+ 0.00013 γ^2
$\theta = 0.65$	0.147- 0.0296 γ+ 0.0024 γ^2	0.1574- 0.092 γ- 0.013 γ^2	0.213- 0.0455 γ+ 0.015 γ^2	0.2385- 0.265 γ- 0.067 γ^2	0.1544- 0.1172 γ	0.409+ 0.013 γ+ 0.00016 γ^2

The expressions in Table 6.8 are used to obtain values for profit by varying the return rate γ between 0 and 1 in steps of 0.1. The results obtained are plotted to show the profit versus return rate γ. The results and discussions are elaborated next.

The values for manufacturer and remanufacturer profit were obtained and tabulate in Table 6.9 for six cases for Scenario-1.

Table 6.9: Profit for investigated cases of Scenario-1

sc-1	CASE 1		CASE 2		CASE 3		CASE 4		CASE 5		CASE 6	
β,θ	0.2, 0.35		0.5, 0.35		0.8, 0.35		0.2, 0.65		0.5, 0.65		0.8, 0.65	
γ	M. Profit	ReM. Profit	M. Profit	ReM. Profit	M. Profit	ReM. Profit	M. Profit	ReM. Profit	M. Profit	ReM Profit	M. Profit	ReM Profit
0	0.368	0	0.195	0.37	0.16615	0.393	0.147	0.1574	0.213	0.2385	0.1544	0.409
0.1	0.34294	-0.0013	0.18276	0.36869	0.15438	0.3914	0.14406	0.14807	0.2086	0.21133	0.14268	0.4103
0.2	0.31676	-0.00259	0.17052	0.36739	0.14261	0.38981	0.14118	0.13848	0.2045	0.18282	0.13096	0.41161
0.3	0.28946	-0.00388	0.15828	0.3661	0.13084	0.38821	0.13834	0.12863	0.2007	0.15297	0.11924	0.41291
0.4	0.26104	-0.00516	0.14605	0.36481	0.11907	0.38662	0.13554	0.11852	0.1972	0.12178	0.10752	0.41423
0.5	0.2315	-0.00644	0.13381	0.36354	0.1073	0.38503	0.1328	0.10815	0.194	0.08925	0.0958	0.41554
0.6	0.20084	-0.00771	0.12158	0.36226	0.09552	0.38345	0.1301	0.09752	0.1911	0.05538	0.08408	0.41686
0.7	0.16906	-0.00898	0.10934	0.361	0.08375	0.38186	0.12746	0.08663	0.1885	0.02017	0.07236	0.41818
0.8	0.13616	-0.01024	0.09711	0.35974	0.07198	0.38028	0.12486	0.07548	0.1862	-0.01638	0.06064	0.4195
0.9	0.10214	-0.0115	0.08488	0.35849	0.06021	0.37871	0.1223	0.06407	0.1842	-0.05427	0.04891	0.42083
1	0.067	-0.01275	0.07265	0.35724	0.04843	0.37713	0.1198	0.0524	0.1825	-0.0935	0.03719	0.42216

6.6.4 Scenario-2 (Collective take back law)

In this case the manufacturer has no control over the price and quantity of returns sold to the remanufacturer; the remanufacturer pays a collection/disposal fee set to the net collection/disposal cost after returned units are sold to the remanufacturer. Substituting the assumed values following results are obtained, as a starting point for further calculations:

$$\begin{aligned} c_{m1} &= k_m = 0.2 \\ c_d &= k_d = 0.0344 \\ c_{m2} &= k_m + \gamma k_d = 0.2 + 0.0344\gamma \\ c_r &= k_r + k_d(1+\gamma) = 0.0624 + 0.0344\gamma \end{aligned} \tag{92}$$

Similar to Scenario-1, computed p_{m2} and p_r are tabulated in Table 6.10 and inserting the values into Eq. (40) and Eq. (41) gives profit expressions shown in Table 6.11.

Table 6.10: p_{m2} and p_r for Scenario-2

Price values	$\beta = 0.2$		$\beta = 0.5$		$\beta = 0.8$	
	p_{m2}	p_r	p_{m2}	p_r	p_{m2}	p_r
$\theta = 0.35$	$0.5205+0.029\gamma$	$0.157+0.024\gamma$	$0.551+0.0295\gamma$	$0.218+0.025\gamma$	$0.612+0.027\gamma$	$0.34+0.02\gamma$
$\theta = 0.65$	$0.398+0.033\gamma$	$0.213+0.032\gamma$	$0.4285+0.0315\gamma$	$0.273+0.029\gamma$	$0.484+0.029\gamma$	$0.384+0.024\gamma$

Table 6.11: Profit expressions for Scenario-2

Profit eqns.	$\beta = 0.2$		$\beta = 0.5$		$\beta = 0.8$	
	Π_m	Π_r	Π_m	Π_r	Π_m	Π_r
$\theta = 0.35$	$0.2602-0.019\gamma-0.00003\gamma^2$	$0.177+0.00049\gamma^2-0.01\gamma$	$0.295+0.0344\gamma+0.008\gamma^2$	$0.084-0.0623\gamma+0.085\gamma^2$	$0.627-0.0406\gamma+0.000014\gamma^2$	$0.497-0.025\gamma+0.00136\gamma^2$
$\theta = 0.65$	$0.249-0.0196\gamma$	$0.182-0.0126\gamma-0.00078\gamma^2$	$0.2005+0.0179\gamma$	$0.366-0.0185\gamma$	$0.209-0.0154\gamma$	$0.473-0.02\gamma+0.00046\gamma^2$

The values obtained by varying the return rate γ from 0 to 1 in steps of 0.1 are tabulated for Scenario-2 in Table 6.12.

Table 6.12: Profit for investigated cases of Scenario-2

Sc 2	CASE 7		CASE 8		CASE 9		CASE 10		CASE 11		CASE 12	
β, θ	0.2, 0.35		0.5, 0.35		0.8, 0.35		0.2, 0.65		0.5, 0.65		0.8, 0.65	
γ	M. Profit	ReM. Profit	M. Profit	ReM. Profit	M. Profit	ReM. Profit	M. Profit	ReM. Profit	M. Profit	ReM. Profit	M. Profit	ReM. Profit
0	0.2602	0.177	0.295	0.084	0.627	0.497	0.249	0.182	0.2005	0.366	0.209	0.473
0.1	0.2583	0.176	0.2985	0.07862	0.6229	0.49451	0.2470	0.18074	0.2022	0.36415	0.2074	0.471
0.2	0.2564	0.17502	0.3022	0.07494	0.6188	0.49205	0.2450	0.17948	0.2039	0.3623	0.2059	0.469
0.3	0.2545	0.17404	0.3060	0.07296	0.6148	0.48962	0.2431	0.17823	0.2056	0.36045	0.2043	0.467
0.4	0.2526	0.17308	0.3100	0.07268	0.6107	0.48722	0.2411	0.17697	0.2073	0.3586	0.2028	0.46501
0.5	0.2506	0.17212	0.3142	0.0741	0.6067	0.48484	0.2392	0.17572	0.2090	0.35675	0.2013	0.46301
0.6	0.2487	0.17118	0.3185	0.07722	0.6026	0.48249	0.2372	0.17447	0.2107	0.3549	0.1997	0.46102
0.7	0.2468	0.17024	0.323	0.08204	0.5985	0.48017	0.2352	0.17322	0.2124	0.35305	0.1982	0.45902
0.8	0.2449	0.16931	0.3276	0.08856	0.5945	0.47787	0.2333	0.17197	0.2141	0.3512	0.1966	0.45703
0.9	0.2430	0.1684	0.3324	0.09678	0.5904	0.4756	0.2313	0.17072	0.2158	0.34935	0.1951	0.45504
1	0.2411	0.16749	0.3374	0.1067	0.5864	0.47336	0.2294	0.16948	0.2175	0.3475	0.1936	0.45305

6.6.5 Sensitivity analysis

The sensitivity analysis of the results obtained is carried out next.

6.6.5.1 Manufacturer profit when β is constant

The data obtained in the previous section are transformed into graphs by congregating variables of different types and permutations. Two forms of plots: one, where β is constant and θ varies and two, vice versa are considered form analysis. By depicting the profit expressions for different scenarios as lines of varying slopes and relative positions on the plot, logical conclusions are drawn.

First, plots of profit versus return rate γ are analyzed with β constant.

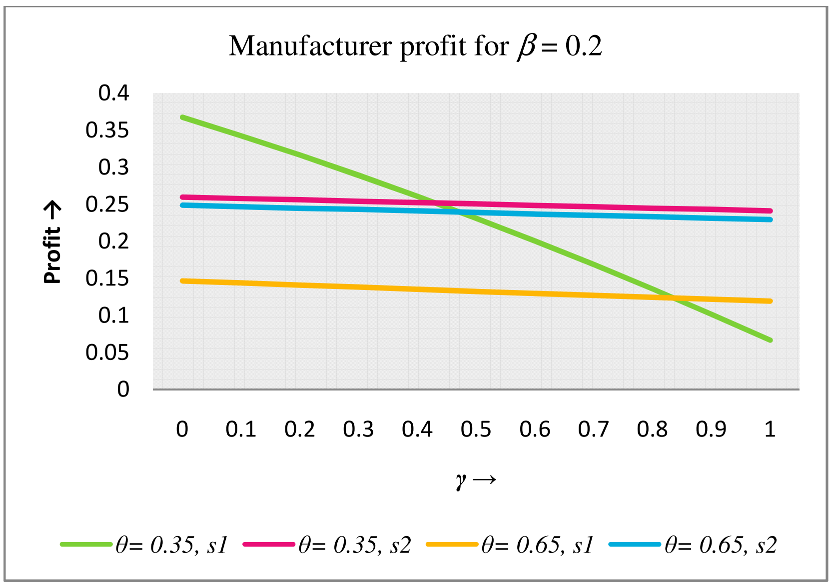


Fig 6.2: Manufacturer profit for β =0.2

The plot for $\beta = 0.2$ is shown in Fig. 6.2, It is observed that for θ=0.35, it is feasible for the manufacturer to operate in Scenario-2 till γ=0.4 and then switch over to Scenario-1 for further values. At the value of γ=0.4, the line depicting Scenario-2 cuts the line depicting Scenario-1 and moves below it as γ increases. In the case of θ=0.65, it is immediately evident that the manufacturer chooses Scenario-2 to operate as the profit earned is higher than any value of profit earned for Scenario-1. When the manufacturer chooses individual take back, it prefers a lower valuation ratio for remanufactured product for most values of the return rate. For the case of collective take back, he would only marginally prefer a lower valuation ratio (θ=0.35) over a higher one.

For the case of β =0.5, as seen in Fig. 6.3, collective take-back (Scenario-2) is preferred at low and high valuation ratios for remanufactured products, irrespective of the return rate. Under a individual take-back regime (Scenario-1) , higher valuation ratio is necessary for higher profits. As seen in Fig. 6.4, irrespective of the return rate, collective take back law (Scenario-2), is more profitable at both low and high valuation ratios. In the event of an individual take-back regime (Scenario-1), the manufacturer's profit remains indifferent towards valuation ratio. In any case, for $\beta \geq 0.5$, collective take-back law should be preferred.

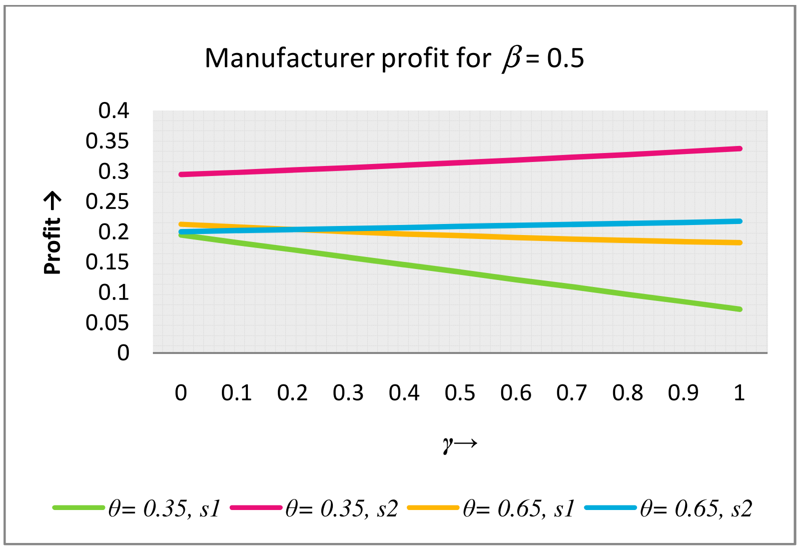


Fig. 6.3: Manufacturer profit for β =0.5

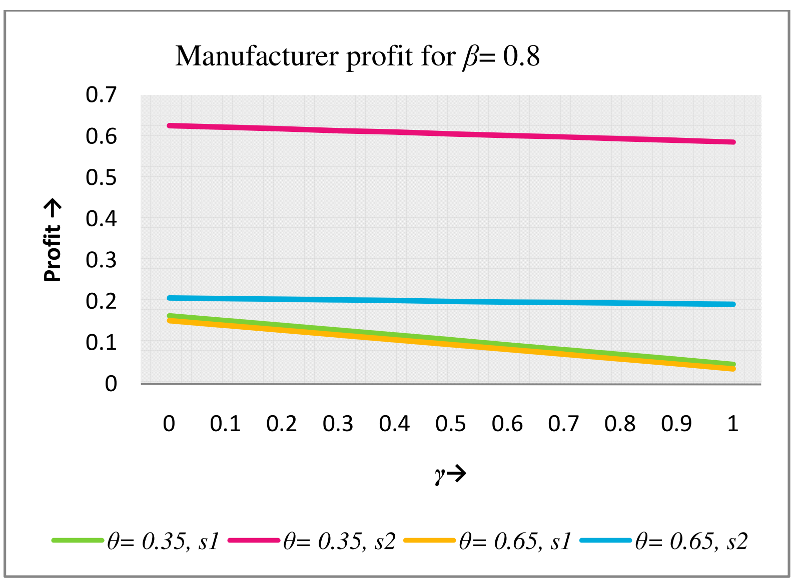


Fig. 6.4: Manufacturer profit for β =0.8

6.6.5.2 Remanufacturer profit when β is constant

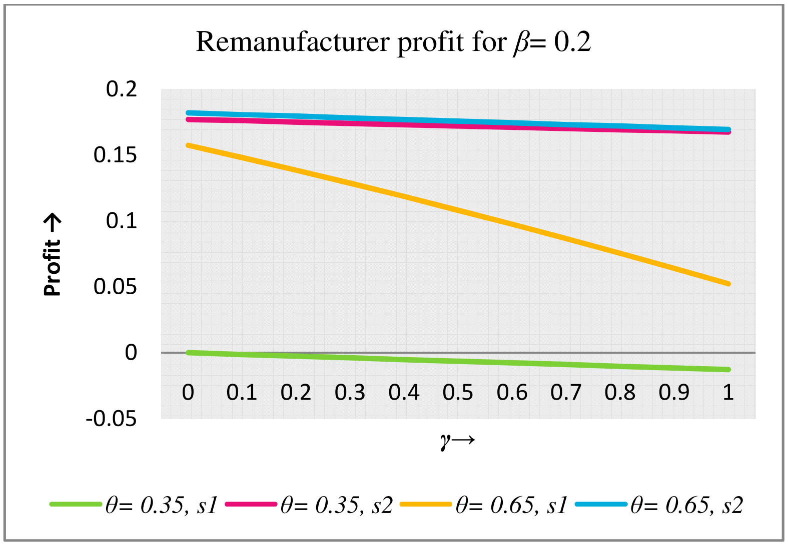


Fig. 6.5: Remanufacturer profit for β =0.2

For the case shown in Fig. 6.5, the remanufacturer in the individual take-back (Scenario-1) remains profitable only when the valuation ratio (or acceptability of remanufactured products) is high. However, it is certain that, irrespective of the return rate, collective take-back (Scenario-2) outperforms individual take-back when there are few green consumers (β =0.2) in the market. The remanufacturer's profit in case of collective take-back, remains indifferent towards valuation ratio.

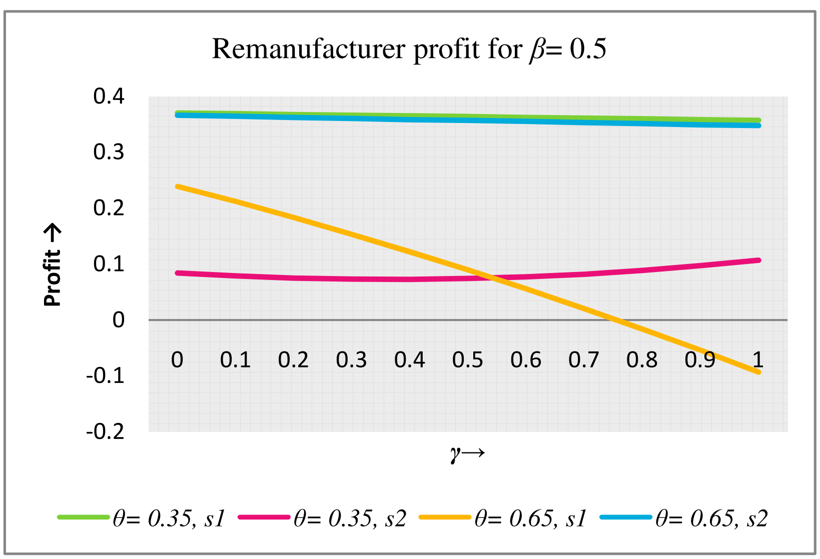


Fig. 6.6: Remanufacturer profit for β =0.5

When half of the customers demonstrate green behavior (see Fig. 6.6) and are under the purview of individual take-back (Scenario-1), the remanufacturer is more profitable only when valuation of remanufactured product is on the lower side. However, under a collective take-back regime (Scenario-2), the remanufacturer is more profitable only when valuation of remanufactured product is on the higher side.

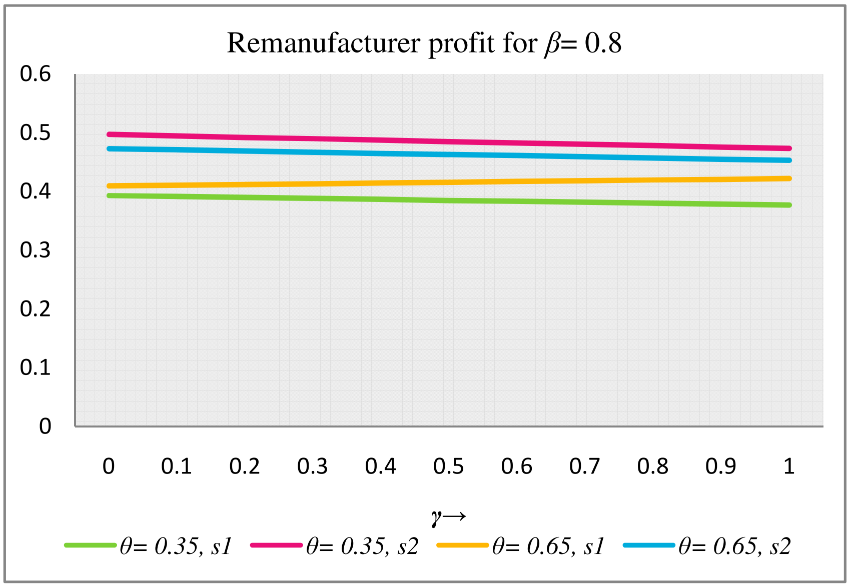


Fig. 6.7: Remanufacturer profit for $\beta = 0.8$

Fig. 6.7 shows remanufacturer profit when most of the customers ($\beta = 80\%$) in the market are green consumers i.e. they prefer remanufactured product over newly manufactured product. Extending this logic, the graph suggests that for all values of return rate, collective take-back (Scenario-2) would result in better profits for the remanufacturer than individual take-back (Scenario-1).

6.6.5.3 Manufacturer profit for constant θ

The results in Fig 6.8 show manufacturer profit when individual take back is in effect and at lower valuations of θ(= 0.35), manufactured product dominates in the product mix on offer. It is implicit that the manufacturer garners greater profit when the proportion of green consumers is lesser ($\beta = 0.2$). Also the profits are more susceptible to changes in the return rate, when $\beta = 0.2$.

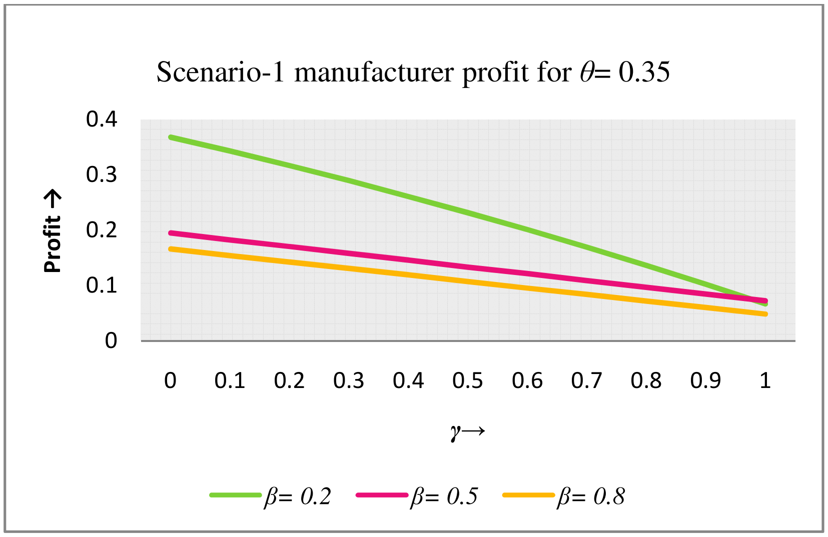


Fig. 6.8: Manufacturer profit for low valuation ratio in Scenario-1

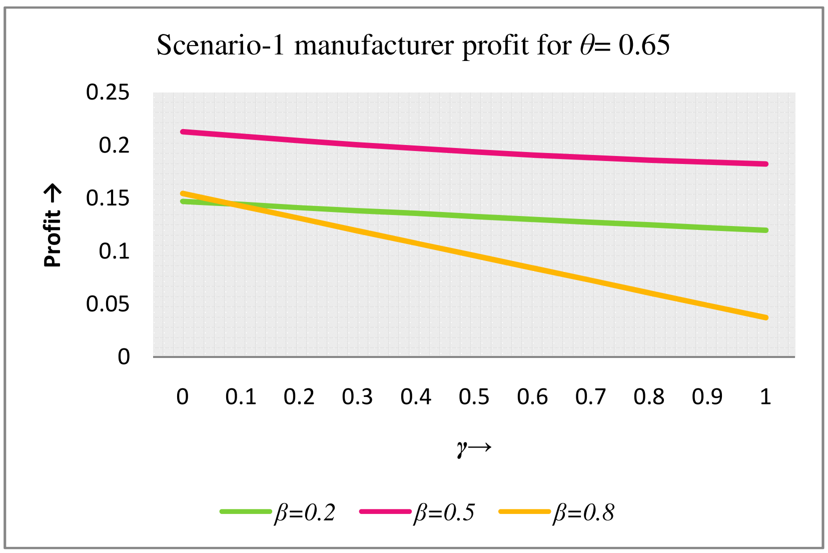


Fig. 6.9: Manufacturer profit for high valuation ratio in Scenario-1

In contrast, for $\theta = 0.65$ (see Fig. 6.9), the manufacturer's profit is maximum when exactly half of the consumers are green ($\beta = 0.5$). However, it must be noted that the profit decreases as the return rate increases. Also the profits are more susceptible to changes in the return rate, when $\beta = 0.8$.

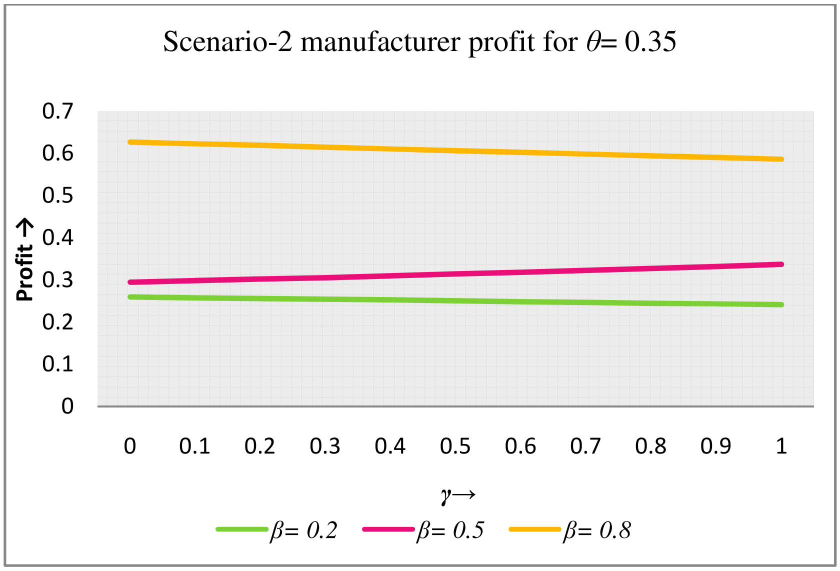


Fig. 6.10: Manufacturer profit for low valuation ratio in Scenario-2

For Scenario-2, as in when $\theta = 0.35$ (which is low consumer acceptability of remanufactured product), Fig. 6.10 stands in contrast to that in Fig. 6.8. For the collective take back situation, from the graph, it is clearly concluded that the greater is the proportion of green consumers in the market, the higher is the manufacturer's profits.

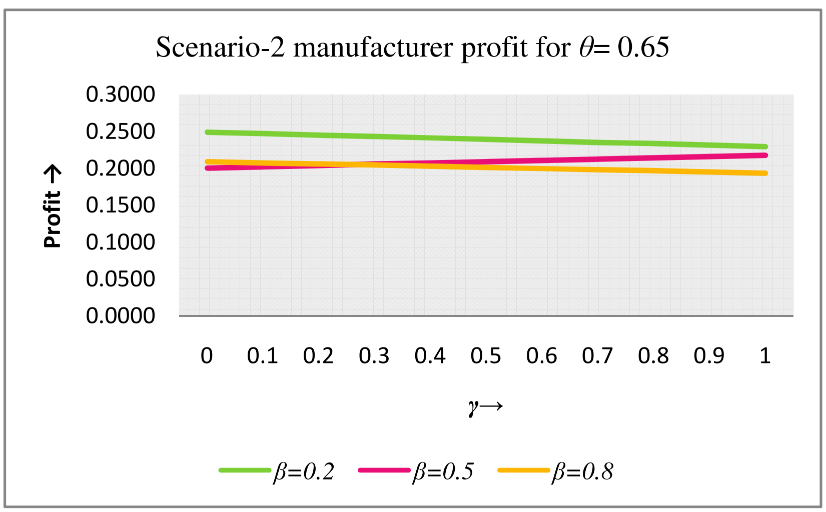


Fig. 6.11: Manufacturer profit for high valuation ratio in Scenario-2

The plot shown in Fig. 6.11 for $\theta = 0.65$, depicts an interesting behavior: when the consumer values remanufactured product higher than new product ($\theta = 0.65$) and collective take back (Scenario-2) is followed, the lower the proportion of green consumers in the market, the more is the profit earned by the manufacturer.

6.6.5.4 Remanufacturer profit for constant θ

In this section, manufacturer and remanufacturer profit for different values of θ and scenarios is investigated.

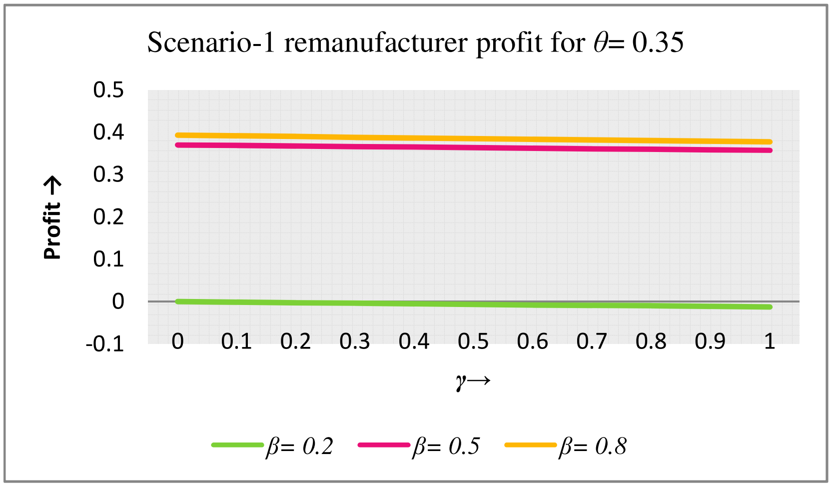


Fig. 6.12: Remanufacturer profit for low valuation ratio in Scenario-1

From Fig. 6.12 and Fig. 6.8, it is obvious that at lower $\theta(=0.35)$, the manufacturer in the individual take-back scheme, maximizes his profits (at $\beta = 0.2$) when they are few green consumers, the remanufacturer, on the other hand, tends to break even and even run at a loss as more products are returned to be remanufactured. The remanufacturer maximizes its profits when there are more green consumers.

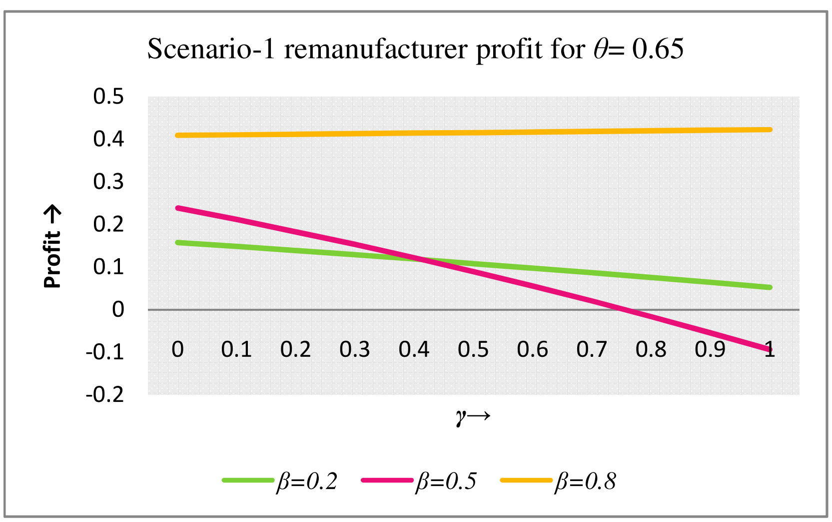


Fig. 6.13: Remanufacturer profit for high valuation ratio in Scenario-1

It can be recalled from Fig. 6.9 that the manufactured earned maximum profit when exactly half the consumers were of green type. The remanufacturer however earns maximum profit throughout when most of the consumers are green type. Individual take back will not be preferred by the remanufacturer because after a certain return rate (=0.75), it starts to run at a loss which keeps increasing.

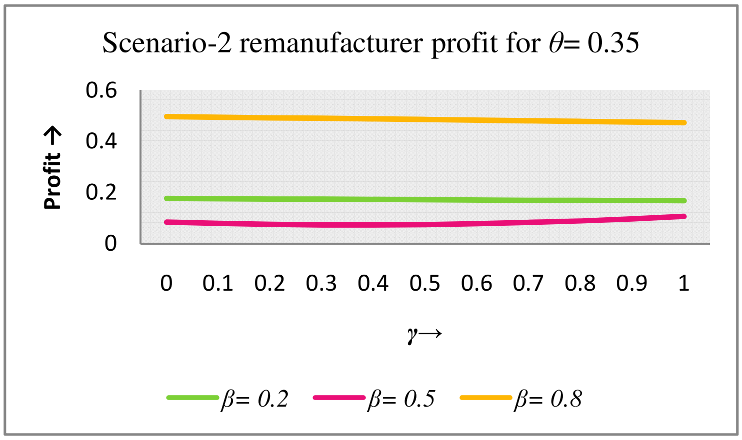


Fig. 6.14: Remanufacturer profit for low valuation ratio in Scenario-2

The case demonstrated by Fig. 6.14 is of importance because viewing it in tandem with Fig. 6.10 brings us to the conclusion that when both parties have agreed to work under the collective take back law, each maximizes its profit when green consumers are greater in number. Hence, it could be termed a win-win situation for both the manufacturer and the remanufacturer. As awareness in society grows about the benefits of remanufacturing and goes green, this case will come to the fore as one where all parties earn maximum profits.

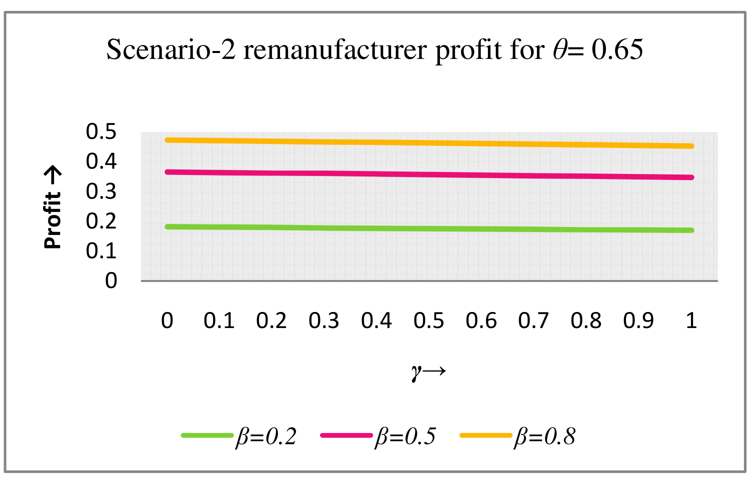


Fig. 6.15: Remanufacturer profit for high valuation ratio in Scenario-2

Fig. 6.15 stands in contrast to Fig. 6.11. A logical conclusion offered by this that when the levels of green consumer are on the lower side but valuation is high, the manufacturer will dominate in terms of profit but as this ratio rises, the remanufacturer starts to earn more profits and will thus outperform the manufacturer.

An overall conclusion is drawn keeping in view how the consumer choice pattern changes. When the valuation ratio, green consumer percentage and the return rate is also on the lower side, the manufacturer will earn a profit in the vicinity of 0.4 (normalized to lie between 0 and 1) by operating under the individual take back law. But at the same time, the remanufacturer tends to run at neither a profit nor a loss, thus breaking even. Over a period of time, as return rates, percentage of green consumers and valuation ratio shows a rise, it is preferable to switch over to collective take back system if both the parties are to earn desirable profits from their operation.

Having analyzed how manufacturer and remanufacturer profit varies with changes in return rates, green consumer percentage and valuation ratio; it becomes important to understand the meaning of the above conclusion in combination and not in isolation. Based on the market situation and the consumer choice pattern, various inferences about the take back laws are summarized in Table 6.7:

Table 6.7: Summary of cases investigated

CASE	**Remarks**		**Verdict**	**Figure Reference**
	Manufacturer Profit	**Remanufacturer Profit**		
Low β, Low θ	**Scenario 1:** Profit value starts at close to 0.375 and decreases with an appreciable slope as γ increases. **Scenario 2:** Profit value remains constant around 0.24, Scenario 1 line cuts scenario 2 line at around γ=0.55	**Scenario 1:** Remanufacturer profit starts at close to zero and decreases gradually to become negative as γ rises, indicating loss. **Scenario 2:** Profit value remains almost constant at around 0.18	Scenario-2 undoubtedly better for the remanufacturer as profit is positive. However it starts to become feasible for manufacturer only for γ>0.55	Figs. 6.8, 6.10, 6.12, 6.14
Low β, High θ	**Scenario 1:** Profit starts at 0.14 and decreases to around 0.125 as γ approaches 1.	**Scenario 1:** Profit value starts at around 0.16 and decreases gradually to around 0.07.	Scenario-2 favorable (Collective take back law)	Figs. 6.9, 6.11, 6.13, 6.15

CASE	Remarks		Verdict	Figure Reference
	Manufacturer Profit	Remanufacturer Profit		
	Scenario 2: Profit starts at 0.25 and remains largely constant.	**Scenario 2:** Profit largely constant at 0.18.		
High β, Low θ	**Scenario 1:** Starts at close to 0.16 and decreases to 0.05. **Scenario 2:** Profit stays around 0.6 throughout	**Scenario 1:** Profit stays close to 0.4 throughout. **Scenario 2:** Profit value stays around 0.5 throughout.	Scenario-2 clearly preferable for the manufacturer and marginally preferable for the remanufacturer.	Figs. 6.8, 6.10, 6.12, 6.14
High β, High θ	**Scenario 1:** Starts at close to 0.15 followed by a pronounced decline to 0.03. **Scenario 2:** Profit stays around 0.2 throughout.	**Scenario 1:** Profit starts at around 0.4 and increases very marginally across the γ values. **Scenario 2:** Profit starts at 0.47 and declines marginally to 0.42.	Scenario-2 favorable for the manufacturer. Scenario-2 marginally favorable for the remanufacturer.	Figs. 6.9, 6.11, 6.13, 6.15

6.7 Conclusion

In this chapter, a two-period remanufacturing model with take-back laws was investigated. The supposed take-back laws are in line with the principle of EPR and incorporates the WEEE directives. The results from the modeling effort suggests that in the industrial setting where remanufacturing is not feasible, may become feasible in the backdrop of a take-back legislation. The competition that might exist between the two stakeholders under different price settings was modeled. From the results of the aforementioned study, it can be argued that even though the manufacturer under individual take-back has the resources to prevent the remanufacturer from entering the market, he will, as the study projects, will benefit more from selling the returns to the remanufacturers than by operating as a monopolist. This is only possible, when the return rates are sustainable in the long term. Collective take-back by a third party, which though seems to be a potential alternative, is not beneficial in the sense that here even though the collection cost reduces and the profits improve, the intensity of competition between the manufacturer and remanufacturer declines which also means higher prices for the consumers.

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Chapter 7

Dual Channel WEEE Remanufacturing

7.1 Introduction

The optimum demand function and manufacturers profit with respect to different critical parameters in the End-of-Life (EOL) returns management of WEEE are analyzed in this chapter. The reverse supply chain stakeholders that are modeled include the manufacturers, retailers and the second hand dealers. An attempt is made to extended the model proposed by Wei Li et al. (2010) and Hong and Yeh (2012), which involved the competition between remanufactured and refurbished products to develop the model for retail channel and 2^{nd} hand channel competition. The model has been extended to involve government subsidy and its distribution between the manufacturer and retailer. The subsidy component was modeled on the lines proposed by Ji and Xiahou (2010). An attempt was made to analyze the demand and pricing for returned goods sale which is in the form of remanufactured goods (channel-1) or just resold (channel-2). The main parameters of interest are λ-the distribution of procured goods into the two available channels of sale and Θ-the customer preference for 2^{nd} hand goods. The optimum demand vs. λ or Θ are analyzed and the circumstances where the manufacturer gets maximum profit and the optimum amount of goods required to procure to attain the profit are explored. It is assumed here that there is only one retailer and one 2^{nd} hand dealer in the field. The focus is on the optimum demand and the manufacturer's profit and the constraints and trends involved therein. The pricing competition is analyzed indirectly through the trends in optimum demand.

7.2 Modeling Competitive Pricing

It is assumed that the manufacturer has no control over the prices quoted by the retailer and the second hand dealer. Let C denote the returned cost per unit returned; D_L denote the quantity or demand of returned products. Under a take-back law, the manufacturer is solely responsible for the collection and disposal cost of returned products. Therefore, the procurement and remanufacture of goods is done by the manufacturer. Savaskan et al. (2006) and Guide et al. (2003) report in their respective returns model that the return cost involved is directly proportional to the quantity or demand of return goods. Therefore, the return function was assumed to be $D_L = C$. This cost would primarily involve storage costs, transportation cost, etc. In this model, the procurement and reuse/resale of product is independent of the original demand and sale of new products. Here, the scope is limited to the concerns that arise from the investigation into the manufacturer's profit and the demand of return products. The schematic representation of the model is shown in Fig 7.1.

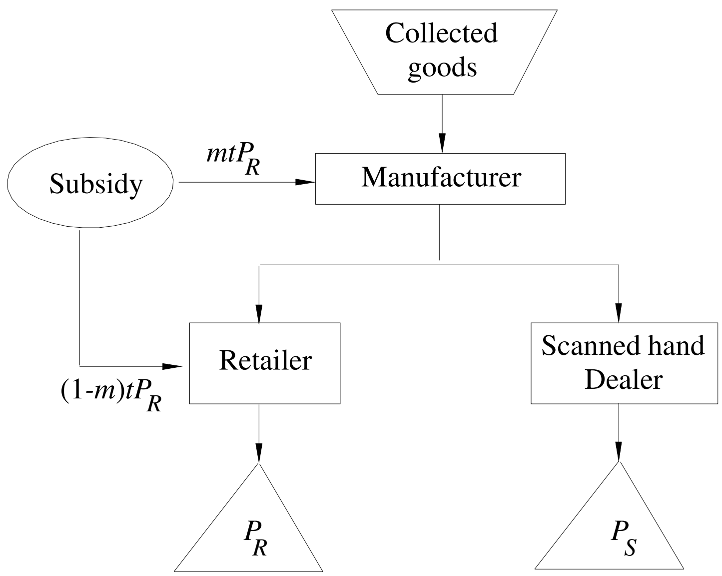

Fig. 7.1: Conceptual remanufacturing model

In the first phase, the manufacturer sells the new product. In the second phase, the manufacturer through the retail channel and the second hand dealer compete for the sale of refurbished return products. In channel-1, the manufacturer refurbish/remanufactures the returned goods at an average cost of C_R and sell it to the retailer at a price of w_2. The retailer invests C_S in its storage and transportation and in turn sells it to the consumer at a price P_R. In the retail channel, the goods are remanufactured and come with a warranty period and hence the customer valuation for these goods would be higher than that of the 2^{nd} hand market goods. The other alternative is the channel-2 which represents the second hand channel, where the manufacturer sells the goods to the second hand market at a price of w_1. The 2^{nd} hand dealer invests C_S in its storage and transportation and sells it to the consumer at price P_S. There is no warranty assured in this channel and hence the customer valuation for these goods is less than that of goods in the retail channel. A consumer may buy either from channel-1 or from channel-2. To model the difference in consumer preferences, the perceived value ν of a refurbished product was assumed to be uniformly distributed over [0, 1] having a density of 1 within the consumer population, which means that the total demand is 1 if all consumers purchase the product. The total population of consumers is normalized to unity. This means that if the customer valuation for refurbished goods in the retail channel be ν; then the customer valuation for 2nd hand market goods will be Θν where $\Theta \in (0, 1)$. In other words, Θ is a measure of the acceptability of products from the second hand channel. Equivalently, 1-Θ represents the customer product differentiation or the gap in quality that exist in the two channels.

The retailer sells the refurbished product at price P_R, so a consumer with valuation ν would derive a net consumer surplus of $\nu - P_R$ by buying the product. All consumers whose valuation is greater than P_R ($\nu - P_R \geq 0$) would buy the refurbished product from the retailer. The marginal consumer whose valuation ν_R equals P_R is indifferent to buying from the retailer or not at all. The 2nd hand products are sold to the consumer at a price P_S. All consumers whose valuations satisfy $\Theta\nu - P_S \geq 0$ would consider buying from the 2nd hand market. The marginal consumer whose valuation ν equals P_S/Θ is indifferent to buying from the 2nd hand market. In cases where, $\nu - P_R > \Theta\nu - P_S$, the customer buys refurbished products from the retailer. The consumer whose valuation (ν^*) equals $(P_R - P_S)/(1 - \Theta)$ is indifferent between the two channels when $\nu - P_R \geq 0 \; and \; \Theta\nu - P_S \geq 0$. A consumer with valuation ν> ν^* ($\nu < \nu^*$) prefers the retailer (2nd hand market). The expressions for the demand functions of the retailer and the second hand channel after making some algebraic manipulations are:

$$D_R(P_R, P_S) = \begin{cases} 1 - P_R & if \; P_R \leq P_S/\theta \\ 1 - \dfrac{(P_R - P_S)}{(1-\theta)} & if \; P_S/\theta \leq P_R \leq P_S + 1 - \theta \\ 0 & if \; P_R \geq P_S + 1 - \theta \end{cases} \tag{1}$$

and

$$D_S(P_S, P_R) = \begin{cases} 1 - P_S/\theta & if \; P_S \leq P_R - 1 + \theta \\ \dfrac{(\theta P_R - P_S)}{\theta(1-\theta)} & if \; P_R - (1-\theta) \leq P_S \leq \theta P_R \\ 0 & if \; P_S \geq \theta P_R \end{cases} \tag{2}$$

For $\nu \geq P_R$ and given that valuation is uniformly distributed having a density of 1, the demand function of the retailer is $D_R = 1 - P_R$, for $0 \leq P_R \leq 1$.

The first segment of the demand functions from Eqs. (1) and (2) occurs when all demand goes to the retailer and second hand dealer, respectively. The second segment on the other hand represents the case where both players exist in the market.

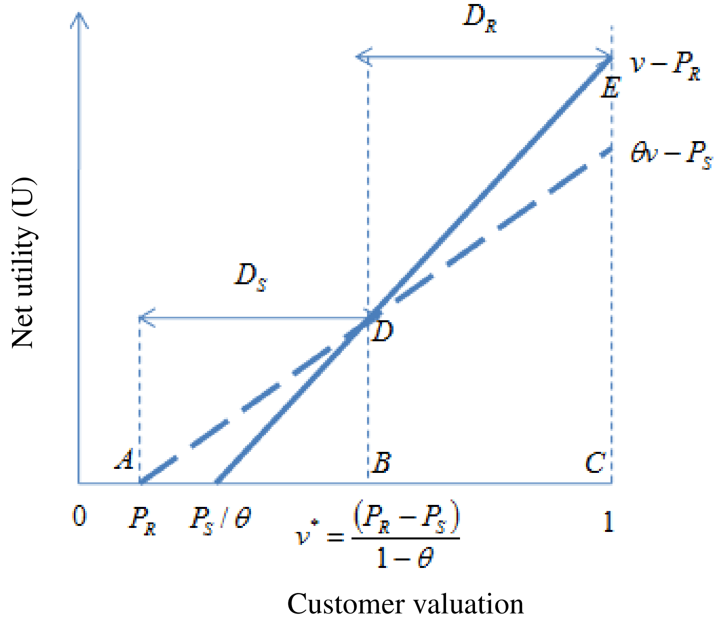

Fig. 7.2: Utility vs. Customer evaluation

As observed from Fig. 7.2 for the case ν ∊ (A, B), the retailer channel has a higher net utility and so is preferred. Similarly, in the case for ν ∊ (B, C), the second hand products are preferred. Given that, ν is assumed to be uniformly distributed between $[0, 1]$, and the market size is normalized to unity, the resulting sales quantities are $D_S = (\Theta P_R - P_S)/\Theta(1-\Theta)$ and $D_R = 1 - (P_R - P_S)/(1-\Theta)$. The resulting consumer surplus in the retail channel and the second hand channel can be estimated from the area of the triangle ABD (which is equivalent to $((\Theta P_R - P_S)^2/(2(1-\Theta)^2))$ and the area of the trapezium BCED ((1-ϴ-$P_R + P_S$)(1-ϴ$-P_R - P_S + 2\Theta P_R)/2(1-\Theta)^2$), respectively.

The third segment occurs when demand in both the channel is zero. It is obvious that as P_R increases, the demand in the second hand channel increases and as P_S increases, the demand in the retail channel increases. This is the classic case of substitution effect of prices of one channel with the demand of the other channel.

The study does not address the collection decision in this investigation. An assumption was made that appropriate take-back schemes are in place to achieve a given collection target rate. The returned product is procured by the manufacturer who then employs a fixed allocation rule where a part of them are refurbished and moves into channel-1. The remaining portion which has comparable better quality moves into channel-2. If λ represents the refurbishing rate, then the fraction of the returned goods that goes to the channel-1 is λ while the remaining fraction (1- λ) moves into the second hand channel, where $0<\lambda<1$. Thus the demand for remanufactured goods D_R and that of 2nd hand goods D_S are expressed as below. It is to be noted here that $C<P_S<P_R$.

$$D_R = 1 - (P_R - P_S)/(1 - \Theta) = \lambda D_L \tag{3}$$

$$D_S = (\Theta P_R - P_S)/\big(\Theta(1 - \Theta)\big) = (1 - \lambda)D_L \tag{4}$$

From Eqs. (3) and (4), respectively

$$P_R - P_S = (1 - \lambda D_L)(1 - \Theta) \tag{5}$$

$$(1 - \lambda)(1 - \Theta)\Theta D_L = \Theta P_R - P_S \tag{6}$$

Subtracting Eq. (6) from Eq. (5) and rearranging the terms, the pricing functions can be expressed as:

$$P_R = 1 - \lambda D_L - \Theta D_L + \lambda\Theta D_L \tag{7}$$

Substituting Eq. (7) in Eq. (5), gives

$$P_S = \Theta(1 - D_L) \tag{8}$$

In order to boost the movement of goods through channel-1 the government gives subsidy so that the demand increases. The subsidy for the resale of each WEEE product is given proportional to P_R. The subsidy is divided between the manufacturer and the retailer in the ratio $m: 1 - m$. The subsidy is given as an incentive to boost reuse of WEEE.

The profit from channel-1 is calculated by adding the profits of the manufacturer and the retailer. The manufacturer procures D_L amount of goods and diverts D_R amount of goods for refurbish and resale. If the cost per unit refurbished is C_R and the total subsidy provided by the government per unit sold is tP_R, $(0 \le t \le 1)$ then the subsidy given to the manufacturer is mtP_R. The subsidy given per unit is a fraction (t) of the product price

(P_R). The manufacturer sells the refurbished goods to the retailer at a price w_2. Accordingly, the manufacturer's profit from this transaction can be expressed as

$$\Pi_{M1} = (w_2 + mtP_R - C_R - C)D_R \tag{9}$$

The retailer in turn invests C_S for the transportation and storage of goods and sells it to the consumer at a price P_R. Thus the retailer's profit can be written as

$$\Pi_R = (P_R + (1-m)tP_R - C_S - w_2)D_R \tag{10}$$

Adding these two profits, the total profit in channel-1 becomes

$$\Pi_1 = (P_R + tP_R - C_R - C - C_S)D_R \tag{11}$$

The manufacture sells D_S amount of procured goods to the 2nd hand market at a wholesale price of w_1.

Thus the manufacturer's profit from this transaction is

$$\Pi_{M2} = (w_1 - C)D_S \tag{12}$$

The 2nd hand dealer invests C_S in its transportation and storage and sells it to the consumer at a price P_S. The 2nd hand dealer's profit can be expressed as

$$\Pi_S = (P_S - C_S - w_1)D_S \tag{13}$$

Therefore, the total profit in channel-2 can be written as

$$\Pi_2 = (P_S - C_S - C)D_S \tag{14}$$

Adding up the profits in the two channels the total profit from the model becomes

$$\Pi_T = (\Pi_1 + \Pi_2) = (P_R + tP_R - C_R - C - C_S)D_R + (P_S - C_S - C)D_S \tag{15}$$

Similarly, the manufacturer's total profit function can be expressed as

$$\Pi_M = \Pi_{M1} + \Pi_{M2} = (w_2 + mtP_R - C_R - C)D_R + (w_1 - C)D_S \tag{16}$$

Assuming that the product returns are homogeneous where $m, t \text{ and } \Theta$ are given, the optimal profit and return quantity are the functions of λ and can be expressed as

$$D_L^* = \frac{[\lambda(w_2 - w_1 - C_R + mt) + w_1]}{2[m(\lambda^2 t + \lambda\theta t - \lambda^2\theta t) + 1]} \tag{17}$$

$$\Pi^* = \frac{[\lambda(w_2 - w_1 - C_R + mt) + w_1]^2}{4[m(\lambda^2 t + \lambda\theta t - \lambda^2\theta t) + 1]} \tag{18}$$

7.3 Analysis and Discussion

Several important outcomes are derived from the analysis of the two models. Here focus is solely on the impact of the parameters of the proposed model on the optimum demand functions. The selling price of the manufacturer to both the channels are assumed to be $w_1 = w_2 = 0.2$. The baseline values assumed for other variables are $C_R = 0.1$, $C_S = 0.05$, $m = 0.7$ and $t = 0.6$. The parameters of interest, θ and λ are varied from 0 to 1 in increments of 0.2 and their effects on the manufacturer's optimal profit and demand plotted using Eq. (17) and Eq. (18).

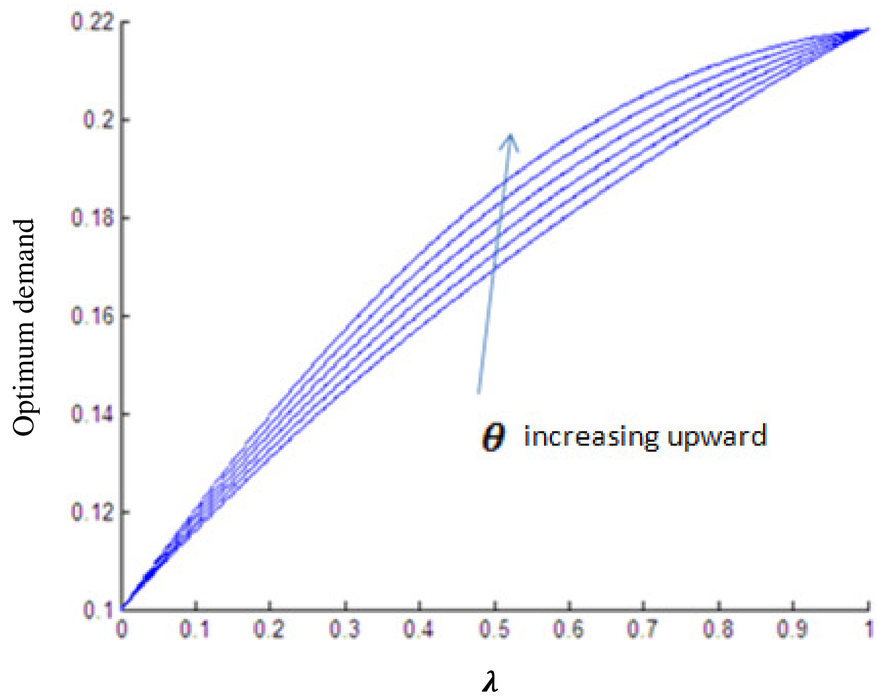

Fig. 7.3: Optimum demand vs. λ at different θ

The possibility of investigating the effect of subsidies on consumer preferences is also explored. As observed from $Fig.$ 7.3, optimum demand of the returned products increases with the increase in Θ which necessarily means that the demand for returned goods can be enhanced by involving the second hand market into the reverse supply chain. It is also clearly evident that the optimum demand at λ=1 and λ=0 are apparently independent of Θ.

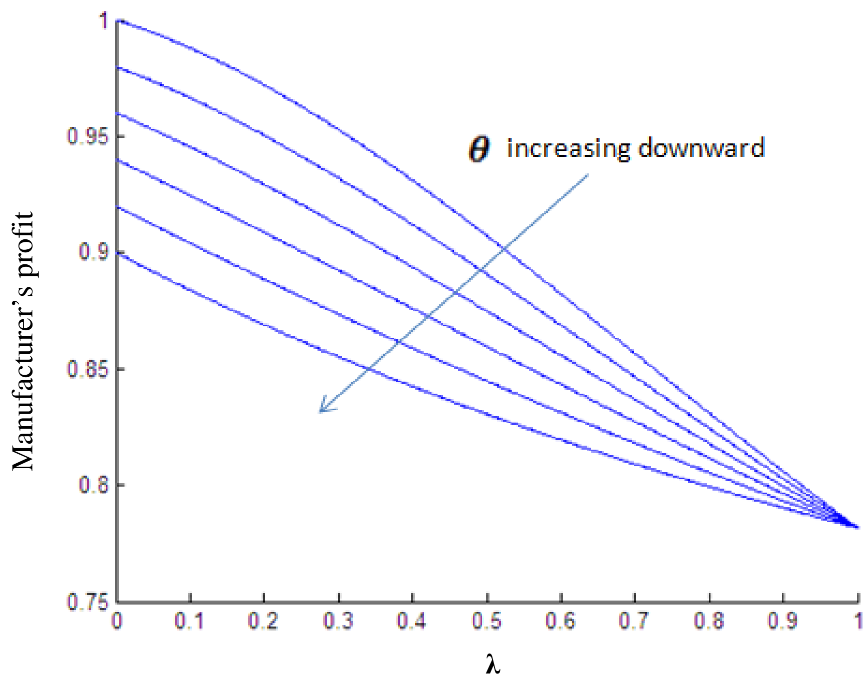

Fig. 7.4: Manufacturer's profit vs. λ at different $\boldsymbol{\theta}$

The manufacturers' optimal profit also shows a similar trend (see $Fig. 7.4$). Apparently, for a given θ, the optimal profit decreases with increase in λ. In the event of decreasing customer acceptability of returned products from the second hand market for a given λ, the optimal profit of the manufacturer also decreases. Another interesting observation is that for sustaining a given profit, in the long run, the manufacturer should encourage increased sale of returned products through the retail channel (by increasing λ), which indirectly results in enhancing the acceptability of the second hand channel as observed from increase in θ. The profit comes mainly from the 2nd hand channel since at lower λ the manufacturer's profit is highest. Evidently, for the manufacturer under a subsidy regimen, it is the second hand market that is the key to generating higher profits.

The price at which the second hand market and the retailer channel sources products from the manufacturer have a direct bearing on the demand for returned products. As observed from Fig. 7.5, the optimum demand decreases with decrease in the procurement price of the second hand market and the retailer, respectively. In other words, with increase in w_2, the manufacturer realizes his optimum profit at a lower demand. The demand however remains unaffected from any increase in w_2 at λ=0 which is clearly understandable given that under this scenario all flows take place in the second hand channel only. With increase in w_1, the optimum demand at λ = 1 remains constant since there is no involvement of the second hand channel.

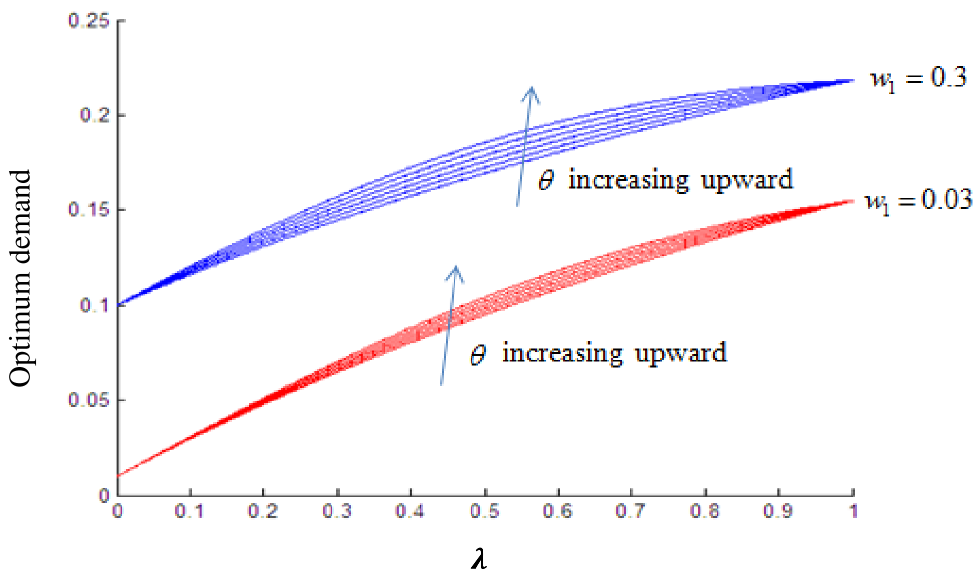

Fig. 7.5: Optimum demand vs. λ at (a) $\boldsymbol{w_1 = 0.03}$, (b) $\boldsymbol{w_1 = 0.3}$

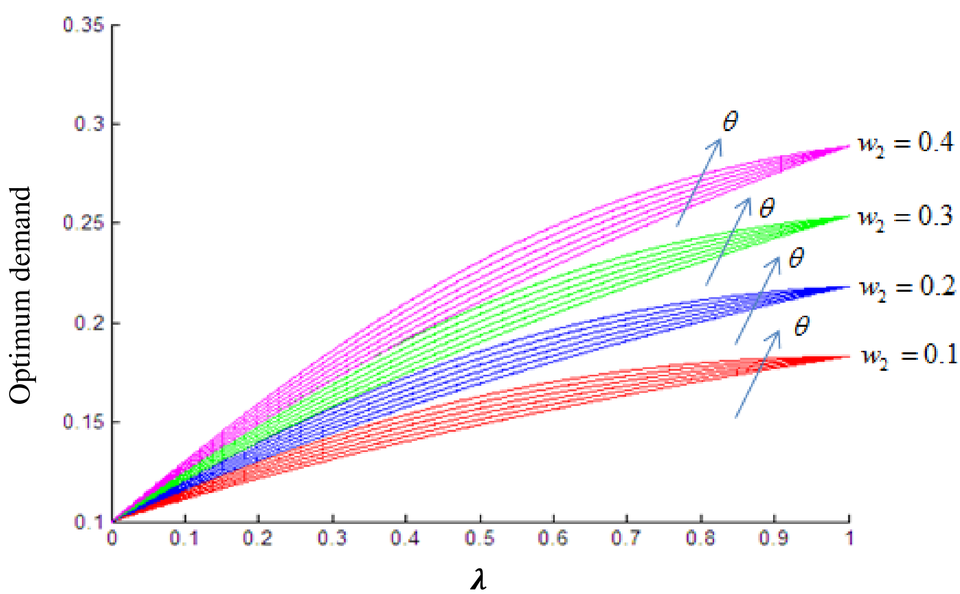

Fig. 7.6: Optimum demand vs. λ at different $\boldsymbol{\theta}$

(a) $\boldsymbol{w_2 = 0.1}$, (b) $\boldsymbol{w_2 = 0.2}$, (c) $\boldsymbol{w_2 = 0.3}$, (d) $\boldsymbol{w_2 = 0.4}$

From Fig. 7.6, it can be observed that with the increase in w_2, the optimum demand increases substantially at λ=1. However, the same demand remains unaffected at λ=0, which is intuitively correct given that there is no movement of goods in the retail channel and w_2 affects only the retail channel. Increasing w_2 without deteriorating the optimum demand will necessitate movement of goods to the second hand channel (low λ).

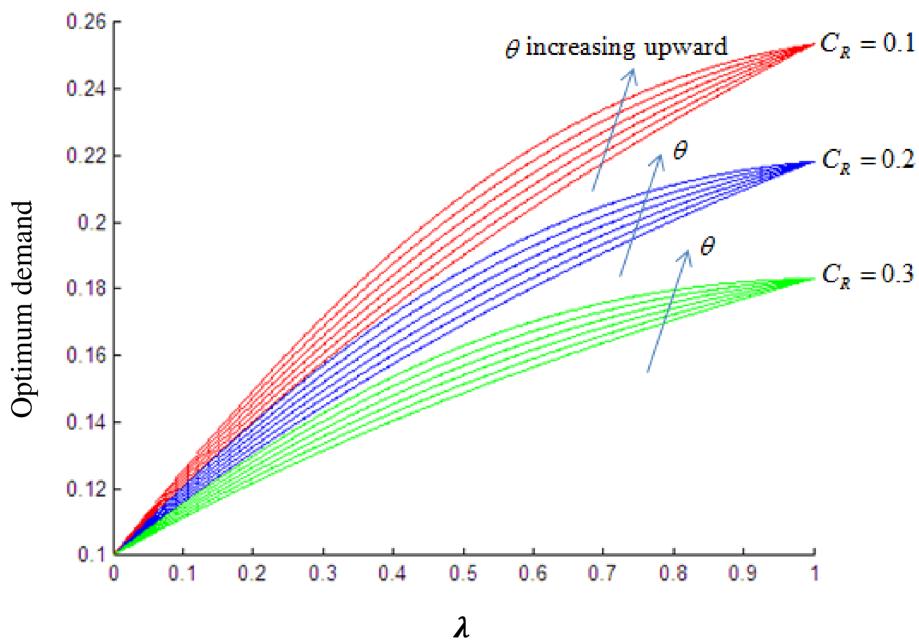

Fig. 7.7: Optimum demand vs. λ at different $\boldsymbol{\theta}$

(a) C_R=0.1 (Red), (b) C_R =0.2 (Blue), (c) C_R =0.3 (Green)

Similarly, with increase in C_R the demand for returned products remains unaffected at $\lambda = 0$ (see Fig. 7.7) since C_R affects only the retail channel. However for all other values of λ, the optimum demand decreases with the increase in unit refurbishment cost (C_R) Incidentally, for a given specific demand, it is observed that with increasing C_R, the demand could be realized at a lower value of λ. This necessarily implies that with increase in unit cost of refurbishing (C_R), the movement of return goods shift to the second hand channel.

The impact of subsidy on the demand for return products was also scrutinized. From Fig. 7.8, it is quite clear that subsidies (m) together with consumer perception of second hand goods (θ) have no impact on the demand for a pure second hand channel

(λ = 0). However, for any given λ, as the subsidy given to the manufacturer decreases, the demand for returned products decreases. Also observed is the fact that with the lowering of subsidy to the manufacturer, the span of the plot becomes narrower indicating that for lower subsidies, variations in the customer acceptability of second hand channel (θ) have least impact on the demand for returned goods. At $m = 0$, i.e., when subsidies are entirely given to the retailer and not to the manufacturer and in the scenario where consumers do not prefer second hand goods, the optimum demand decreases linearly with increasing flow of remanufactured goods to the retail channel (λ) till the point λ =1 (pure retail channel) where the optimum demand becomes zero. As subsidy approaches very low values and very high values (where maximum goes to a particular channel), consumer acceptability of second hand goods have less influence on the variations in demand.

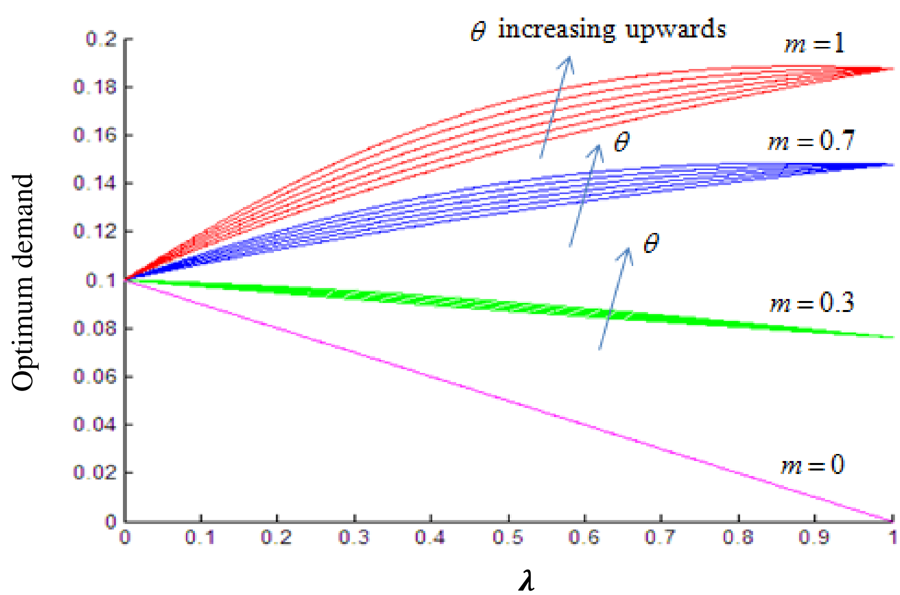

Fig. 7.8: Optimum demand vs. λ at different θ

(a) $m = 0$ (Magenta), (b) $m = 0.3$ (Green), (c) $m = 0.7$ (Blue), (d) $m = 1$ (Red)

Similarly, the effect of $'t'$ (fraction of P_R as subsidy and $0 < t < 1$) on the demand (see Fig. 7.9) show a matching similarity with that of the effect of 'm'.

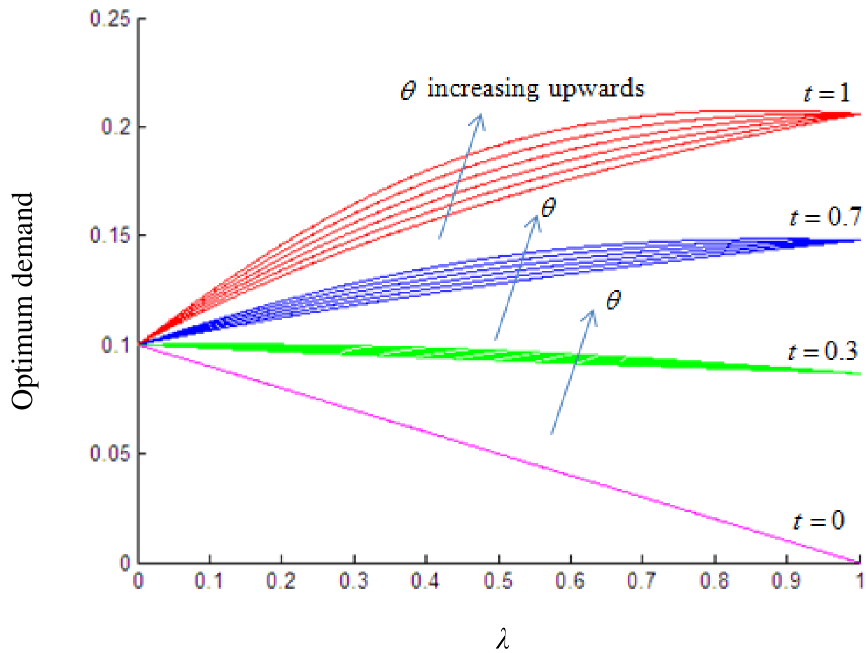

Fig. 7.9: Optimum demand vs. λ at different θ

(a) $t=0$ (Magenta), (b) $t=0.3$ (Green), (c) $t=0.7$ (Blue), (d) $t=1$ (Red)

The combined influence of m, Θ and t on the optimum demand (see Fig. 7.8 and Fig. 7.9) reiterates what was already observed earlier. At $m=0$, the optimum demand is independent of Θ. Additionally, it can also be reckoned that for a pure retail channel ($\lambda=1$), the optimum demand is always independent of Θ and this demand increases with increase in subsidy (m) provided to the manufacturer. This validates the fact that subsidies can bolster the demand in a pure retail channel.

Similarly, for higher values of m, the optimum demand in a pure retail channel is insensitive to small variations in subsidy given to manufacturers regardless of the value of Θ. Interestingly, for a given higher subsidy $(m \neq 0 \; and \; m \to 1)$ the optimum demand decreases with increasing customer acceptability of second hand returned products, which is predominantly the case when more number of returned products are diverted to the second hand channel (low value of λ).

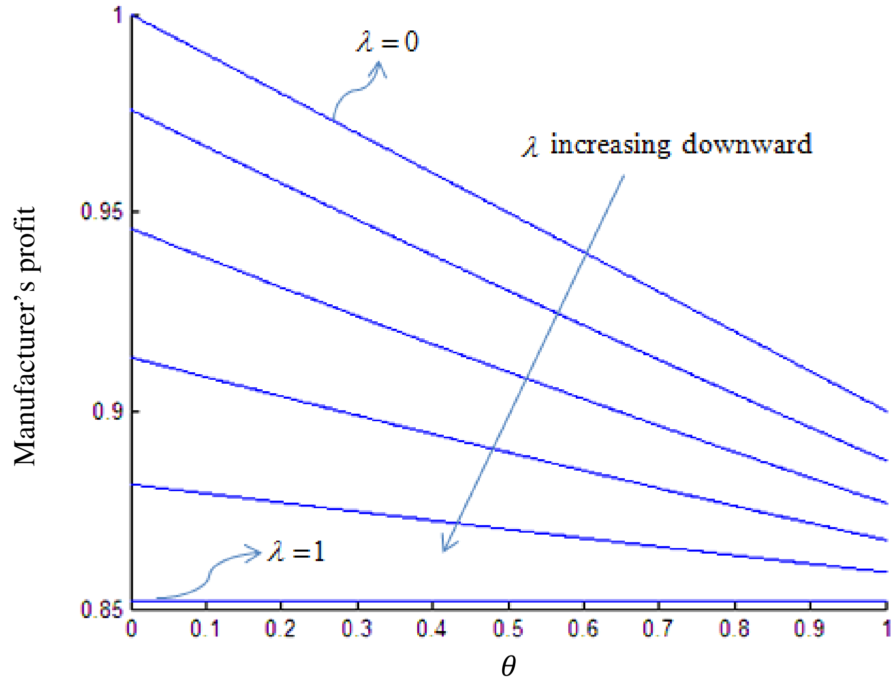

Fig. 7.10: Manufacturer's profit vs θ for varying λ

Incidentally, for a given λ (see Fig. 7.10), manufacturer's profit decreases with increasing customer acceptability of second hand channel (increasing Θ). However, the sensitivity of profit to Θ is more pronounced for lower values of λ, where the second hand channel is dominant. Also observed is the fact that for a certain Θ value, this profit decreases with increasing flow of goods to second hand channel (increasing λ). The results are validated given that for a pure retail channel ($\lambda = 1$), manufacturer's profit remains unaffected irrespective of the value of Θ.

7.4 Conclusion

In this chapter, an effort was made to develop and analyze a model of an industry comprised of a remanufactured products and 2nd hand products. The model deals with the interaction of the manufacturer, retailer and the second hand channel for an effective returns management of electrical and electronic products. A mathematical model was proposed with the objective of studying the effects of consumer behavior on the demand for returned goods in the second hand channel vis-à-vis the retail channel. Through simulation, the response of the system to changes in the parameter values was obtained ad evaluated. The model can be used to predict industry behavior and resulting performance measures taking into account the subsidies for remanufactured products. The results lend insight into the impact of these subsidies on measures of interest to the remanufacturer and government policy-maker. The results of our study lead to important conclusions. The analysis shows that involving the second hand market into the reverse supply chain is positively correlated to the success of reuse business. With the increase flow of returned goods to the 2nd hand channel and increased consumer acceptability of second hand goods, the manufacturer's profit also increases.

The analysis shows that involving the second hand market into the reverse supply chain is positively correlated to the success of reuse business. With the increase flow of return goods to the 2nd hand channel and increased consumer acceptability of second hand goods, the manufacturer's profit increases. In the likelihood of lower acceptability of second hand goods, then the manufacturer can respond by selling more returned products to the retailer, and in the event of higher acceptability of second hand goods, the manufacturer can respond by selling more returned products to the second hand channel.

The most critical factor that affects manufacturer's profit is the selling price of returned goods to the different channels. The manufacturer can trigger a higher demand for return products, if he chooses to settle for a lower price for his products. The manufacturer has absolute control over the market wherein he can dictate the sales of a particular channel by appropriately quoting a price which suits its profits. Similarly, the manufacturer can retain higher demand for returned products, even in the case of products that have high remanufacturing costs by ploughing in more returned products to the second hand channel. The investigation clearly proves that as the subsidy given to the manufacturer decreases, the demand for returned products decreases which means that government subsidies are best served when delivered to the manufacturer and not to the retailers, in the hope of improving reuse targets.

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Chapter 8

Conclusions and Policy Recommendations

This thesis concludes by drawing on the analysis and findings in Chapter 2, 3, 4, 5, 6 and 7 to answer the central research themes and the fundamental issues raised in Chapter 1. Section 8.1 discusses the generic chapter-wise conclusions while Section 8.2 states the policy recommendations for implementing a sustainable e-waste management framework in India. The recommendations are drawn from the conclusions of this thesis and may be applicable to three groups of people: consumers, manufacturers of electronics and legislators.

8.1 Summary of conclusions

As our society continues to consume more electronic products every year, the amount of e-waste produced, and its associated hazards continue to increase manifold. Several electronic waste management systems now exist in many different forms in the context of developed nations, and the amount of related legislation continues to increase. Numerous approaches have been proposed including landfill bans, extended producer responsibility (EPR) and advance recovery fee (ARF) funded recycling systems. In fact, the breadth of combinations of e-waste management system architectures currently in operation is so large that there is no obvious correlation between architectural choices and observed performance. In order for policymakers and system architects to establish the optimal e-waste management systems for their location, they need to juxtapose and assimilate the experience from established practices of developed nations with the unique needs, sensitivities and aspirations of their region.

A review of the current literature regarding e-waste management systems demonstrated a need to better understand what mechanisms is best suited to the Indian context. This thesis therefore makes a limited attempted to address the question: What is the best system architecture of e-waste management system in India? The research is aimed at examining some of fundamental issues in the field of e-waste management. Therefore, the main objective of the research is to identify and explore these issues and suggest necessary solutions towards conceptualizing an e-waste management framework for the Indian context.

In ***Chapter 2***, a mass flow multiple life span time delay model was developed to examine the current and historical e-waste generation estimates in India. By incorporating important system characteristics such as first and reuse life span of products, product possession, and product EOL fate, the author was able to utilize the model to quantify the historical e-waste generation quantities in India. The total WEEE estimates during 2007-2011 was estimated to be around 2.49 million tonnes. The WEEE generated in the coming years would be even greater in view of increasing penetration rate and the obsolescence rate of such appliances, added to the huge import of junk electronics from the developed nations. To assess whether e-waste in future will reach alarming proportions or not, the authors attempted to quantify the future projection of e-waste from computers. Using data on historical stock and sales, PC sales and generation of obsolete PCs are forecasted for the next two decades using the logistic function. The address this challenge through a bounding analysis which considers three scenarios: upper, baseline as well as lower carrying capacity, to identify trends which are insensitive to the choice of bounds. Combining the logistic model with materials flows analysis (MFA) enables estimation of the generation of obsolete/discarded devices.

From the bounding analysis, the long term equilibrium in penetration rate carrying capacity could be reached in the next 30-60 years. The investigation also demonstrates that it might take another 40 years time from now to achieve the magical figure of 1 computer per capita. From the fact that India in all likelihood might overtake the per capita PC penetration rate of the US sometime by the year 2046, our study clearly underscores the reality that e-waste arising emanating from PCs will continue to rise abnormally in the near future. Therefore, the chapter findings argue for an effective take back policy, together with necessary collection and recovery/recycling programs through appropriate national legal and regulatory instruments. Adequate EPR regimes need to be conceptualized and explored to resolve the problems emanating from such waste in India.

In ***Chapter 3***, an attempt was made to investigate the e-waste flow dynamics through different stakeholders in India. This was contemplated by modeling the e-waste trade flow as a Markov chain. The idea was to observe the equilibrium behavior of the system to small matrix perturbations and propose a sustainable e-waste management strategy in the Indian context. Several scenarios were studied for investigating the possibility of reuse/recycling business by focusing on how the transitions take place in the e-waste trade chain. The micro level interventions within the system boundary are modeled and evaluated. From the ensuing analysis, it was observed that from the economic and environmental perspective, product take back designed specifically for recycling/reuse system wherein the reverse supply chain partners make concerted efforts to prioritize reuse over recycling by diverting a proportion collected back to the consumers, looks more promising. Therefore, extension of lifespan by making reuse as a national strategy can go a long way in mitigating the lifecycle impacts of WEEE. On the economic side, the high lifecycle cost of recycling WEEE and the ensuing environmental pressure from the recycling residue justifies reuse prior to recycling. Our study clearly proves that in the event of any future EPR legislation, the entire reverse logistic focus for collecting WEEE should be reorganized so that not only the defective units reach the recycler, but also quality used products which could be further refurbished. The results from our simulation effort are tested and verified through a survey. Data from the survey indicate that respondents preferred to exchange their old electronic goods with the dealer/retailer followed by the alternative "selling to second hand shops". A further breakdown of survey responses for the purchasing decision of the respondents indicate that only 14% have actually purchased a reusable product and about 45% of the respondents are willing to purchase with an additional 5% strongly willing to purchase a reusable electronic product. Majority of the respondents prefer to purchase remanufactured or new-like products specifically if the manufacturer through his dealer/retailer gets involved in the remanufacturing business. This confirms the finding of our simulation effort. Also the respondents indicated quality and cost as the principal deciding factor in the purchase of a remanufactured product followed by warranty and label.

Having established a potential national strategy for the management of e-waste, further investigations were made to identify the critical factors that affect reuse business in general. Following the leads from our analysis and a thorough survey of literature concerning developed nations, a conceptual framework and the system architecture for the adoption of EPR principles in the context of India was proposed. The fundamental assumption behind the success of this conceptual framework at the strategic level remains the existence of a nationwide legislation with mandated recycling and reuse targets. The framework supports the hypothesis of a recycling fund to sponsor recycling activities in the future. The purported recycling fund generated from product sales will be used to develop recycling infrastructure and finance recycling activities. However, this hypothesis will have to be validated and the exact configuration of such a recycling fund determined. Furthermore, compliance, monitoring and book keeping are tactical objectives which are to be enforced either by the government or the PRO. The proposed EPR framework assumes that there is a prosperous e-waste reuse market, which as the study shows is likely the case in the near future. However, any future policy resulting from extended role of dealers in a dealer/retailer take back regime will in all likelihood will translate to neutral profits as a consequence of the additional role of dealers and the revenues from refurbish/resell. This notwithstanding, the chapter argues that a sustained mass flow of used e-products in an EPR regime to refurbish/reuse business sector is central for competing with new products. To explore this scenario, additional studies are attempted to ascertain the level and the extent of competition that may exist in remanufacturing systems.

In ***Chapter 4***, an attempt was made to explore which of the current end-of-life product take back policies practiced in the developed countries are suited to developing countries like India. To this effect, the investigation builds upon the existing baseline European take back schemes for waste electrical and electronic equipment (WEEE) recycling: Individual and Collective take-back scheme. The EPR model practiced in the developed countries is likely to fail because it imposes cost to consumers. Therefore an effort to gain insight into the impact of such market conditions into alternate and competing take-back schemes was performed using an analytical framework. Our results showcase win-win outcomes for both the consumers and the manufacturers. The equilibrium price is always higher in the collective take-back case, and the equilibrium profit is always higher in the individual take-back case. Higher product prices translate to lower demand, lowering the profit margins for manufacturers that favor collective take back scheme. Thus, the individual take-back case is a win-win situation with respect to the consumers and the manufacturers. The EPR system architecture proposed in Chapter 3, envisages a recycling fund to finance the recycling of e-waste in India, the success of which is critically dependent on consumer participation in recycling.

An attempt therefore, was made in ***Chapter 5***, to model and investigate consumer attitudes, consumer e-waste behavior and willingness to participate in recycling activities through an online survey. Preliminary findings from the survey indicate some interesting trends. About 15% of the respondents are not aware about the issues and problems concerning e-waste, while the remaining 73% and 12% respectively have a brief and a very high understanding of the problem. Interestingly, despite the high awareness level of the respondents, overwhelming majority of the respondents (92%) are not aware about the rules and regulations concerning e-waste. Also a greater part of the respondents (83%) reported no formal access to recycling facilities. The primary disposal method for majority of the respondents was "sold in second hand market/ exchange for new products" illustrating the fact that individuals look for some form of financial benefit from their used appliances. The other notable attribute was that on an average, households view "donation and passing on to friends, relatives etc" as preferred choice over "selling to scrap dealer", clearly indicating that households would either like to maximize the returns from selling or prefer donating over selling for a pittance.

A further investigation into the most important consideration while disposing shows that "best exchange offer" followed by "best price" are arguably the prime considerations for consumers to dispose-off their e-waste. So far as respondent's choice for the financial management of e-waste was concerned, "pay afterwards" was the favored payment mode amongst the respondents. The results for the "deposit/refund" and "monthly recycling fee" are roughly the same, while the least preferred remains the "pay in advance" scheme. Apparently, the respondents show overwhelming support for "retailer collection with discount in exchange for new products" as against the alternative "retailer collection for buy-back". Consumer willingness to participate and pay for recycling of e-waste was modeled using logistic regression of multivariate data captured from an online survey.

It was observed that the only explanatory variable significant at the 5% level is "Income Level" which in our case refers to the "upper middle class". Those that are significant at 10% level are "Place", "Recycling habit" and "Economic benefits". The estimated coefficient for all the significant explanatory variables are positive except "Economic benefits". it was observed that the odds of willingness to participate in recycling of e-waste increases, when the income level changes from lower class to upper middle class. Alternatively, this could be interpreted as that the odds of willingness to participate are 8.813 times higher for upper middle class than they are for the low income respondent. Similar trend is observed at 10% significance level when the income level changes from lower class to lower middle class. From the investigation, it was observed that for each unit increase in 'Economic benefit', the subjects were 59% less likely to participate in any future recycling schemes. In India, household consider it a privilege to explore economic benefits when they dispose off their e-waste. Physically, this signifies that when market externalities (informal collection by kabbadiwalas, repair shops and scrap merchants) offer economic incentives during collection of e-waste as against no forthcoming incentive from the formal sector, the study reveals a doubling ($= 2.44$) of the odds that the respondents would not be willing to participate in formal recycling. Residents in India have historically benefited financially from selling their waste to hawkers, scrap dealers and second hand market. The thriving repair business and second hand market are market conditions that are realities in China and India, as our study shows. This relationship naturally evolved over the years in the absence of any formal channel, implying that any future take back policy implementing EPR will not be successful in isolation so long as competition from these non-formal channels exists. Formal recyclers are liable to comply with pollution control measures and environmental standards, which the informal sector apparently flouts thereby allowing them to buy e-waste at higher prices than what the formal sector can afford.

A further breakdown of survey responses, show that roughly about 59% of the respondents (majority constitute middle class) are willing to pay a modest recycling fee in the range of 1-2% of the product market price. An equally large percentage (23.6%) is not willing to pay any form of recycling fee. As for those respondents respondent's who are not willing to pay, 38% of this population feared that the cost of living will increase, 28% stated their inability to contribute on account of lack of time, 27% argue that the current laws and regulations do not mandate and a smaller proportion (7%) believe that it is the responsibility of the state to pay for the recycling of e-waste. The significance of the variable 'Place' could be explained from the view that people living in cities and metros have higher odds of participating in e-waste recycling schemes than those from villages. A similar argument suggests that when recycling habit is instilled on households having no such prior habits, will result in increase in the odds of participating in recycling by a factor of 2.6. This raises the possibility of involving the communities in inculcating household recycling habits, which in the long run might bolster voluntary participation in future recycling schemes.

This study uncovers a peculiar nature of market for recycling in India. As most of the e-waste materials in India are being collected by informal scrap collectors at a monetary exchange rate much higher than any formal recycler can competitively match, Extended Producer Responsibility (EPR) model of e-waste recycling is likely to fail because it imposes cost to consumers. However, as India becomes urbanized rapidly, the people's mindset will change in future so that they will gradually participate (as the results show). More environmental awareness and habit formation will also help. The results show that competition from informal scrap dealers is the most crucial hindrance to moving towards a formal re-cycling model in India. What should government do now as informal recycling is environmentally more costly (larger social cost and more economic benefit for individual)? Clearly market mechanism fails here due to externality. This is not an easy task for policy makers to choose either side as livelihood of large section of poor people depends on this informal sector.

One possible way would be to giving informal sector some economic incentive to collaborate with the formal sector. This low-cost informal network can be channelized by manufacturers in their future collection program. So long as this informal channel is not reined in, the 'pay afterward' scheme which is the preferred financing model for the respondents in our sample invariably might become ineffective because consumers can sell obsolete goods to such channels for financial gain.

Given the reluctance of the state to participate in the business of managing e-waste, which it considers as an additional burden, 'monthly recycling fee' scheme may not be the viable alternative. The only plausible alternative which complements the respondents' perception of getting economic benefits from the disposal of used EEE goods is the 'deposit-refund' scheme.

In the event of EPR becoming a policy instrument in India, the possibility of realizing increased returns through the dealer/retailer channel needs further exploration.

Supposedly, our study substantiates this, given that majority of the respondents' prefer for "best exchange offer" as a criterion for disposing off their e-waste. Illegal imports of WEEE have the potential to undermine future EPR legislation. Illegal imports together with the informal downstream processes are existing market anomalies that needs to be addressed since they represent major dysfunctions of the current EPR legislation. The proposed e-waste management framework shown below have to be tested further to ascertain whether remanufacturing can become a successful reuse strategy, given the stiff competition from new products.

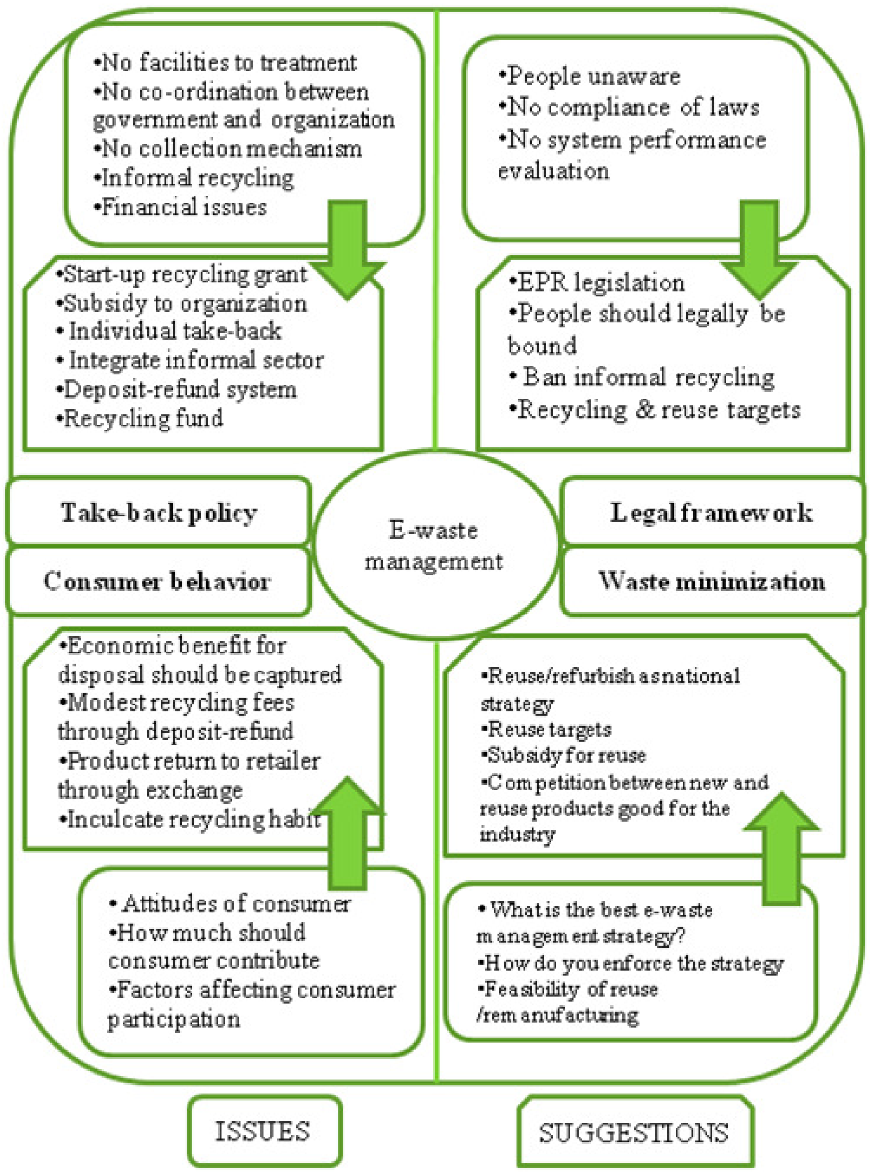

Fig. 8.1: Key issues and suggestions in e-waste management framework in India

Fig. 8.1 shows the key issues of e-waste management discussed in the thesis and the suggestions stated to mitigate such issues. In Chapter 6 and Chapter 7, two different modes of remanufacturing were investigated and assessed, namely: third party remanufacturing and individual dual channel remanufacturing. In Chapter 6, a 2-period third party remanufacturing model was investigated assuming that take-back laws in vogue. The results from our modeling effort suggests that in an industrial setting where remanufacturing is not feasible, may become feasible in the backdrop of a take-back legislation. From the aforementioned study, it can be argued that even though the manufacturer under individual take-back has the resources to prevent the remanufacturer from entering the market, he will, as the study projects, will benefit more from selling the returns to the remanufacturers than by operating as a monopolist. This is only possible, when the return rates are sustainable in the long term. Collective take-back by a third party, though is a potential alternative, is not beneficial in the sense that here even though the collection cost reduces and the profits improve, the intensity of competition between the manufacturer and remanufacturer declines which also means higher prices for the consumers. So our study clearly proves that individual manufacturer take-back, wherein return products collected are sold to a third party, who in turn remanufacture them to be finally sold in the demand market can be profitable. But in the event of green consumers dominating the market, which is less likely to happen in the near future, then a collective take back makes more sense than the individual take back.

The second remanufacturing mode which is individual remanufacturing is discussed in ***Chapter 7***. This chapter analyses the optimum demand function and manufacturers profit with respect to different critical parameters of a dual channel. The reverse supply chain stakeholders modeled in the returns model include the manufacturers, retailers and the second hand dealers. A mathematical model was proposed with the objective of studying the effects of consumer behavior on the demand for returned goods in the second hand channel vis-à-vis the retail channel. The model deals with the interaction of the manufacturer, retailer and the second hand channel for an effective returns management of electrical and electronic products. The study shows that involving the second hand market into the reverse supply chain is positively correlated to the success of reuse business. With the increase flow of return goods to the 2nd hand channel and increased consumer acceptability of second hand goods, the manufacturer's profit increases.

In the likelihood of lower acceptability of second hand goods, then the manufacturer can respond by selling more return products to the retailer, and in the event of higher lower acceptability of second hand goods, then the manufacturer can respond by selling more return products to the second hand channel. The most critical factor that affects manufacturer's profit is the selling price of returned goods to the different channels. The manufacturer can trigger a higher demand for return products, if he chooses to settle for a lower price for his products. The manufacturer has absolute control over the market wherein he can dictate the sales of a particular channel by appropriately quoting a price which suits its profits. Similarly, the manufacturer can retain higher demand for returned products, even in the case of products that have high remanufacturing costs by ploughing in more returned products to the second hand channel. The investigation clearly proves that as the subsidy given to the manufacturer decreases, the demand for returned products decreases which means that government subsidies are best served when delivered to the manufacturer and not to the retailers, in the hope of improving reuse targets.

8.2 Policy Recommendations

This study will be helpful in shaping Indian policies and practices towards e-waste management in India. The experiences from this study could be drawn upon to help guide the implementation of e-waste legislation in India. The following policy guidelines may contribute to the development of effective e-waste legislation in India:

A. Develop clear terminology, definition and scope of e-waste.

B. Create a national nodal center for e-waste who will be responsible for tracking the sales of e-goods (both exports and imports). This will help in future assessment studies.

C. Develop clear targets for India's e-waste legislation. We should not only set collection and recycling targets, as is the common practice in the developed countries, but also a holistic reuse target. These targets should be dynamic in nature and could be based upon the assessment studies made by the proposed nodal center.

D. Develop and implement recycling standards. Adopt a licensing scheme for e-waste recycling in India. This will make the informal recycling illegal by establishing a recycling license certification system.

E. Define and allocate responsibilities of producers and other stakeholders. Make EPR mandatory. Manufacturer's to promote the refurbishment and re-use market chain for their products in India. The informal e-waste sector to be included in their collection programs.

F. Determine appropriate financing schemes and methods of determining subsidy rates. For the Indian conditions, as our study suggests, a national Deposit-Refund scheme or advance recycling fees looks more promising.

G. Establish a monitoring system for legislative implementation and improve transparency in book keeping, compliance enforcement and systems to impose penalties.

H. Stimulate product eco-design through legislation. Promote individual collection as our study envisages. Design products for easy disassembly, reuse and material separation.

I. While consumer participation is influenced by the factors including income, recycling habit and place, the degree to which each of these factors influence participation needs to be assessed. However, increasing public awareness of e-waste can increase participation. Raise public awareness of e-waste issues and recycling behavior. Our studies show that establishment of effective collection channels and schemes with strong public participation are also functional for achieving higher collection rates.

J. Create learning loops and mechanisms for stimulating competition in the reuse business through subsidy. Promote eco-labeling of reused products.

SURVEY ON CONSUMERS PERCEPTION OF REUSED PRODUCTS

Questionnaire consists of three parts. Part 1 consists of the profile of the respondent, Part 2 consists of the respondent's awareness about WEEE and Part 3 consists of the respondent's awareness about reuse business. Please enter theanswer preference number against the space provided for the same.

<table>
<tr><th colspan="3">Part-I: Profile of Respondents</th></tr>
<tr><td>1</td><td>What is your age?
1. 15 – 25 years
2. 25 – 45
3. 45 – 65
4. >65</td><td></td></tr>
<tr><td>2</td><td>What is your gender?
1. Male
2. Female</td><td></td></tr>
<tr><td>3</td><td>What is your annual household income?
1. 2 Lakhs
2. 2 – 5 Lakhs
3. 5 – 10 Lakhs
4. >10 Lakhs</td><td></td></tr>
<tr><td>4</td><td>What is your level of education?
1. School
2. Graduate
3. Post Graduate</td><td></td></tr>
<tr><td>5</td><td>Which part of the country you belong to?
1. East
2. West
3. North
4. South</td><td></td></tr>
<tr><th colspan="3">Part-II: Awareness about WEEE</th></tr>
<tr><td>1</td><td>Are you aware about the negative Environmental and Health issues related to WEEE in India?
1. Highly Aware
2. Aware but less knowledge about it
3. Not Aware</td><td></td></tr>
</table>

2	Source of information about WEEE and their impact on Environment, Society and Health? 1. Friends & Relatives 2. Print Media 3. Electronic Media 4. Others 5. Not Aware	
Part-III: Awareness about Reuse Business		
1	Have you ever purchased a reusable electronic product? 1. Yes 2. No	
2	If the answer to above Question (1) is Yes, then from where? 1. Retailers or Dealers 2. Second hand market , shops 3. Friends or Unknown persons	
3	Are you willing to purchase a reusable electronic product from the market? 1. Strongly Willing 2. Willing 3. Not Sure 4. Not Willing	
4	Given the option of purchasing as new like used products, whom would you prefer as a reliable seller of such products? 1. Retailers or Dealers 2. Second hand market shops 3. Friends or Unknown persons	
5	Which of the following electronic items do you possess? 1. Computer 2. Laptop 3. Mobile Phone 4. Refrigerator 5. Washing Machine 6. Air Conditioner	
6	What will you do with your old electronic equipment? 1. Sell it to another customer for further use. 2. Sell it to dealer / retailer for exchange with new products. 3. Sell it to second hand shops. 4. Donate to someone. 5. Store it in your house / garage etc. 6. Throw it in municipal garbage	

7	What are the attributes you will look for when you purchase a reusable electronic product? 1. Lesser cost as compared to new product 2. Lesser age of product in use 3. Warranty on Reusable product (Reliability) 4. Quality of the product	
8	When you will dispose – off your used electronic equipment?	
	1. Existing product not fulfilling your requirement 2. Better features available in newly launched products 3. Out of fashion and trend 4. Before the resale value of the product declines	
9	If the Reusable electronic product has the same features as that of a new electronic product, rank the attributes you will be looking for, if you are willing to purchase a Reusable electronic product from the market? Please give Rank 1 / Rank 2 / Rank 3 / Rank 4 / to the 4 – options *(**1**– for highest priority and **4** – for Lowest Priority)*	
	1. Cost	
	2. Quality	
	3. Warranty	
	4. Label of Original Equipment Manufacturer	

SURVEY ON CONSUMERS WILLINGNESS TO PARTICIPATE IN RECYCLING

Q. No	Question	Option
1	Please state your gender	
	0. for female and 1. for male	
2	What is your education level?	
	1. for Secondary education 2. College education (Bachelors) 3. Higher education (Masters and PhD)	
3	What is your geological region?	
	1. Eastern India 2. Western India 3. Northern region 4. Southern region	
4	Which better describes the place where you come from?	
	1. Village and small towns 2. City 3. Metropolitan city	
5	What is your age?	
	1. Less than 20 years 2. 20-29 years 3. 30-39 years 4. 40-49 years 5. 50 years and above	

Q. No	Question	Option
6	What is your household size?	
	1. One 2. Two 3. Three 4. Four 5. Five	
7	What is your monthly household income in Indian Rupee (INR)?	
	1. Less than 14, 000 INR 2. 14, 000 INR – 28, 000 INR 3. 28, 000 INR – 1.4 lakh 4. Greater than 1.4 lakh	
8	Please state the type of dwelling of your family	
	1. Rented house in a locality/village 2. Rented house in apartment building 3. Own house in a locality/village 4. Own house in an apartment 5. Owns more than one house	
9	Out of your total monthly expenditure, please state your average food expenses (in percentages) per month.	
	(Example: It could be 60% of your total monthly expenditure)	
10	How many of the following items are in possession by your family? *State in numbers from 1to 5.*	
	Mobile	
	Television	
	Computer (Desktop and Laptop)	
	Refrigerator	
	Washing machine	
	Air conditioner	

Q. No	Question	Option
11	What is your e-waste awareness level? How much understanding do you have about the problems emanating from e-waste?	
	1. Do not know about the problem 2. Have a very brief understanding of the problem 3. Have a very high understanding of the problem	
12	Are you aware about e-waste managementlaws and regulations in India?	
	0. Haven't heard of the laws 1. Clearly knows the law	
13	Have you participated in recycling before? (Ex: have you segregated plastics before disposal etc)	
	0. Not participated in recycling before 1. Participated in recycling	
14	Are you concerned about the deteriorating environment around you?	
	0. Not my concern 1. Definitely, my concern	
15	Are you affiliated with any environmental organization?	
	0. Not affiliated 1. Affiliated	
16	Do you have any access to any e-waste collection center or recycling facility in your city where your family reside?	
	0. No access exists 1. Yes access exists	
17	Are you looking for some form of economic benefits to participate in e-waste recycling?	
	0. No 1. Yes	

Q. No	Question	Option
18	Are you willing to participate and pay for e-waste recycling schemes in India?	
	0. Not willing 1. Willing to pay	
19	How much are you willing to pay for e-waste recycling in India?	
	1. Not willing to pay for recycling of the products 2. 1% of the product price 3. 2% of the product price 4. 3% of the product price 5. 4% of the product price 6. 5% of the product price	
20	Why are you not interested in participating?	
	1. E-waste recycling is not my responsibility, but the responsibility of the government. 2. Currently we don't pay for recycling in India and this should continue in future too 3. If I pay for recycling, then my cost of living will increase 4. I am too busy to be involved in such activities 5. Others	
21	What type of model would you prefer for financing e-waste recycling in India?	
	1. Pay in advance (PIA): where fees set to recover the annual costs of the scheme are added to the price of new products 2. Pay afterward (PA): where consumers pay recycling fees when they discard their electronic products 3. Deposit and Refund scheme (DR): where consumers deposit a sum in addition to the product price, but can claim some refund equal to a fraction of the deposit, at the time of discard 4. Monthly recycling fee (which we pay for wastewater treatment to municipality)	

Q. No	Question	Option
22	Which is the most important consideration before you dispose off your mobile?	
	1. Best Price 2. Convenience 3. Best exchange offer 4. Credibility of buyer 5. Environment friendly behavior	
23	Which is the most important consideration before you dispose off your TV?	
	1. Best Price 2. Convenience 3. Best exchange offer 4. Credibility of buyer 5. Environment friendly behavior	
24	Which is the most important consideration before you dispose off your Computer?	
	1. Best Price 2. Convenience 3. Best exchange offer 4. Credibility of buyer 5. Environment friendly behavior	
25	Which is the most important consideration before you dispose off your Refrigerator?	
	1. Best Price 2. Convenience 3. Best exchange offer 4. Credibility of buyer 5. Environment friendly behavior	

Q. No	Question	Option
26	Which is the most important consideration before you dispose off your Washing machine?	
	1. Best Price 2. Convenience 3. Best exchange offer 4. Credibility of buyer 5. Environment friendly behavior	
27	Which is the most important consideration before you dispose off your Air conditioner?	
	1. Best Price 2. Convenience 3. Best exchange offer 4. Credibility of buyer 5. Environment friendly behavior	
28	Please state your preferred method of disposal for your mobile?	
	1. Given to relatives/friends 2. Donated to driver/maid/other charity 3. Thrown in dustbin / municipal waste 4. Sold in second hand market 5. Sold to scrap dealer 6. Exchanged for new products 7. Others	
29	Please state your preferred method of disposal for your Television?	
	1. Given to relatives/friends 2. Donated to driver/maid/other charity 3. Thrown in dustbin / municipal waste 4. Sold in second hand market 5. Sold to scrap dealer 6. Exchanged for new products 7. Others	

Q. No	Question	Option
30	Please state your preferred method of disposal for your Computer?	
	1. Given to relatives/friends 2. Donated to driver/maid/other charity 3. Thrown in dustbin / municipal waste 4. Sold in second hand market 5. Sold to scrap dealer 6. Exchanged for new products 7. Others	
31	Please state your preferred method of disposal for your Refrigerator?	
	1. Given to relatives/friends 2. Donated to driver/maid/other charity 3. Thrown in dustbin / municipal waste 4. Sold in second hand market 5. Sold to scrap dealer 6. Exchanged for new products 7. Others	
32	Please state your preferred method of disposal for your Washing machine?	
	1. Given to relatives/friends 2. Donated to driver/maid/other charity 3. Thrown in dustbin / municipal waste 4. Sold in second hand market 5. Sold to scrap dealer 6. Exchanged for new products 7. Others	

Q. No	Question	Option
33	Please state your preferred method of disposal for your Air conditioner?	
	1. Given to relatives/friends 2. Donated to driver/maid/other charity 3. Thrown in dustbin / municipal waste 4. Sold in second hand market 5. Sold to scrap dealer 6. Exchanged for new products 7. Others	
34	Which collection method from the manufacturer would you prefer to dispose-off your e-waste?	
	1. Telephonic reservation system to collect e-waste 2. Availability of permanent collection space in your city 3. Designated collection time and collection place 4. Retailer collection for buy-back 5. Retailer collection with discount in exchange for new products	

List of Publications

Published

[1] **Dwivedy, M.**, Mittal, R. K., 2010. Estimation of future outflows of e-waste in India. Waste management 30 (3), 483-491. (Elseveir Publication, Impact Factor: 2.428)

[2] **Dwivedy, M.**, Mittal, R. K., 2010. Future trends in computer waste generation in India. Waste management 30 (11), 2265-2277. (Elseveir Publication, Impact Factor: 2.428)

[3] **Dwivedy, M.**, Mittal, R. K., 2012. An investigation into e-waste flows in India. Journal of Cleaner Production 37, 229-242. (Elseveir Publication, Impact Factor: 2.727)

[4] **Dwivedy, M.**, Mittal, R. K., 2013. Willingness of residents to participate in e-waste recycling in India. Environmental Development (Online). (Elseveir Publication) http://dx.doi.org/10.1016/j.envdev.2013.03.001

Accepted

[5] **Dwivedy, M.**, Mittal, R. K., 2013. A Glance at the World: Attitudes and Behavior of residents towards e-waste recycling in India. Waste Management. (Elseveir Publication, Impact Factor: 2.428)

Conferences

[6] **Dwivedy, M.**, and Mittal, R. K., (Dec-2007). R K, e-waste: Current practices and pitfalls in India, QRMAES, NIT-Hamirpur.

[7] **Dwivedy, M.**, and Mittal, R. K., (Dec-2007). Issues in Disassembly Planning for Product and Material Recovery, QRMAES, NIT-Hamirpur.

[8] **Dwivedy, M.**, and Mittal, R. K., (Dec-2007). Justification of Fly Ash as a viable alternative to conventional bricks using ANP, QRMAES, NIT-Hamirpur.

Communicated

[9] **Dwivedy, M.**, Mittal, R. K., 2013. A fuzzy time-series based analysis of e-waste projections in India from desktop PC. Expert System with Applications. Submitted on 25th March, 2013.

[10] **Dwivedy, M.**, Mittal, R. K., 2013. Investigations into WEEE product take-back schemes in India. Resources, Conservation and Recycling. Submitted on 27th March, 2013.

Brief Biography of the Candidate

MAHESHWAR DWIVEDY did his B.E. (Mechanical Engineering) from College of Engineering & Technology, Bhubaneswar in 1999 and M.Tech. (Production Engineering) from NIT-Rourkela in 2005. He is presently working as a Lecturer with Department of Mechanical Engineering, BITS-Pilani, Pilani campus and is currently a nucleus member of Academic Registration and Counselling Division (ARCD) at Pilani Campus. He has over 9 years of teaching experience at both under graduate and graduate levels. His areas of research interest are environmental modelling and assessment, network flow modelling (traffic flow/energy flow/material flow/river water flow etc), convex optimization, life cycle assessment, multivariate statistics, queuing theory, numerical computation, perturbation theory and hyperbolic PDEs.

Brief Biography of the Supervisor

R K MITTAL is currently Senior Professor and Director at Birla Institute of Technology & Science (BITS) - Pilani, Dubai Campus, Dubai from April 16, 2010.

He obtained his B.E, M.E and Ph.D Degrees from BITS-Pilani, Pilani Campus. He was awarded Institute's Gold Medal for standing First in M.E. program. Prof. Mittal was leading the Academic Registration and Counselling Division as the Dean until he was appointed as Deputy Director Administration of BITS Pilani, Pilani Campus form Sept. 8, 2009 to April 15, 2010. He is credited and acknowledged for computerizing the student registration process of the university and spearheading the BITS Alumni Association (BITSAA). He is also instrumental in establishing and developing the state-of-the-art Centre for Robotics at BITS-Pilani. Under his leadership, the Mechanical Engineering Department achieved the rare distinction of developing the first ever Indian prototype of a humanoid ACYUT, widely acclaimed in several competitions and the press alike. He is the co-author of two bestselling books, "Elements of Manufacturing Processes" and "Robotics & Control". His research interests include: mobile robotics, robust robot motion planning, vision based robot guidance, mechatronics, modelling software reliability, MEMS/NEMS, nanotechnology and environmental policy making.

He has published extensively in various peer-reviewed, SCI indexed and high impact national and international journals. Under his able guidance, the Mechanical Engineering department conducted its first international conference "Emerging Mechanical Technologies: Macro to Nano EMTM2N-2007". He was also instrumental in the successful conduct of the first International Conference on Cloud Computing in the Middle East region ICCTAM-12 at BITS-Pilani, Dubai Campus. He has extensively delivered invited talks and chaired numerous sessions in International Conferences.