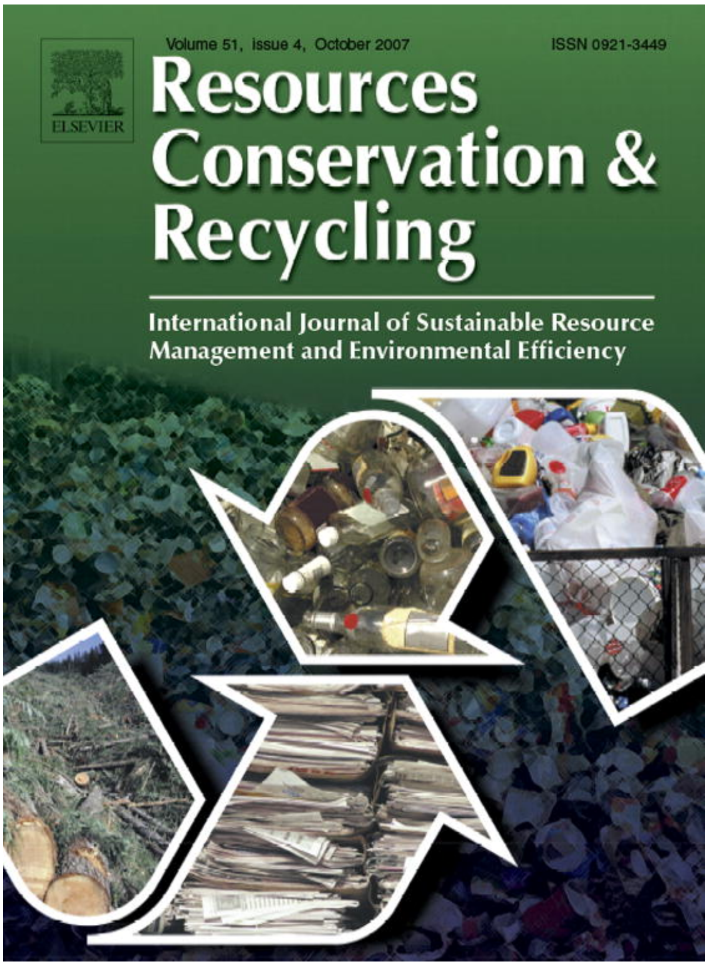
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A life cycle based multi-objective optimization model for the management of computer waste

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Abstract

The accelerating pace of waste generation from used electrical and electronic equipment is of growing global concern. Within this waste stream, computer hardware is quite significant in terms of both volume and risk to the environment because of the hazardous materials within it. The waste management hierarchy of prevention, reuse, recycle, treatment and disposal in landfill is accepted as a universal guideline for waste management. The contemporary concept of integrated solid waste management is very complex comprising of not only the environmental aspects or the technical aspects of the waste management hierarchy, but also incorporating economic, institutional, perceived risk and social issues in the context of complete life cycle of waste. Moreover, when to shift from one stage of hierarchy to another, is an involved decision warranting inclusion of several case specific issues. This paper presents a life cycle based multi-objective model that can help decision makers in integrated waste management. The proposed model has been applied to a case study of computer waste scenario in Delhi, India, which apart from having computer waste from its native population receives large quantities of imported second hand computers. The model has been used to evaluate management cost and reuse time span or life cycle of various streams of computer waste for different objectives of economy, perceived risk and environmental impact. The model results for different scenarios of waste generation have been analyzed to understand the tradeoffs between cost, perceived risk and environmental impact. The optimum life cycle of a computer desktop was observed to be shorter by 25% while optimizing cost than while optimizing impact to the environment or risk perceived by public. Proposed integrated approach can be useful for determining the optimum life cycle of

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computer waste, as well as optimum configuration of waste management facilities, for urban centers where computer waste related issues are of growing concern.

Keywords: Computer waste; Integrated waste management; Multi-objective optimization; Life cycle analysis; Perceived risk

1. Introduction

It is estimated that obsolete personal computers (PC's) were around 2.25 million units in India in 2005, which are expected to touch a figure of 8 million obsolete units by the year 2010 at an average annual growth rate of approximately 51% (Boralkar, 2005). Considering an average weight of 27.18 kg (Toxics Link, 2003) for a desktop/personal computer approximately 61,155 tonnes of obsolete computer waste would have been generated in India in 2005, which would increase to about 217,440 tonnes by the year 2010 at the projected growth rate.

Computer hardware would appear to have up to 3 distinct product lives: the original life or first product life (when it is being used by the primary user) and up to 2 further lives depending on reuse. Fig. 1 depicts the flow of computer hardware units from point-of-sale to the original purchaser and on to the reuse phases. The duration of the product's first life is estimated to be between 2 and 4 years for corporate users and between 2 and 5 years for domestic users. Herein, we would like to define the life cycle of computer waste as, the period from when it is discarded by the primary user to when it goes for recycling or is disposed of in a landfill (Fig. 1).

There are different options available for managing computer waste. These options can be broadly categorized under reuse, recycle, incineration and landfilling. It is to be noted that incineration of e-waste is being discouraged worldwide because of the generation of toxic substances such as furans and dioxins in the environment.

The waste management hierarchy of prevention, reuse, recycle and disposal in a landfill is accepted as a universal guideline for waste management. However, when it is desirable to shift from one stage of hierarchy to another, would depend on several factors such as cost, impact to the environment and risk perceived by the public. A schematic diagram showing the influence of these factors on the different stages of waste management hierarchy is given in Fig. 2. The waste management hierarchy can typically be depicted by an inverted triangle with reuse at the top which has maximum width, signifying maximum preference to this management option. For minimization of environmental impact the ideal scenario would be maximum possible reuse and disposal in a landfill only when it cannot be reused or recycled. Typically that would mean maximum possible time span of life cycle of waste. The case would be the same while minimizing perceived risk, as it has been observed that, people perceive minimum risk for reuse and maximum for disposal in a landfill. As recycling is a preferred option than disposal in a landfill for the objectives of minimization of environmental impact and perceived risk, recycling of the waste would be preferred even after it is no longer economically attractive than disposal. This would mean a delay in shift from recycling stage of hierarchy to disposal, as compared to the scenario of priority to

Nomenclature

Asc	Amount of chemical/component (c) in waste type (s)
$As'c$	Amount of chemical/component (c) in waste type (s')
$As''c$	Amount of chemical/component (c) in waste type (s'')
As^*c	Amount of chemical/component (c) in waste type (s^*)
BLR	Baseline risk
$Bsgk$	Cost of segregation per unit quantity of waste in time step (k)
$Bs'k$	Cost of processing unit quantity of waste (s') in time step (k)
$Brs'k$	Cost recovered from the sale of unit quantity of processable waste type (s') in time step (k)
$Bs''k$	Cost recovered from the sale of unit quantity of reusable waste type (s'') in time step (k)
$Bstk$	Cost of storage per unit quantity of waste in time step (k)
CPd'	Capital cost for locating disposal facility (d')
$CPsr'$	Capital Cost for locating processing facility sr'
d'	Disposal facility
$D_{(g-sr')}$	Distance between the source node (g) and processing facility (sr')
$D_{(sr'-d')}$	Distance between the processing facility (sr') and disposal facility (d')
$D_{(g-d')}$	Distance between the source node (g) and disposal facility (d')
$D_{(g-g')}$	Distance between the source node (g) and reuse facility (g')
e	Total number of time steps
e'	Total number of time steps in which primary waste s can arrive back as waste after a cycle of reuse
g	Source node
g'	Reuse facility
IFc	Importance factor for chemical/component (c)
k	Time step
k'	Time step in which primary waste (s) going for reuse in time step (k) arrives back as waste on source nodes
$Mdis\_d'_{(s)}$	Risk multiplication factor for disposal of waste type (s) at disposal facility (d')
$Mdis\_d'_{(s')}$	Risk Multiplication Factor for disposal of waste type (s') at disposal facility (d')
$Mdis\_d'_{(s'')}$	Risk multiplication factor for disposal of waste type (s'') at disposal facility (d')
$Mdis\_d'_{(s*)}$	Risk multiplication factor for disposal of waste type (s^*) at disposal facility (d')
$Mseg\_g_{(s)}$	Risk multiplication factor for segregation of waste type (s) at source node (g)
$Mpro\_sr'_{(s')}$	Risk Multiplication Factor for processing of waste type (s') at processing facility (sr')

$Mreu\_g'_{(s)}$ Risk Multiplication Factor for reuse of waste type (s) at reuse facility (g')
$Mreu\_g'_{(s'')}$ Multiplication Factor for reuse of waste type (s'') at reuse facility (g')
$Msto\_g_{(s)}$ Risk multiplication factor for storage of waste type (s) at source node (g)
$Mt_{(s)}$ Risk multiplication factor for transportation of waste type (s)
$Mt_{(s')}$ Risk multiplication factor for transportation of waste type (s')
$Mt_{(s'')}$ Risk multiplication factor for transportation of waste type (s'')
$Mt_{(s*)}$ Risk multiplication factor for transportation of waste type (s^*)
n Total number of source nodes
n' Total number of reuse facilities
Psk Period in units of time step for which waste type (s) is stored in time step (k)
$QGsk_{(g)}$ Quantity of new primary waste type (s) generated in time step (k) at source node (g)
$Qsk_{(g)}$ Quantity of primary waste type (s) generated at source node (g) in time step (k)
$Qsk'_{(g)}$ Quantity of primary waste type (s) coming after a cycle of reuse in time step (k')
$Qsk_{(g-d')}$ Quantity of primary waste type (s) at source node (g) in time step (k) going directly to disposal site d'
$Qsk_{(g-g')}$ Quantity of primary waste type (s) generated at source node (g) in time step (k) going to reuse facility g'
$Qs'k_{(g-sr')}$ Quantity of processable waste type (s') (generated after segregation of primary waste types) at source node 'g' in time step 'k' going to processing facility sr'
$Qs'k_{(g-d')}$ Quantity of processable waste type (s') (generated after segregation of primary waste types) at source node 'g' in time step (k) going to disposal facility (d')
$Qs'k_{(sr'-d')}$ Quantity of processable waste type (s') (generated after segregation of primary waste types) left as residue at processing facility in time step (k) going to disposal facility (d')
$Qs''k_{(g-d')}$ Quantity of reusable secondary waste type (s'') (generated after segregation of primary waste types) at source node (g) in time step (k) going to disposal facility (d')
$Qs''k_{(g-g')}$ Quantity of reusable secondary waste type (s'') (generated after segregation of primary waste types) at source node (g) in time step (k) going to reuse facility (g')
$Qs^*k_{(g-d')}$ Quantity of non-reusable, non-processable secondary waste type (s^*) (generated after segregation of primary waste types) at source node (g) in time step (k) going to disposal facility (d')
$rssr$ Total number of processing facilities
$Rstk_{(g)}$ Ratio of stored waste to waste arriving at source node (g) in time step (k)
$Rs'k$ Ratio of waste type s' which could be processed w.r.t. its total quantity

s	Primary waste type
s'	Processable waste type (secondary waste type generated after segregation of primary waste type)
s''	Reusable waste type (secondary waste type generated after segregation of primary waste type)
s^*	Non-processable, non-reusable waste type (secondary waste type generated after segregation of primary waste type)
sr'	Processing facility
Td'	Total number of disposal facility
Tsk	Cost of transportation of primary waste type (s) per unit weight per unit distance in time step (k)
$Ts'k$	Cost of transportation of processable waste type (s') per unit weight per unit distance in time step (k)
$Ts''k$	Cost of transportation of secondary waste type (s'') per unit weight per unit distance in time step (k)
Ts^*k	Cost of transportation of secondary waste type (s^*) per unit weight per unit distance in time step (k)
w	Total number of primary waste types
w'	Total number of processable waste types
w''	Total number of secondary reusable waste types
$w*$	Total number of non-processable, non-reusable waste types
Yd'	Logical variable associated with disposal facility (d')
Ysr'	Logical variable associated with processing facility sr'

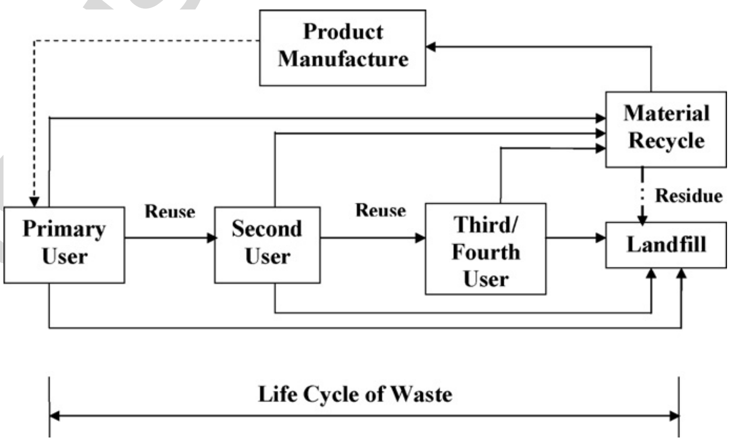


Fig. 1. Flow of waste during its life cycle.

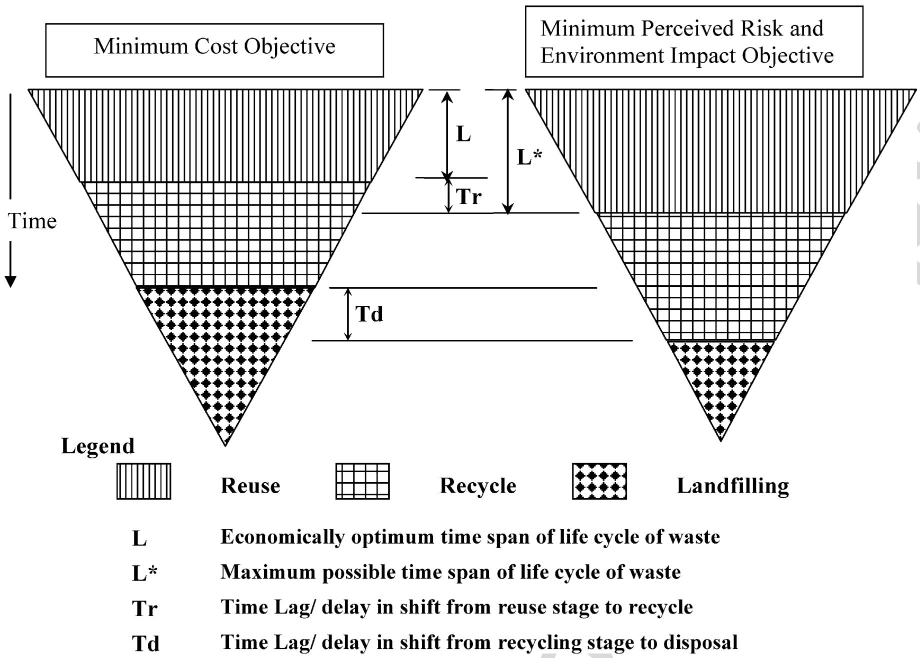


Fig. 2. Relative time span of waste in different stages of waste management hierarchy under different objectives.

minimization of cost. However, when the objective shifts to minimization of cost, reuse will be preferred only till it is economically more attractive than recycle and recycling would be continued only till it is economically more attractive than disposal in a landfill. This would mean a shorter reuse span/life cycle than under the priority of minimization of perceived risk or environmental impact.

A decision maker needs to visualize the various tradeoffs between such conflicting factors, to be able to reach the best possible configuration of such waste management systems, over the whole life cycle of waste. For example, the decision as to when is it appropriate to landfill the waste rather than extend it's life by sending it for reuse again can only be answered by a life cycle approach. This warrants a serious need to analyze the waste management system from life cycle perspective.

The study presents a life cycle based decision support model, which may be used to guide managers working in the field of solid waste management in the following ways:

- To select the optimum configuration of waste management facilities and transportation routes. The objective of planning could be minimization of cost, minimization of impact to the environment, minimization of risk perceived by the public or a compromise between these objectives. The model can guide managers in the planning of new facilities at appropriate locations and select the routes depending on their priority of objectives.
- To allocate waste to the waste management facilities. The proposed model can help the decision makers in deciding the allocation of waste quantities to the various waste management facilities (existing as well as newly sited), so as to achieve the desired objective.

- To arrive at the reuse time span of a particular waste which, as already stated, can be interpreted as the life cycle of a waste. This inference could guide the authorities to protect infiltration of computers coming in the name of donations and charity, by restricting their import after their optimum life span.

2. Literature review

Life cycle analysis (LCA) forms the core theme of this paper. Hence, relevant literature pertaining to LCA is being reviewed and cited. There is now a widespread agreement amongst industry, government and other stakeholders, that environmental issues and impacts must be considered from a life cycle perspective. Several researchers have adopted LCA based methodology to characterize environmental considerations with respect to an array of pollutants (Powell et al., 1996). LCA is currently being used in several countries to evaluate different strategies for integrated solid waste management (ISWM) and to evaluate treatment options for specific waste fractions. The first solid waste management models were optimization models viewing specific aspects of the problem in the life cycle perspective (Finnveden, 1999; Craighill and Powell, 1996; Denison, 1996). More recent models based on the life cycle approach are focused around integrated waste management (Finnveden et al., 1995; Barton et al., 1996; Ekvall, 1999; Harrison et al., 2001; Arena et al., 2003).

While most life cycle studies have been comparative assessments of substitutable products delivering similar functions (e.g. glass versus plastic for beverage containers), there has been a recent trend towards the use of life cycle approaches in comparing alternative production processes, and, this includes the use of LCA in comparing waste management strategies (Berkhout and Howes, 1997). LCA has been stated as one of the tools in the “environmental management toolbox”, which should not be used in isolation to decide issues such as which waste management option, is to be preferred (Finnveden and Ekvall, 1998). LCAs have been mostly restricted around environmental impact issues, although several studies extend the lifecycle assessment methodology to incorporate an economic evaluation of such issues (Harrison et al., 2001; Craighill and Powell, 1996).

Solano et al. (2002) presented a model for municipal solid waste with targets for cost, energy and emissions, wherein a life cycle approach was used to compute energy consumption and emission of CO, fossil- and biomass-derived CO_2, NOx, SOx, particulate matter, PM10 and greenhouse gases.

For computer waste management, it is important to find out optimum waste flow from source to reuse, recycle and disposal facilities, over the life cycle/span of waste based on the governing socio-economic scenario. Although, several studies have been done related to solid waste management utilizing life cycle approach, it is to be noted that the optimum material flow from one management option to other has not been covered so far. Also the approach to estimate environmental impact and estimation of risk perceived by the public, from management of computer waste is not being stated in any of the cited studies.

The objective of this paper is to present a model which gives the best possible configuration of computer waste management facilities and allocates wastes to these facilities, to achieve the required objective (minimization of cost, minimization of perceived risk (PR), minimization of environmental impact (EI) or a compromise between cost, PR and EI) in the life cycle perspective.

3. Proposed model formulation

The proposed model for the management of computer waste is based on life cycle approach, and, is multi-time step and multi-objective. Since printers and computer peripherals are integral to a personal computer and are quite substantial in volume, computer waste would henceforth refer to a mixed waste of personal computers, printers and other computer peripherals. Herein, we would like to define 'time step' as that period of time, for which the waste generation and associated costs per unit quantity of weight, for a management activity (transportation, storage, disposal, etc.) remain constant. The time step could be 1 year, 6 months or any other unit of time for which the waste generation and associated management costs are assumed constant. The objectives addressed in the present mathematical formulation are: (i) minimization of total cost (which includes cost of transportation, segregation, storage, processing/treatment and disposal), (ii) minimization of EI (which has been formulated as a function of waste quantity being disposed of in landfills and its composition), and (iii) minimization of total risk perceived by the people. Each of these objectives can be minimized individually or a compromise solution can be arrived at by assigning different weightings to each objective. As each of these objectives has different units, they have been combined using a utility function approach (Nema and Gupta, 1999). In case of utility function, objective = minimize (U), where, U = weighting to cost × (cost/minimum achievable cost) + weighting to PR × (PR/minimum achievable PR) + weighting to EI × (EI/minimum achievable EI).

The decision maker can assign different weightings to cost, PR and EI, depending on the governing socio-economic scenario. Various scenarios of different weightings to each of the objectives can also be analyzed to arrive at the various tradeoffs between these objectives.

The problem is subjected to the following constraints:

- Mass balance of wastes at each node (i.e. all source cum storage nodes, processing and disposal nodes/facilities).
- Allowable capacities at various facilities.
- Logical constraints at processing and disposal sites.

Equations for the proposed model are given in Appendix A.

3.1. Estimation of cost

Costs considered are the cost of segregation and storage at source nodes, cost of transportation of waste from source nodes to processing facilities, cost of processing waste at processing facilities, transportation cost of reusable waste types to reuse facilities, transportation cost of non-reusable, non-recyclable portion of waste from source nodes to disposal facilities, transportation cost of non-recyclable residue of waste from processing facilities to disposal facilities, capital cost for locating facilities (processing and disposal), cost of disposal, cost recovered from the sale of recyclable portion of generated waste and cost recovered from the sale of reusable portion of generated waste.

Cost of segregation at source nodes [refer Eq. (1)] has been arrived at by multiplying the quantity of waste arriving at the source node, minus the waste directly going for reuse and disposal, with the cost of segregation per unit weight of waste. Cost of storage at the source nodes [refer Eq. (2)] has been estimated as the quantity of waste arriving at the source node, multiplied by the cost of storage per unit weight of waste, the period for which the waste was stored and ratio of stored waste to incoming waste. Cost of transportation of waste from one node to another [refer Eqs. (3), (6) and (7)] is the quantity of waste traveling from the origin node to the destination node at a particular time step, multiplied by the unit cost of transportation per unit weight per unit distance for the waste type, and, the distance between the origin node and the destination node. Cost of processing or disposal at any facility [refer Eqs. (4) and (9)] is the quantity of waste reaching the facility at any time step multiplied by the cost of processing/disposal per unit weight at that facility.

Capital cost for siting new facilities [refer Eqs. (5) and (8)] is the equitable capital cost of waste processing/disposal facility per time step, multiplied by a binary variable with value1 or 0, depending on whether the facility is sited by the model or not. Cost recovered from the sale of recyclable portion of waste [refer Eq. (10)] is the quantity of a waste type reaching the processing facility at any time step, multiplied by the cost recovered from the sale of processed waste per unit weight at any time step and the ratio of processed/recycled waste to incoming waste for processing/recycling. As this cost is recovered, it is being subtracted from the total cost spent. Cost recovered from the sale of reusable portion of generated waste [refer Eq. (11)] is the quantity of a waste type, reaching the reuse facility at any time step, multiplied by the cost recovered by sale of reusable waste per unit weight at that time step. As this cost is recovered, it is being subtracted from the total cost spent. Unit cost of transportation, segregation, storage, processing, disposal and cost recovered from sale of recycled and reusable waste vary with time step.

3.2. Estimation of PR

Risk managers and risk-management institutions are faced with an ever-increasing set of challenges to foster good relationships with the public, as illustrated by the conflicts that exist in siting the new facilities. There is a distinction between scientifically assessed risk and risk perceived by the people. The public's beliefs about environmental risk are often very different from the experts (Jenkins and Bassett, 1994; Lindell and Earle, 1983; McClelland et al., 1990). McClelland et al. (1990) stated that the public perception of health risk in close proximity to a hazardous waste site is higher than the assessments of experts. Sjöberg (1996) stated that PR is often assumed to be a central factor in social and political dilemmas. It is related to the "acceptance" of a technology and a lifestyle and hence is an important concept.

Many decision support models have been developed so far which addressed the issue of PR. ReVelle et al. (1991) developed a model that located storage facilities and selected routes for shipments of spent nuclear fuel, considering minimization of transportation burden and minimization of PR. Jacobs and Warmerdam (1994) presented a mathematical model for optimally siting and routing hazardous waste operations, conditioned on public perception towards acceptable costs and risks. They stated that the routing and siting of hazardous waste operations is governed as much by the public's perception of acceptable costs and risks as by any other factor. Giannikos (1998) presented a multi-objective model for locating disposal or treatment facilities and transporting hazardous waste, considering objectives of minimization of cost, PR, equitable distribution of risk and disutility caused by the operation of the treatment facilities.

There are significant public policy implications that come from evolving risk perceptions and the distinction between scientifically assessed risk and PR. The Comprehensive Environmental Response, Compensation and Liability Act (US EPA, CERCLA, 2006) required that the US EPA establish criteria to prioritize sites based on risks to health, environment, and welfare. A significant relationship has been found between physical health and psychological well-being necessitating accounting for PR (Bevc et al., 2007). Also, it is desirable to include public perception of risk while resource allocation (McCluskey and Rausser, 2001). From the literature it is clear that there is a need to assess and account for the risk perceived by public. No such assessment has been done for waste streams such as that of computer waste. Hence, an attempt has been made to bridge that gap in this paper.

The PR associated with various activities associated with computer waste management (storage, segregation, transportation, reuse, recycling/processing and disposal) has been estimated as a function of the waste quantity at each activity multiplied by the PR per unit quantity of waste at that activity. PR for various management options for each waste type was estimated using expert opinion. Information regarding the hazardous constituents of e-waste and the potential hazards and relative possibility of accident (*source*: Toxics Link, 2003 and personal survey for expert opinion) was provided to various experts (Table 3). The experts were asked to relatively rank their PR associated with a particular management activity at a certain facility, as compared to certain similar management activities (SMA).

A set of 47 experts in the field of risk analysis and assessment were approached. Each expert was asked to give PR value of management activities associated with different waste types as compared to SMA [storage of liquefied petroleum gas (LPG), transportation of LPG, repair and reuse of televisions, dismantling of televisions, recycling of PET plastic and landfilling of municipal solid waste]. After first cycle of inputs, the results were compiled and the mean value of risk perceived for each management activity and its upper and lower bounds ($\pm$ two times the standard deviation) were calculated. The results were conveyed to each expert in order to arrive at a consensus through their revised inputs. The cycle was repeated three times. The opinions of five experts were discarded as they were found to be outliers (outside the range of $\pm$ two times the standard deviation).

Opinions were also sought on relative risk perceived for management activities chosen for comparison (i.e. SMA) as compared to a baseline management activity (BMA) of landfilling of municipal solid waste. Consensus was achieved on this subjective judgment through discussion. Analytical hierarchy process technique (Saaty, 1980) was utilized to combine subjective judgment (PR of SMA as compared to BMA) with objective results of the Delphi analysis (PR of computer waste management activities as compared to SMA) to arrive at the value of PR for each management activity (at a facility for each type of waste) as compared to BMA.

The estimated overall individual non-cancer and cancer risks for landfill disposal have been reported as 1.18×10^{-5} and 4.14×10^{-11} respectively/tonne of waste per year (Moy, 2005). The two have been added to estimate overall risk from landfilling of municipal solid waste/tonne (BMA) as approximately 1.18×10^{-5}. Risk from BMA was multiplied with the value of PR as compared to BMA to arrive at the absolute value of PR for each management activity (at a facility for each type of waste). The final PR values for management activities associated with different waste types as compared to SMA and to BMA of landfilling of municipal solid waste have been given in Table 4a. Relative risk perceived for management activities chosen for comparison (SMA) as compared to BMA of landfilling of municipal solid waste is given in Table 4b. It may be noted that the risk perceived at various source nodes due to segregation and storage was the same.

3.3. Estimation of EI

The need to encourage the minimization of EI associated with electronic products across their total life cycle has already been emphasized. This includes upstream impacts arising from the choice of materials and from the manufacturing process as well as the downstream impacts, i.e. from the use and disposal of products. The EI and human health concerns associated with computer hardware are many and varied, particularly when measured over their whole life cycle. The most immediate of these concerns is those surrounding disposal and the high toxic content of computer hardware.

The list of toxic materials in computer components includes lead and cadmium in circuit boards, lead oxide in computer monitors' cathode ray tubes, mercury in switches and flat screen monitors, cadmium in computer batteries, polychlorinated biphenyls (PCBs) in older capacitors and transformers, and brominated flame retardants on printed circuit boards, cables and plastic casing (Silicon Valley Toxics Coalition, 2001, 2002). In America it has been estimated that about 70 percent of the heavy metals showing up in landfills come from electronic equipment, which is only 1 percent of the waste stream (Slowinski, 2000). If electronic items are disposed of in a landfill, toxic substances can be emitted via the landfill leachate, eventually contaminating groundwater. In April 2000, the Commonwealth of Massachusetts adopted a first-in-the-nation approach to reuse and recycle discarded computer monitors and televisions. Cathode ray tubes (CRTs), the leaded glass picture tubes found in computer monitors and televisions, are now banned from disposal in Massachusetts landfills and waste combustors due to their high lead content (Massachusetts Department of Environmental protection, 2006).

There are three main environmental concerns surrounding computer hardware disposal (Resource NSW, 2001):

- The high volumes of hardware reaching final end of life introduces the immediate concern of landfill space provision for these bulky items.
- Presence of hazardous materials, such as; chlorinated and brominated substances, toxic metals, photoactive materials, plastics and plastic additives.
- Disposal of computer hardware is the loss of potentially valuable resources. Recovery of these materials may reduce raw materials extraction and the environmental impacts of computer hardware production. For example, the primary production of metals accounts for 10% of global CO_2 emissions. Recycling of these metals will save 70–95% of the energy required for raw materials (Environment Australia, 2001).

From the above discussion, it is clear that of all the end of life options, landfilling would result in maximum impact to the environment. Recycling also results in negative impacts to the environment, but when offset by the positive impacts of reduced raw material extraction, overall negative impact may be considered minimal compared to the disposal in landfills.

In this study, EI is considered as a function of waste quantity being disposed in a landfill, its characteristics, receptor population being exposed and probability of accident and failure at the landfill. Based on available toxicity database in international toxicity estimates for risk database (ITER), 17 key components/chemicals were chosen. The basis of selection of the above chemicals was documentation of their adverse effects. Since, data regarding cancer toxicity was unavailable/not listed specifically for most of identified chemicals (except arsenic), non-cancer oral risk[1] (NCOR) values were considered a basis for arriving at the importance factor, which was a parameter defined to quantify characteristics. The minimum of the reported NCOR values (mg/kg-day) from the database was chosen. The chemical/parameter with a maximum value of risk dose (and hence relatively lowest risk potential) was assigned importance factor 1 (titanium). Other chemicals were then assigned importance factors based on the ratio of risk dose of titanium to risk dose identified for them. The importance factor for plastics was derived using experts' opinion. Tentative composition of various types of plastics and their impact on the environment was taken from a report prepared by 'Meinhardt Infrastructure and Environment Group' for Environment Australia and the experts were asked to assign a importance factor to the general category "Plastics" with respect to titanium and arsenic having minimum and maximum importance factors respectively (Computer and Peripherals Material Project, 2001).

It was assumed that a chemical/component with a lesser value of NCOR would result in a higher negative impact to the environment by the same ratio. The approximate quantity of these key parameters in each type of waste was estimated on the basis of published literature (Toxics Link, 2003) and survey conducted (Personal Survey, during May-June 2006) at the existing segregation facilities in Delhi. The EI equation was formulated as the quantity of each key parameter reaching the landfill multiplied by its importance factor, receptor population exposed and probability of accident/failure.

3.4. Formulation of constraints

Mass balance at various nodes ensures that the waste quantity arriving at a node (source node/facility) is equal to the waste present at the node and waste leaving the node. Capacity constraint at various facilities ensures that the waste quantity reaching a facility at any time step is less than the designated capacity of the facility for that time step. Logical constraint at facilities to be selected will ensure that if no waste is arriving at a facility over all the time steps, the binary variable associated with a facility is assigned a value 0 (i.e. the facility is not sited).

[1] A dose in mg of chemical per kg of body weight per day (expressed as mg/kg-day), that for non-cancer toxicity is generally considered to be without adverse effects in populations of humans (including sensitive subpopulations) for the duration of exposure specified.

4. Example problem

The case study undertaken is that of computer waste management in Delhi, the National Capital Region of India. Presently recycling and recovery of precious metals and other useful parts of computer waste is being done mostly by unskilled labor in small centers located in Delhi. The map giving locational details of various nodes is shown in Fig. 3. The methods employed are very rudimentary and pose grave environmental and health hazards (Toxics Link, 2003). The case study of computer waste management network consists of 16 nodes, the details of which are given in Table 1. The sources cum segregation nodes are the nodes where computer waste collected from all round the city/region arrives and is segregated. Storage facility is available at these nodes and is assumed up to 20% of the waste arriving at each node. Two nodes represent potential options for disposal sites. Two potential processing facilities for segregated plastic and two potential processing facilities for segregated metal scrap are also included in the study. Segregation as stated in the study means physical separation of various fractions of waste, e.g. separation of plastic and metal components. By recycling the authors mean the processing a waste fraction has to undergo to be useful as a raw material in any product manufacture, e.g. pelletization of ABS plastic so that it could be used in the manufacture of toys. The case study is analyzed for a total of thirty time steps; each of which spans a year. The proposed waste types considered in the example problem, their description and unit cost of transportation are given in Table 2.

The waste generation varies at each source node with each time step. Three scenarios of waste generation rates at various source nodes were considered, the details of which are given in Fig. 4a–c. Scenario 2 for personal computers (WA) and deskjet printers (WC) basically extrapolates the observed growth rate in the past 5 years into the future. Scenario

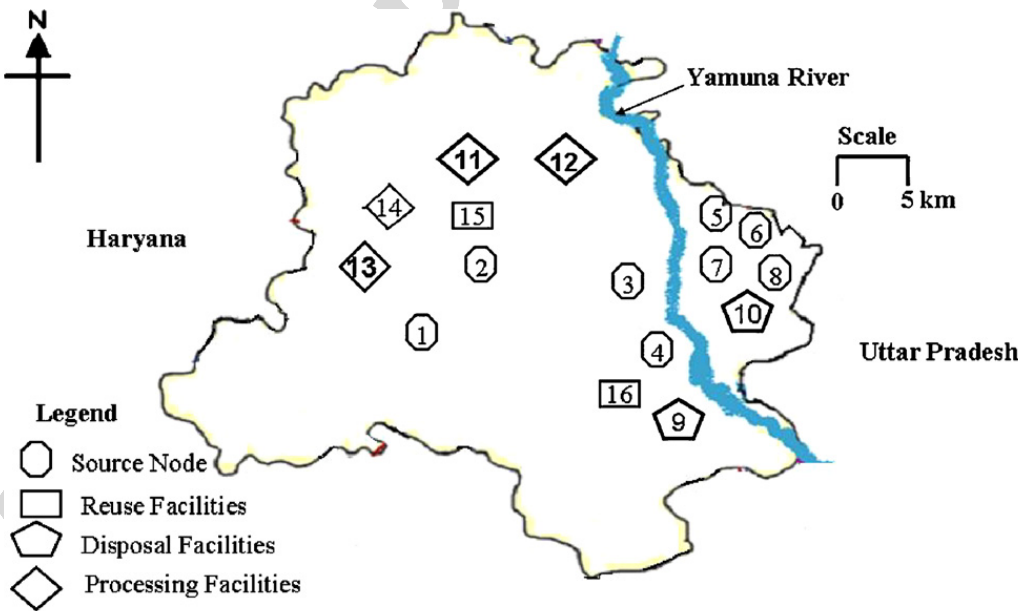


Fig. 3. Map giving locational details of various source nodes and facilities.

Table 1
Description of various nodes in the case study

Node no.	Name of place	Node type
1	Maya Puri	Source cum segregation sites
2	Kirti Nagar	
3	Turkman Gate	
4	Lajpat Nagar	
5	Mustafabad	
6	Mandoli	
7	Shastri Park	
8	Old Seelampur	
9	Okhla Landfill	Proposed secured landfill units
10	Ghazipur	
11	Wazirpur Industrial Area	Proposed site for plastic pelletization plant
12	Timarpur	Proposed site for processing metal scrap
13	Uday Vihar	Proposed site for plastic pelletization plant
14	Mangolpuri Industrial Area	Proposed site for processing metal scrap
15	Dr. Lohia Industrial Area	Reuse facility for old intact CRT's
16	Nehru Place	Reuse facility for old working PC's, dot matrix and deskjet printers, intact floppy drives, processor chip, hard disk, speeder motor and cartridge

Source: Personal survey.

Table 2
Proposed waste types of the example problem, their description and unit cost of transportation

Waste type	Description	Source nodes	Unit cost of transportation ($/tonne/km)
Primary waste types			
WA	Computer/PC	1, 2, 5	4
WB	Dot matrix printers	3, 6	4
WC	Deskjet printers	4, 7, 8	4
Sub waste types of primary wastes generated after segregation			
W1	Cathode ray tube (CRT)	1, 2, 5	5
W2	Processor chip, reusable floppy drive, hard disk	1, 2, 5	5
W3	Printer motor	4, 7, 8	5
W4	Printer cartridge	4, 7, 8	5
W5	Brominated or ABS (acrylonitrile-butadiene styrene) plastic	1, 2, 3, 4, 5, 6, 7, 8	4
W6	Circuit boards, damaged CRT's, defective IC, mother boards, CPU, condensers, capacitors, PVC wires, non-reusable hard disk, floppy drive, non-reusable printer motor and cartridge	1, 2, 3, 4, 5, 6, 7, 8	5
W7	Metal Casings and scrap metal	1, 2, 3, 4, 5, 6, 7, 8	4

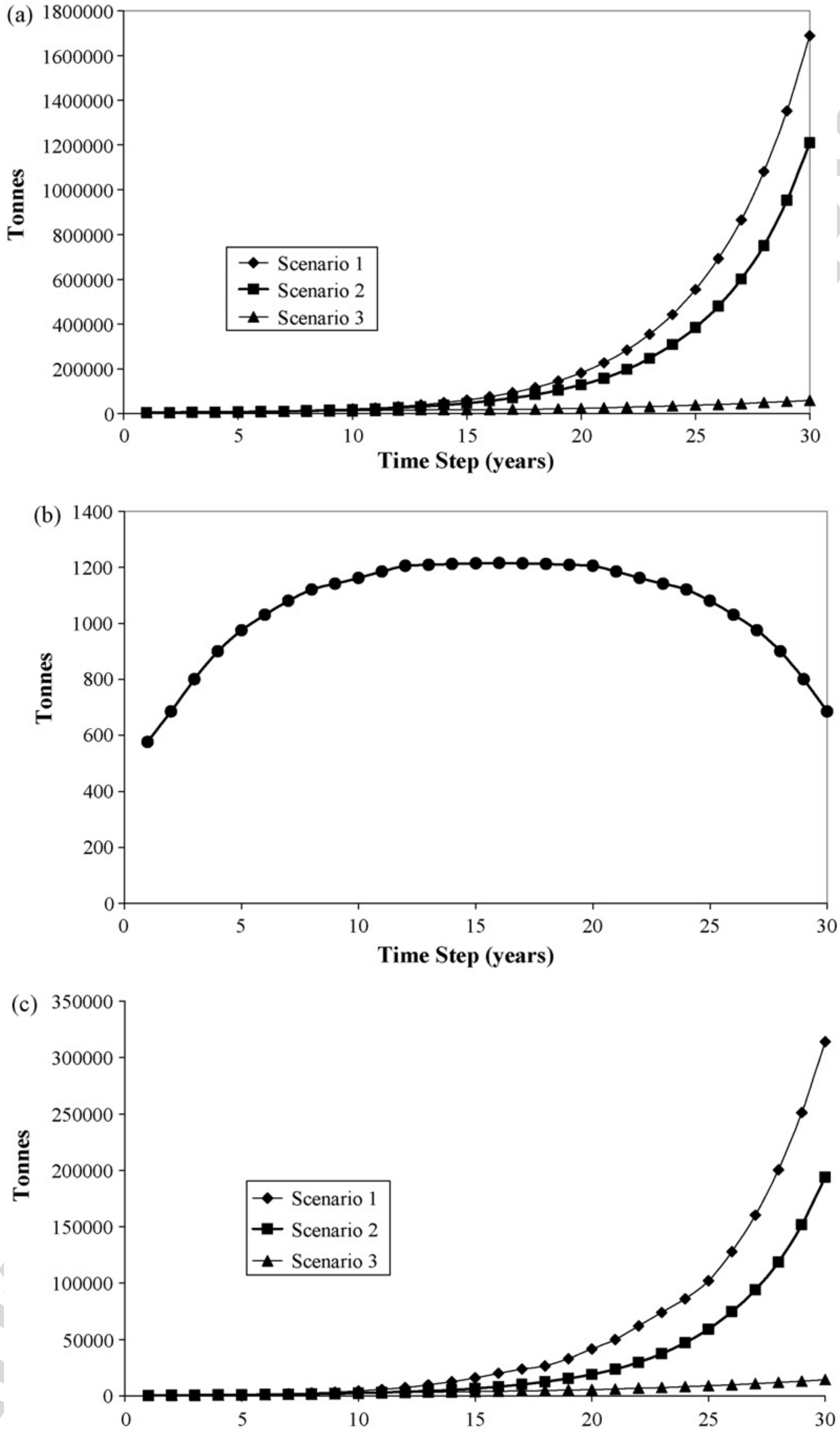


Fig. 4. (a) Generation of waste WA (personal computer) in various scenarios. (b) Generation of waste WB (dot matrix printer) in various scenarios. (c) Generation of waste WC (deskjet printer) in various scenarios.

1 and scenario 3 for WA and WC have been arrived at using expert survey for the possibility of exponential increase and decrease in volume of discarded computers and deskjet printers over the present trend (scenario 2), owing to unexpected computer boom or the advent of lighter computers and printers respectively. The waste generation trend was perceived the same for dot matrix printers for all the scenarios. The experts felt that the volume of waste WB would be at its maximum around year 2021, and would decline thereafter because of its predicted obsolescence in the coming years. The waste generation quantity for each waste type depicted in Fig. 4a–c is only that discarded by primary user (refer Fig. 1). This quantity plus the waste quantity arriving in that time step after reuse phases, has been considered the total waste quantity for that time step, and has been assumed to be equal at various source nodes of that waste.

Management activities associated with different waste types, possible hazards of each activity and possibility of accident provided to the experts for estimating PR is given in Table 3. The PR values for management activities associated with different waste types as compared to SMA and to BMA of landfilling of municipal solid waste have been given in Table 4a. Relative risk perceived for management activities chosen for comparison (i.e. SMA) as compared to BMA of landfilling of municipal solid waste is given in Table 4b. Distance between source nodes and various facilities (in kilometer) are given in Table 5. Recovered cost from various waste types and their weight wise fractions are given in Table 6. Details of various source nodes such as segregation and storage costs are given in Table 7a. Further details of various facilities such as the capacity, capital and operating costs are given in Table 7b. List of key parameters for estimating EI, their importance factors and quantities in different waste types is given in Table 8. Receptor population impacted due to waste management activities at node 9 and node 10 was considered as 2000 and 4000 respectively. Probability of accident at node 9 and node 10 were assumed to be 1.5×10^{-6} and 2×10^{-6} respectively. A schematic showing various management options for each type of the waste stream is given in Fig. 5.

5. Results and discussion

The proposed model was solved using LINGO version 9.0 (LINDO Systems Inc.), an integer linear programming solver. The example problem has been solved for the following sets of joint functions of cost, PR and EI: (i) minimization of cost (cost weighting = 1, EI and PR weighting = 0); (ii) equal weightings to cost, EI and PR (cost, EI and PR weighting = 1/3); (iii) minimization of PR (PR weighting = 1, EI and cost weighting = 0); (iv) minimization of EI (EI weighting = 1, PR and cost weighting = 0). The constraints were checked for each time step and the results were summarized over all the time steps to give total cost and total risk over all the thirty time steps. The results are summarized in Fig. 6a–c. Time step (in years) at which various facilities were sited under different scenarios of waste generation and different objectives is given in Table 9. Cost for various factors was taken from the actual and secondary data and has been converted to US$ (Rs 45 = 1 US$). The results for scenario 1 are discussed in detail. The trend of results for the other two waste generation scenarios is similar.

Table 3
Management activities associated with different waste types, possible hazards of each activity and possibility of accident

S. no	Waste type	Management activity	Possible hazards (*Source*: Toxic links,2003 & personal survey)	Possibility of accident (*Source*: personal survey)
1	WA	T	Health hazard of acute nature to workers while handling the broken fragments of waste containing sharps, toxic and reactive elements like lead, cadmium, phosphor coating, mercury	*Remote possibility* – of spillage of waste in surroundings in case of a road accident
		R	No significant hazards	–
		Seg	• Health hazard of acute nature to workers while handling the waste containing toxic and reactive elements like lead, cadmium, phosphor coating, mercury	*Moderate possibility* – of accidental cutting of skin due to sharps, leading to injury, infection and exposure to certain elements from waste like lead, cadmium,beryllium
			• Air emissions while heating process for removing components like IC chips from circuit boards • Health hazard due to absorption of cadmium through respiration • Hazard due to corrosive nature of chromium. • Long term exposure to beryllium dust can cause chronic beryllium disease • Exposure to dioxins and furans while heating plastic components	*Remote to moderate possibility* – of accidental fire forming dioxin and furans due to burning of plastic material
		L	• Air emission of oxidants of beryllium and other toxic components. (Chronic in nature) • Impact on environment due to infinite life time of toxic metals • Leaching of various hazardous elements like mercury, lead, cadmium, barium, beryllium to soil and ground water, etc	*Moderate possibility* – of accidental rupture of landfill layer leading to leaching of toxic metals and their compounds to soil and ground water *Remote possibility* – of accidental fire leading to the formation of toxic metal fumes, dioxins and furans, etc
2	WB & WC	T	Health hazard of acute nature to workers while handling the broken fragments of waste containing sharps, toxic and reactive substances like toner dust, beryllium dust, etc	*Remote possibility* – of spillage of waste in surroundings in case of a road accident
		R	No significant hazards	–
		Seg	• Health hazards of both acute and chronic nature due to toxic and reactive substances like toner dust, beryllium dust from waste	*Moderate possibility* – of accidental cutting of skin due to sharps, leading to injury, infection and exposure to certain elements from waste like lead, cadmium,beryllium

Table 3 (*Continued*)

S. no	Waste type	Management activity	Possible hazards (*Source*: Toxic links,2003 & personal survey)	Possibility of accident (*Source*: personal survey)
			• Health hazards of chronic nature due to long time exposure to elements like cadmium from waste • Exposure to dioxins and furans while heating plastic components	*Remote to moderate possibility* – of accidental fire forming dioxin and furans due to burning of plastic material
		L	• Air emission of oxidants of toxic components (Chronic in nature). • Impact on environment due to infinite life time of plastic and metal components • Leaching of various hazardous elements like cadmium, toner dust to soil and ground water etc in case of rupture of landfill liner	*Moderate possibility* – of accidental rupture of landfill layer leading to leaching of toxic metals and their compounds to soil and ground water. *Remote possibility* – of accidental fire leading to the formation of toxic metal fumes, dioxins and furans, etc
3.	W1	T	Health hazard of acute nature to workers while handling the broken fragments of waste containing sharps, toxic and reactive elements like lead, cadmium, phosphor coating, mercury	*Remote possibility* – of spillage of waste in surroundings in case of a road accident
		R	No significant hazards	–
		L	• Air emission of oxidants of toxic components (Chronic in nature) • Impact on environment due to infinite life time of metal components • Leaching of toxic components to soil and ground water • Injury due to improper handling of CRT because of the presence of sharps further resulting in contact with toxic components such as phosphor coating	*Moderate possibility* – of accidental rupture of landfill layer leading to leaching of toxic metals and their compounds to soil and ground water *Moderate possibility* – of injury due to an accident *Remote possibility* – Accidental fire leading to the formation of toxic metal fumes
4.	W 2	T	Health hazard of acute nature to workers while handling the broken fragments of waste containing sharps	*Remote possibility* – of spillage of waste in surroundings in case of a road accident
		R	No significant hazards	–
		L	• Air emission of oxidants of toxic components like cadmium, barium, beryllium, etc. (chronic in nature) • Leaching of various hazardous elements like mercury, lead, cadmium, barium, beryllium to soil and ground water, etc	*Moderate possibility* – of accidental rupture of landfill layer leading to leaching of toxic metals and their compounds to soil and ground water *Remote possibility* – of accidental fire leading to the formation of toxic metal fumes

Table 3 (*Continued*)

S. no	Waste type	Management activity	Possible hazards (*Source*: Toxic links,2003 & personal survey)	Possibility of accident (*Source*: personal survey)
5.	W3	T	Health hazard of acute nature to workers while handling the broken fragments of waste containing sharps	*Remote possibility* – of spillage of waste in surroundings in case of a road accident
		R	No significant hazards	–
		L	Impact on environment due to infinite life time of metal components	*Remote possibility* – of rupture of landfill lining causing contamination of soil and ground water and of injury due to an accident during handling
6.	W 4	T	Health hazard of acute and chronic nature to workers due to injestion of toxic ink remains via dermal contact while handling the broken fragments of cartridge	*Remote possibility* – of spillage of waste in surroundings in case of a road accident
		R & R	Possible ingestion of toxic ink through contaminated hands.	*Remote to moderate possibility* – of ingestion.
		L	• Possible injestion of toxic ink through contaminated hands during handling while landfilling the waste	*Remote to moderate possibility* – of injestion
			• Leaching of toxic ink remains, and contamination of soil and ground water	*Remote to moderate possibility* – of leakage of toxic ink due to accidental rupture of landfill lining
7.	W 5	T	No significant hazards	*Remote possibility* – of spillage of waste in surroundings in case of a road accident
		Rec	Pellatisation process of plastic has very minor chance of formation of dioxin and furans	*Moderate possibility* – of accidental fire
		L	• Infinite lifetime of ABS plastic into the environment • Leaching of bromine and other components into soil and ground water • Emission of oxidants of bromine into air	*Remote to moderate possibility* – of leaching of toxic components due to rupture of lining of landfill
			• Emission of dioxins and furans during an accidental fire	*Remote possibility* – of accidental fire
8.	W 6	T	Health hazard of acute nature to workers while handling the broken fragments of waste containing sharps, toxic and reactive elements like lead, cadmium, phosphor coating, mercury	*Remote possibility* – of spillage of waste in surroundings in case of a road accident
		L	• Infinite lifetime of ABS plastic, metal components into the environment	*Moderate possibility* – of accidental cutting of skin due to sharps, leading to injury, infection and exposure to certain elements from waste like lead, cadmium,Beryllium

Table 3 (*Continued*)

S. no	Waste type	Management activity	Possible hazards (*Source*: Toxic links,2003 & personal survey)	Possibility of accident (*Source*: personal survey)
			• Air emissions of oxidants of beryllium, bromine, cadmium, barium, lead and other compounds (chronic in nature) • Leaching of various hazardous elements like cadmium, toner dust to soil and ground water etc in case of rupture of landfill liner • Emission of dioxins and furans during an accidental fire • Possible injestion of toxic ink through contaminated hands during handling while landfilling the waste • Leaching of toxic ink remains, and contamination of soil and ground water • Injury due to improper handling of CRT because of the presence of sharps further resulting in contact with toxic components such as phosphor coating	*Remote to moderate possibility* – of injestion *Remote to moderate possibility* – of leakage of toxic ink due to accidental rupture of landfill lining *Remote possibility* – of injury due to an accidental breaking of CRT *Remote possibility* – of accidental fire leading to the formation of toxic metal fumes, dioxins and furans, etc
9.	W 7	T	Health hazard of acute nature to workers while handling the broken fragments of waste containing sharps	*Remote possibility* – of spillage of waste in surroundings in case of a road accident
		Rec	• Injury while handling • Inhalation of fumes formed due to use of heat for dismantling • Impact on environment due to infinite life time	*Moderate possibility* – of inhalation of toxic fumes while recovery using a heating process *Remote to moderate possibility* – of injury due to an accident
		L		*Remote to moderate possibility* – of injury due to handling of metal sharps *Remote to moderate possibility* – of leaching of toxic components due to rupture of lining of landfill *Remote possibility* – of accidental fire

Notations: T – transportation, R – reuse, L – landfilling, Rec – recycling, R & R – refilling and reuse, Seg – segregation.

Table 4a
Perceived risk (PR) of management activities associated with different waste types as compared to similar management activities (SMA) and to baseline management activity (BMA) of landfilling of municipal solid waste (MSW)

S. No.	Waste type	Management activity for computer waste	SMA chosen for comparison	PR as compared to SMA	PR with respect to BMA
1	WA	Storage	Storage of LPG	0.4	0.5
		T	T of LPG	2.5	3.0
		R	R & R of televisions	2.0	0.5
		Seg	Dismantling of televisions	1.6	2.0
		L at Okhla (node 9)	L of municipal solid waste	23.0	23.0
		L at Ghazipur (node 10)	L of municipal solid waste	27.0	27.0
2	WB & WC	Storage	Storage of LPG	0.4	0.5
		T	T of LPG	2.5	3.0
		R	R & R of televisions	2.0	0.5
		Seg	Dismantling of televisions	0.4	0.5
		L at Okhla (node 9)	L of municipal solid waste	18.0	18.0
		L at Ghazipur (node 10)	L of municipal solid waste	22.0	22.0
3.	W1	T	T of LPG	3.3	4.0
		R	R & R of televisions	12.0	3.0
		L at Okhla (node 9)	L of municipal solid waste	16.0	16.0
		L at Ghazipur (node 10)	L of municipal solid waste	17.0	17.0
4.	W2	T	T of LPG	2.5	3.0
		R	R & R of televisions	2.0	0.5
		L at Okhla (node 9)	L of municipal solid waste	18.0	18.0
		L at Ghazipur (node 10)	L of municipal solid waste	22.0	22.0
5.	W3	T	T of LPG	2.5	3.0
		R	R & R of televisions	2.0	0.5
		L at Okhla (node 9)	L of municipal solid waste	8.0	8.0
		L at Ghazipur (node 10)	L of municipal solid waste	12.0	12.0
6.	W4	T	T of LPG	2.5	3.0
		R	R & R of televisions	12.0	3.0
		L at Okhla (node 9)	L of municipal solid waste	13.0	13.0
		L at Ghazipur (node 10)	L of municipal solid waste	17.0	17.0
7.	W5	T	T of LPG	2.5	3.0
		Rec at Wazirpur facility (node 11)	Rec of PET plastic	7.2	6.0

Table 4a (*Continued*)

S. No.	Waste type	Management activity for computer waste	SMA chosen for comparison	PR as compared to SMA	PR with respect to BMA
		Rec at Uday Vihar facility (node 13)	Rec of PET plastic	12.0	10.0
		L at Okhla (node 9)	L of municipal solid waste	18.0	18.0
		L at Ghazipur (node 10)	L of municipal solid waste	22.0	22.0
8.	W6	T	T of LPG	3.3	4.0
		L at Okhla (node 9)	L of municipal solid waste	23.0	23.0
		L at Ghazipur (node 10)	L of municipal solid waste	27.0	27.0
9.	W7	T	T of LPG	2.5	3.0
		Rec at Timarpur facility (node 12)	Rec of PET plastic	4.8	4.0
		Rec at Mangolpuri facility (node 14)	Rec of PET plastic	9.6	8.0
		L at Okhla (node 9)	L of municipal solid waste	13.0	13.0
		L at Ghazipur (node 10)	L of municipal solid waste	17.0	17.0

Notations: T - transportation, R – reuse, L – landfilling, Rec – recycling, R & R – repair and reuse, Seg – segregation.

The management cost per tonne of waste ranges from 382.71$ (cost weighting = 1, EI and PR weighting = 0) to 462.97$ (EI weighting = 1, PR and cost weighting = 0). The management cost per tonne was 462.28$ while considering minimization of the PR. Cost of 462.97$/tonne of waste is for minimal possible EI, but it does not mean that this cost if spent would result in no EI. Moreover, even though the cost incurred on waste management increases by approximately 23% while minimizing PR, the risk perceived by public decreases by 22% besides a 49% decrease in EI. Further details regarding selected facilities and the time step in which they were selected is given in Fig. 6a–c. It was observed from the

Table 4b
Relative risk perceived for similar management activities (SMA) as compared to baseline management activity (BMA) of landfilling of municipal solid waste

S. No	SMA	Perceived risk as compared to BMA
1	Transportation of LPG	Marginally High
2	Repair and reuse of televisions	Very low
3	Dismantling of televisions	Marginally high
4	Storage of LPG	Marginally high
5	Recycling of PET plastic	Marginally low

Table 5
Distance between source nodes and various facilities (in kilometer)

Node no.	1	2	3	4	5	6	7	8	9	10
9	22.8	19.6	12.7	5.4	22.3	23.6	16.2	17.2	0.0	12.0
10	43.0	16.3	7.6	12.4	11.6	11.2	7.6	7.1	12.0	0.0
11	9.7	12.9	10.1	2.5	14.6	15.9	10.6	11.6	28.9	16.5
12	12.5	16.2	8.9	21.2	6.3	10.1	8.9	9.9	19.2	12.1
13	5.9	7.0	22.4	18.0	18.6	23.6	16.2	17.2	29.1	30.1
14	7.0	7.1	16.6	21.3	16.1	21.1	16.5	17.5	29.1	30.1
15	6.2	5.4	10.1	16.2	15.9	17.9	13.2	14.3	27.5	27.5
16	15.0	14.0	11.1	4.1	21.3	21.3	15.6	16.6	5.0	14.4

Table 6
Recovered cost from various waste types and their weight wise fractions

Waste type	Recovered cost (US$/tonne)[a] in time step T1	Weight wise fractions of primary waste[a]
Re-usable primary waste		
WA	900.00	=0.1 WA[b]
WB	450.00	=0.2 WB[b]
WC	400.00	=0.2 WC[b]
Sub waste types		
W1	300.00	=0.14 WA
W2	250.0	=0.10004 WA
W3	200.0	=0.01 WC
W4	150.0	=0.001 WC
W5	100.00	=0.20 WA + 0.35 WB + 0.35 WC
W6	0.0[c]	=0.30996 WA + 0.339 WC + 0.35 WB + 0.15 (W5 + W7)
W7	150.00	=0.15 WA + 0.1 WC + 0.1 WB

[a] *Source*: Data collected through personal survey during the period- April to July, 2006 from various computer vendors in Delhi.
[b] It implies 10% of the waste type WA, 20% of the waste type WB and 20% of the waste type WC arriving at the respective source nodes is in working condition and is reusable. This has been assumed constant for all the time steps.
[c] W6 waste type cannot be recycled or reused, hence the recovered cost = 0.

results of sensitivity analysis (given by LINGO) that disposal of CRT (W1) was the most critical during the objective of minimization of cost. Increase in disposal of one tonne of W1 would increase the cost value by approximately 980$. Disposal of non-reusable, non-processable waste (W6) was observed to affect the objective of minimization of perceived and environmental risk the most. However, we would like to state that the stated results are

Table 7a
Segregation and storage costs at various source nodes

Node no.	Segregation cost (US$/tonne) in time step T1	Storage cost (US$/tonne) in time step T1
1, 2, 5	220	60
3, 4, 6, 7, 8	220	60

Table 7b
Capacities and running costs for various facility options

Node no.	Capital cost for locating facility (US$/time step)	Running/processing/disposal cost (US$/tonne) in time step T1
9	150000	32
10	135000	30
11	25000	20
13	23500	20
12	25000	18
14	23500	18

based on the available and estimated cost functions, and are specific to the example problem chosen.

As is evident from the results (Fig. 6a–c), there is an inverse relationship between cost and PR and cost and EI. The total cost incurred on waste management varied significantly

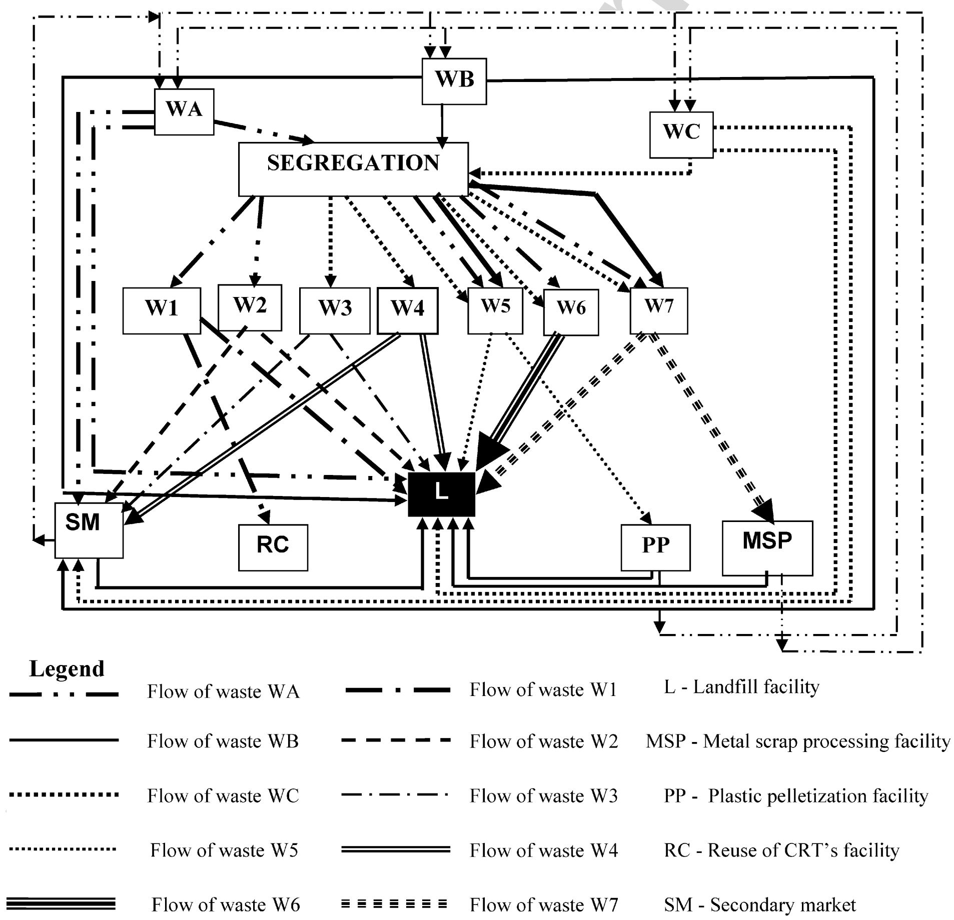
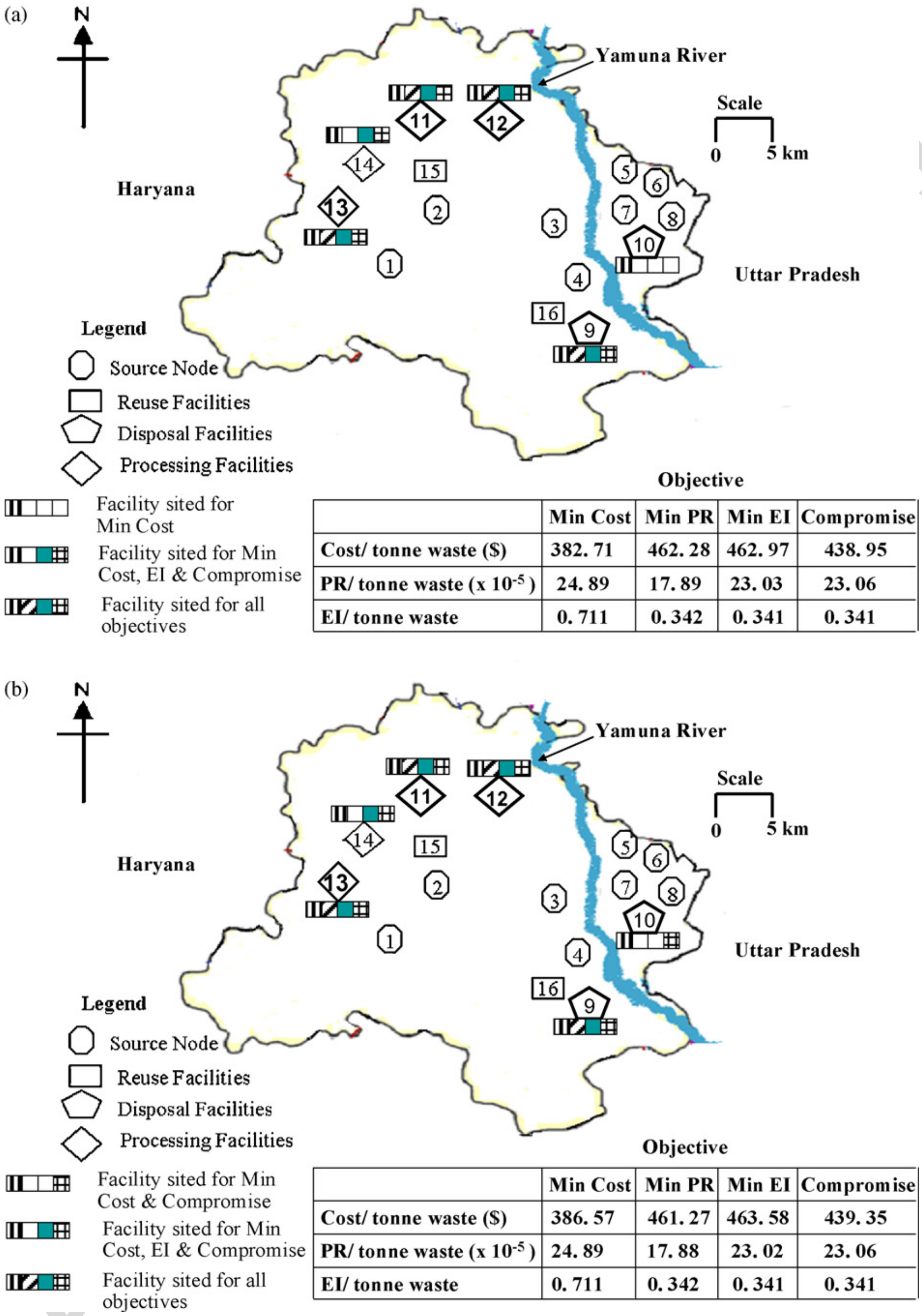


Fig. 5. Management options available for various waste types. #*Source*: Ahluwalia and Nema (2006).

Table 8
List of key parameters/components for estimating environmental impact, their importance factors and quantities in different waste types

Component	Quantity/tonne ($\times 10^{-3}$)[a]										Importance factor
	WA	WB/WC	WC	W1	W2	W3	W4	W5	W6	W7	
Plastics	229.9	500	500	0.0	100	0.0	800	1000	50	0.0	15.0[b]
Lead	62.988	2	2	10.0	2	0.5	0.0	0.0	314	62.988	833.0
Copper	69.287	20	20	10.0	20	0.0	0.0	0.0	345	69.287	21.4
Barium	0.315	0	0	2.0	0	0.0	0.0	0.0	1.5	0.315	15.0
Nickel	8.503	2	2	3.0	2	0.0	0.0	0.0	42	8.503	150.0
Zinc	22.046	1	1	2.0	1	0.0	0.0	0.0	105	22.046	10.0
Beryllium	0.157	0.2	0.2	0.0	0.2	0.0	0.0	0.0	0.5	0.157	1500.0
Titanium	0.157	0.1	0.1	0.0	0.1	0.0	0.0	0.0	0.5	0.157	1.0
Cobalt	0.157	0.1	0.1	2.0	0.1	0.0	0.0	0.0	0.5	0.157	2142.8
Manganese	0.315	0.1	0.1	3.0	0.1	0.0	0.0	0.0	1.5	0.315	21.4
Silver	0.189	0.1	0.1	0.0	0.1	0.0	0.0	0.0	1.0	0.189	600.0
Antimony	0.094	0.0	0.0	0.5	0.0	0.0	0.0	0.0	0.5	0.094	7500.0
Chromium	0.063	0.06	0.06	0.0	0.06	0.0	0.0	0.0	0.4	0.063	1000.0
Cadmium	0.094	0.05	0.05	0.05	0.05	0.0	0.0	0.0	0.5	0.094	15000.0
Selenium	0.016	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.07	0.016	600.0
Mercury	0.022	0.02	0.02	0.0	0.02	0.0	0.0	0.0	0.12	0.022	10000.0
Arsenic	0.013	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.07	0.013	440000.0
Others	605.684	474.27	474.27	967.45	874.27	999.5	200	0.0	136.84	835.584	–

[a] Approximate.
[b] Derived using experts opinion.



(a)

	Objective			
	Min Cost	Min PR	Min EI	Compromise
Cost/ tonne waste ($)	382. 71	462. 28	462. 97	438. 95
PR/ tonne waste (x 10^{-5})	24. 89	17. 89	23. 03	23. 06
EI/ tonne waste	0. 711	0. 342	0. 341	0. 341

(b)

	Objective			
	Min Cost	Min PR	Min EI	Compromise
Cost/ tonne waste ($)	386. 57	461. 27	463. 58	439. 35
PR/ tonne waste (x 10^{-5})	24. 89	17. 88	23. 02	23. 06
EI/ tonne waste	0. 711	0. 342	0. 341	0. 341

Fig. 6. (a) Results of the case study (scenario 1). (b) Results of the case study (scenario 2). (c) Results of the case study (scenario 3).

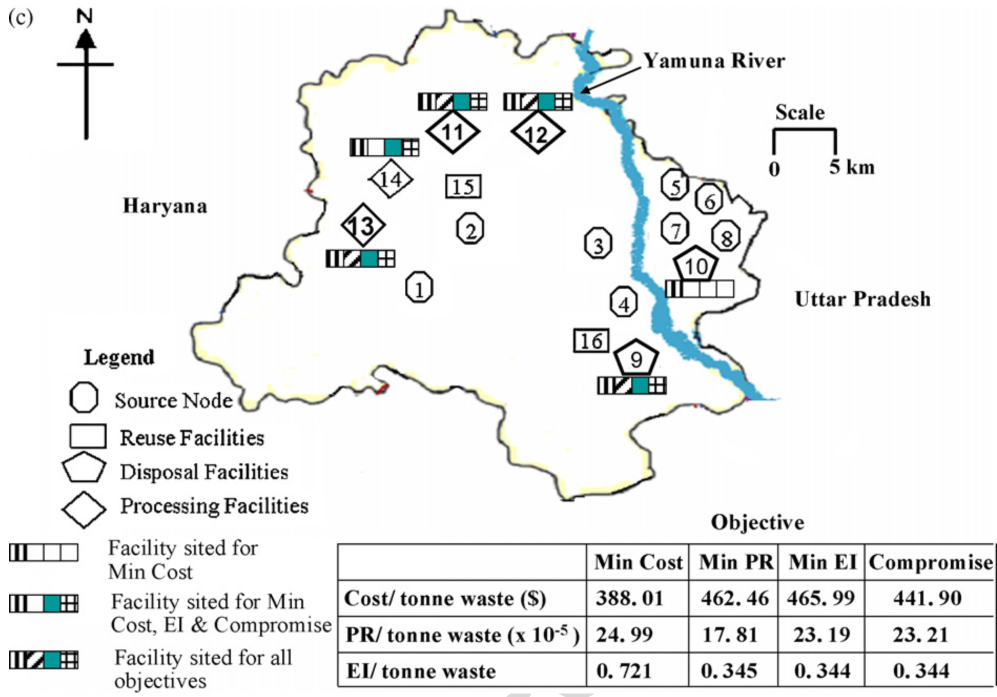


Fig. 6. (*Continued*).

Table 9
Time step (in years) at which facilities were sited under different scenarios of waste generation and different objectives

	Objective											
	Min cost			Min PR			Min EI			Compromise		
	S1	S2	S3	S1	S2	S3	S1	S2	S3	S1	S2	S3
Disposal facility												
9	1[a]	1	1	1	1	1	1	1	1	1	1	1
10	1	1	1	NS[b]	NS	NS	NS	NS	NS	NS	NS	NS
Plastic processing facility												
11	1	1	1	1	1	7	2	1	1	1	1	1
13	1	1	1	1	1	2	1	18	3	7	7	3
Metal scrap processing facility												
12	1	1	1	9	7	11	1	1	1	1	9	1
14	1	1	1	NS	NS	NS	3	1	3	8	9	5

[a] It implies that disposal facility at node no. 9 was sited in the year 1 (first year) of planning under the objective of minimization of cost in waste generation scenario 1 (S1).
[b] It implies that disposal facility at node no. 10 was not sited at all under the objective of minimization of perceived risk (PR) in waste generation scenario 1 (S1).

from being the minimum in the objective of minimization of cost to being the maximum for the objective of minimization of EI (24% more than the minimum cost scenario). This was because in the minimum cost scenario a waste was sent for recycling even though it could be reused (had a positive demand), when recycling was economically a more attractive option than reuse. However, in the case of minimization of EI the cost incurred on waste management was the maximum, because both reuse and recycle were being done till maximum possible, to divert as much waste as possible away from the landfill. The output from this model can be studied to arrive at the reuse time span of a particular waste which as we have already stated can be interpreted as the life cycle of a waste. The results were similar for the scenario of minimization of PR, as it was observed that people perceive minimum risk for reuse and maximum risk for waste disposal in a landfill. This again ensured maximum possible reuse and recycle diverting as much waste as possible from the landfill. The average life cycle of a computer, desktop in the minimum cost scenario was observed as 6 years, which extended up to 8 years for the objective of minimization of EI and for minimization of PR. Hence, it can be inferred that it is not economically viable to reuse a 6-year-old desktop. This inference could guide the authorities to protect infiltration of computers coming into our country in the name of donations and charity, by restricting their import after their optimum life span.

6. Summary and conclusions

A life cycle based multi-time step, multi-objective decision support model has been presented in the study. The proposed model can assist the decision makers to select the optimum configuration of waste management facilities and transportation routes, allocate waste to the waste management facilities and, to arrive at the optimum reuse time span of a particular waste which, as already stated, can be interpreted as the life cycle of a waste. This inference could guide the authorities to protect infiltration of computers coming in the name of donations and charity, by restricting their import after their optimum life span. Moreover, analysis of tradeoffs between conflicting objectives, such as minimization of cost, minimization of PR and minimization of EI significantly facilitates a compromise between conflicting interests, e.g. it was observed in the case study that a slight increase in the cost incurred on computer waste management, though decreased the PR by the same degree, significantly reduced the impact to the environment.

Delhi is presently not only generating substantial quantity of e-waste itself, but also attracting computer waste from other metropolitan cities in India like Bombay and Chennai. Computer waste management under the present scenario is only limited to rudimentary methods of segregation and recycling, at small scale centers scattered all over Delhi. Presence of such centers located in the heart of densely populated areas is posing grave hazards to the surrounding population and the environment. Integrated approach of computer waste management as analyzed by the proposed model is expected to greatly resolve environmental and other concerns such as associated health and PR. Moreover, addressing the risk perceived by the public may significantly ensure public support for such management activities. Though the case study presented belongs to Delhi, the suggested approach of integrated waste management can be useful for other urban centers of developing countries where computer waste related issues are of growing concern.

Appendix A. Equations of the proposed mathematical model

(A) Total cost = total cost can be summarized under the headings (a) to (k).

(a) Cost of segregation at source nodes

$$= \sum_{k=1}^{e}\sum_{g=1}^{n}\sum_{s=1}^{w}\left[\left\{Qsk_{(g)} - \sum_{d'=1}^{Td'} Qsk_{(g-d')}\right\} \times Bsgk\right] \tag{1}$$

(b) Cost of storage at source nodes

$$= \sum_{k=1}^{e}\sum_{g=1}^{n}\sum_{s=1}^{w}\left[Qsk_{(g)} \times Bstk \times Rstk_{(g)} \times Psk\right] \tag{2}$$

(c) Cost of transportation of waste from source nodes to processing facilities and of residue from processing facilities to disposal facilities

$$\begin{aligned} &= \sum_{k=1}^{e}\sum_{g=1}^{n}\sum_{s'=1}^{w'}\sum_{sr'=1}^{rssr}\left[Qs'k_{(g-sr')} \times Ts'k \times D_{(g-sr')}\right] \\ &\quad + \sum_{k=1}^{e}\sum_{d'=1}^{Td'}\sum_{s'=1}^{w'}\sum_{sr'=1}^{rssr}\left[Qs'k_{(sr'-d')} \times (1 - Rs'k) \times Ts'k \times D_{(sr'-d')}\right] \end{aligned} \tag{3}$$

(d) Cost of processing waste at processing facilities

$$= \sum_{k=1}^{e}\sum_{g=1}^{n}\sum_{s'=1}^{w'}\sum_{sr'=1}^{rssr}\left[Qs'k_{(g-sr')} \times Bs'k\right] \tag{4}$$

(e) Capital cost for locating processing facilities

$$= \sum_{sr'=1}^{rssr}[CPsr' \times Ysr'] \tag{5}$$

(f) Transportation cost of reusable waste types to reuse facilities

$$= \sum_{k=1}^{e}\sum_{g=1}^{n}\sum_{g'=1}^{n'}\left[\left\{\sum_{s=1}^{w} Qsk_{(g-g')} \times Tsk + \sum_{s''=1}^{w''} Qs''k_{(g-g')} \times Ts''k\right\} \times D_{(g-g')}\right] \tag{6}$$

(g) Transportation cost of non-reusable, non-processable portion of waste from source nodes to disposal facilities

$$= \sum_{k=1}^{e}\sum_{s*=1}^{w*}\sum_{g=1}^{n}\sum_{d'=1}^{Td'}[Qs*k_{(g-d')} \times Ts*k \times D_{(g-d')}] \tag{7}$$

(h) Capital cost for locating disposal facilities

$$= \sum_{d'=1}^{Td'}[CPd' \times Yd'] \tag{8}$$

(i) Cost of disposal

$$\begin{aligned} &= \sum_{k=1}^{e}\sum_{d'=1}^{Td'}\left[\sum_{g=1}^{n}\left\{\sum_{s*=1}^{w*}Qs*k_{(g-d')}+\sum_{s=1}^{w}Qsk_{(g-d')}+\sum_{s''=1}^{w''}Qs''k_{(g-d')}\right\}\times Bd'k\right] \\ &\quad + \sum_{k=1}^{e}\sum_{d'=1}^{Td'}\left[\sum_{s'=1}^{w'}\left\{\sum_{g=1}^{n}Qs'k_{(g-d')} + \sum_{sr'=1}^{rssr}Qs'k_{(sr'-d')}\right\} \times Bd'k\right] \end{aligned} \tag{9}$$

(j) Cost recovered from the sale of recyclable portion of generated waste

$$= (-)\sum_{k=1}^{e}\sum_{s'=1}^{w'}\sum_{g=1}^{n}\sum_{sr'=1}^{rssr}[Qs'k_{(g-sr')} \times Brs'k \times Rs'k] \tag{10}$$

(k) Cost recovered from the sale of reusable portion of generated waste

$$= (-)\sum_{k=1}^{e}\sum_{s''=1}^{w''}\sum_{g=1}^{n}\sum_{g'=1}^{n'}\left[Qs''k_{(g-g')} \times Bs''k\right] \tag{11}$$

(B) Total PR = total PR can be summarized under the headings (l) to (t).

(l) PR due to transportation of waste from generation nodes to processing facilities

$$= \sum_{k=1}^{e}\sum_{s'=1}^{w'}\sum_{g=1}^{n}\sum_{sr'=1}^{rssr}[Qs'k_{(g-sr')} \times Mt_{(s')} \times BLR] \tag{12}$$

(m) PR due to transportation of reusable portion of waste to reuse facilities

$$= \sum_{k=1}^{e}\sum_{g=1}^{n}\sum_{g'=1}^{n'}\left[\left\{\sum_{s=1}^{w}Qsk_{(g-g')} \times Mt_{(s)} + \sum_{s''=1}^{w''}Qs''k_{(g-g')} \times Mt_{(s'')}\right\} \times BLR\right] \tag{13}$$

(n) PR due to transportation of non-reusable waste from source nodes to disposal

$$= \sum_{k=1}^{e}\sum_{s*=1}^{w^*}\sum_{d'=1}^{Td'}\sum_{g=1}^{n}\left[Qs*k_{(g-d')} \times Mt_{(s*)} \times BLR\right] \quad (14)$$

(o) PR due to transportation of waste directly going to disposal without segregation

$$= \sum_{k=1}^{e}\sum_{s=1}^{w}\sum_{d'=1}^{Td'}\sum_{g=1}^{n}[Qsk_{(g-d')} \times Mt_{(s)} \times BLR] \quad (15)$$

(p) PR at source nodes due to segregation

$$= \sum_{k=1}^{e}\sum_{g=1}^{n}\sum_{s=1}^{w}\left[\left\{Qsk_{(g)} - \sum_{d'=1}^{Td'}Qsk_{(g-d')}\right\} \times Mseg\_g_{(s)} \times BLR\right] \quad (16)$$

(q) PR at source nodes due to storage

$$= \sum_{k=1}^{e}\sum_{g=1}^{n}\sum_{s=1}^{w}[Qsk_{(g)} \times Rst_{(g)} \times Msto\_g_{(s)} \times BLR] \quad (17)$$

(r) PR at disposal facilities

$$\sum_{k=1}^{e}\sum_{d'=1}^{Td'}\left[\sum_{g=1}^{n}\left\{\sum_{s*=1}^{w*}Qs*k_{(g-d')} \times Mdis\_d'_{(s*)} + \sum_{s=1}^{w}Qsk_{(g-d')} \times Mdis\_d'_{(s)} + \sum_{s''=1}^{w''}Qs''k_{(g-d')} \times Mdis\_d'_{(s'')}\right\} \times BLR\right] + \sum_{k=1}^{e}\sum_{d'=1}^{Td'}\left[\sum_{s'=1}^{w'}\left\{\sum_{g=1}^{n}Qs'k_{(g-d')} + \sum_{sr'=1}^{rssr}Qs'k_{(sr'-d')}\right\} \times Mdis\_d'_{(s')} \times BLR\right] \quad (18)$$

(s) PR at processing facilities

$$= \sum_{k=1}^{e}\sum_{g=1}^{n}\sum_{s'=1}^{w'}\sum_{sr'=1}^{rssr}\left[Qs'k_{(g-sr')} \times Mpro\_sr'_{(s')} \times BLR\right] \quad (19)$$

(t) PR at reuse facilities

$$= \sum_{k=1}^{e}\sum_{g'=1}^{n'}\sum_{g=1}^{n}\left[\left\{\sum_{s=1}^{w}Qsk_{(g-g')} \times Mreu\_g'_{(s)} + \sum_{s''=1}^{w''}Qs''k_{(g-g')} \times Mreu\_g'_{(s'')}\right\} \times BLR\right] \quad (20)$$

(C) Total EI/risk = the total impact/risk to the environment can be summarized under the heading (u).

(u) EI

$$
\begin{aligned}
&= \sum_{k=1}^{e}\sum_{d'=1}^{Td'}\left[\sum_{g=1}^{n}\left\{\sum_{s*=1}^{w*}\left|Qs*k_{(g-d')}\times\sum_{c=1}^{cn}(As*c\times IFc)\right| + \sum_{s=1}^{w}\left|Qsk_{(g-d')}\right.\right.\right.\\
&\quad\left.\left.\left.\times\sum_{c=1}^{cn}(Asc\times IFc)\right|\right\} xPA_{(d')}\,xPI_{(d')}\right]\\
&\quad+\sum_{k=1}^{e}\sum_{d'=1}^{Td'}\left[\sum_{s'=1}^{w'}\left\{\sum_{g=1}^{n}Qs'k_{(g-d')}+\sum_{sr'=1}^{rssr}Qs'k_{(sr'-d')}\right\}\right.\\
&\quad\left.\times\sum_{c=1}^{cn}(As'c\times IFc)\times PA_{(d')}\times PI_{(d')}\right]+\sum_{k=1}^{e}\sum_{d'=1}^{Td'}\left[\sum_{s''=1}^{w''}\left\{\sum_{g=1}^{n}Qs''k_{(g-d')}\right\}\right.\\
&\quad\left.\times\sum_{c=1}^{cn}(As''c\times IFc)xPA_{(d')}xPI_{(d')}\right] \qquad (21)
\end{aligned}
$$

A.1. Constraints

(i) Mass balance for primary waste type going for reuse in time step k and arriving at source nodes in time step k'

$$\sum_{g=1}^{n}\sum_{g'=1}^{n'}Qsk_{(g-g')}=\sum_{k'=1}^{e'}\sum_{g=1}^{n}Qsk'_{(g)} \qquad \forall \mathrm{k},\ s \qquad (22)$$

(ii) Mass balance for waste arriving at source nodes

$$QGsk_{(g)}+\sum_{k'=1}^{e'}Qsk'_{(g)}=Qsk_{(g)} \qquad \forall k'=k,\ \forall k,\ s \qquad (23)$$

(iii) Mass balance at source nodes

$$
\begin{aligned}
\sum_{k=1}^{e}\sum_{s=1}^{w}[Qsk_{(g)}] &= \sum_{k=1}^{e}\left[\sum_{d'=1}^{Td'}\left\{\sum_{s*=1}^{w*}Qs*k_{(g-d')}+\sum_{s=1}^{w}Qsk_{(g-d')}\right\}\right.\\
&\quad\left.+\sum_{g'=1}^{n'}\sum_{s''=1}^{w''}Qs''k_{(g-g')}+\sum_{sr'=1}^{rssr}\sum_{s'=1}^{w'}Qs'k_{(g-sr')}\right] \quad \forall g \qquad (24)
\end{aligned}
$$

(iv) Mass balance at processing facilities

$$\sum_{g=1}^{n}\sum_{s'=1}^{w'}[Qs'k_{(g-sr')} \times (1-Rs'k)] = \sum_{s'=1}^{w'}\sum_{d'=1}^{Td'}[Qs'k_{(sr'-d')}] \qquad \forall\, sr',\ k \tag{25}$$

(v) Capacity constraint at processing facilities

$$\sum_{g=1}^{n}\sum_{s'=1}^{w'}[Qs'k_{(g-sr')}] \leq Cap.sr'.k \qquad \forall sr',\ k \tag{26}$$

(vi) Logical constraint at processing facilities

$$\left[\sum_{k=1}^{e}\sum_{g=1}^{n}\sum_{s'=1}^{w'}\left[Qs'k_{(g-sr')}\right] / \sum_{k=1}^{e}\sum_{s=1}^{w}\left[Qsk_{(g)}\right]\right] \leq Ysr' \leq \sum_{k=1}^{e}\sum_{g=1}^{n}\sum_{s'=1}^{w'}\left[Qs'k_{(g-sr')}\right] \forall\, sr' \tag{27}$$

(vii) Capacity constraint at disposal facilities

$$\sum_{sr'=1}^{rssr}\sum_{s'=1}^{w'}Qs'k_{(sr'-d')} + \sum_{g=1}^{n}\left[\sum_{s=1}^{w}Qsk_{(g-d')} + \sum_{s*=1}^{w*}Qs*k_{(g-d')}\right] \leq Cap.d'.k \qquad \forall\, d',\ k \tag{28}$$

(viii) Logical constraint at disposal facilities

$$\left[\sum_{k=1}^{e}\left[\sum_{sr'=1}^{rssr}\sum_{s'=1}^{w'}Qs'k_{(sr'-d')} + \sum_{g=1}^{n}\left\{\sum_{s=1}^{w}Qsk_{(g-d')} + \sum_{s*=1}^{w*}Qs*k_{(g-d')}\right\}\right] / \sum_{k=1}^{e}\sum_{s=1}^{w}\left[Qsk_{(g)}\right]\right] \leq Yd' \leq \sum_{k=1}^{e}\left[\sum_{sr'=1}^{rssr}\sum_{s'=1}^{w'}Qs'k_{(sr'-d')} + \sum_{g=1}^{n}\left\{\sum_{s=1}^{w}Qsk_{(g-d')} + \sum_{s*=1}^{w*}Qs*k_{(g-d')}\right\}\right] \qquad \forall d' \tag{29}$$

(ix) Capacity constraint at reuse facilities

$$\sum_{g=1}^{n}\sum_{s''=1}^{w''}\left[Qs''k_{(g-g')}\right] \leq Cap.g'.k \qquad \forall\, g',\ k \tag{30}$$

Ysr' = either 1 or 0
Yd' = either 1 or 0

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