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A Goal Programming Based Multi-Time Step Optimal Material Flow Analysis Model for Integrated Computer Waste Management

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ABSTRACT. Management of computer waste is a growing concern and is more serious in developing countries where rudimentary methods of reuse, recovery and disposal are in frequent use which poses grave environmental and health hazards. Hence there is a clear reason to be concerned about the management scheme for computer waste which will be cost effective and also environmentally friendly. However, assessment of risk from the management of computer waste is a difficult task due to uncertainty in exact composition of toxic constituents and their release mechanism in the environment. The present study attempts to assess the risk associated with various computer waste management activities in relative terms and presents an integer linear goal programming based multi time step optimal material flow analysis model to achieve satisfaction of multiple objectives of economy and health and environmental risk. The model selects various treatment and disposal facilities from a given set and allocates optimum quantities of waste to them along chosen transportation routes, depending on different priorities to cost and risk. An illustrated hypothetical example of computer waste management is presented to demonstrate the usefulness of the proposed formulation. Uncertainty in the waste generation quantities has been addressed using Monte Carlo simulation.

Keywords: computer waste, goal programming, integrated waste management, Monte Carlo simulation, multi-objective optimization, optimal material flow

1. Introduction

With rapid growth and advancement in information technology (IT) sector, the average life span of computer has shrunken. Solid waste management, which is already a mammoth task in India, has become more complicated by the arrival of computer waste in India. This is mainly the result of computer boom in the IT sector. The estimated number of obsolete personal computers emanating from business and individual households in India were around 1.38 million (Agarwal et al., 2003). The import of electronic waste (e-waste) in the name of donations and metal scrap adds to this burden. Due to the absence of proper mechanisms and standards of disposal, these toxics-laden high tech products often end their lives in the waste stream meant either for recycling or are landfilled. Computer waste contains various toxic materials e.g. cadmium, mercury, lead, brominated flame-retardants etc. which can contaminate soil, ground water and air if not handled properly. In India, computer scrap is managed through various low-end management alternatives such as product reuse, conventional disposal in landfills, open burning, and back yard recycling. Computer waste, which does not have any resale or reuse value, is openly burnt extract metallic parts from them. The computer waste management facilities pose considerable risk to both the workers and the environment, which is both acute and chronic in nature. There is a need to assess risk associated with various management activities for computer waste, so that actions can be taken to minimize it.

The objectives of this paper are to: (1) assess risk associated with various management activities for computer waste in a relative manner, (2) present goal programming based optimal material flow analysis (OMFA) model addressing multiple goals of cost and risk, and (3) address uncertainty in the estimated waste quantities using Monte Carlo Simulation.

2. Review of Existing Models for Hazardous Waste Management

The focus of the paper is assessment of risk from various computer waste management analysis and developing an OMFA model to study the tradeoffs between associated costs and risks. Hence, literature review is being covered in three sections, the first one pertaining to status of management of computer waste especially in Indian context, the second citing research in development of optimal material flow models for waste management and the third summarizing key research addressing the issues of uncertainty in input parameters. The need for the present study is highlighted in another section at the end of the literature review.

2.1. Status of Management of Computer Waste in India

A report by Agarwal et al. published in 2003 described the problem of e-waste specially computer waste in the Indian Scenario. It discussed the various sources of computer waste and its fate in recycling stream. It also stated the market me-

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chanism of old personal computers and described the environmental legislation in India with relevance to e-waste.

EMPA (2004) carried out a fieldwork in New Delhi (India) and documented various aspects of computer recycling trade in the city. It stated that the entire industry is based on a network existing of collectors, traders and recyclers, each adding value, and creating jobs, at every point in the chain. It concluded that e-waste recycling was a profitable business in the city, flourishing as an unorganized sector, mainly as backyard workshops.

Baud et al. (2001) in a fieldwork carried out in Chennai (India) observed a series of relationships among waste pickers, buyers, dealers, wholesalers and recycling enterprises. It stated that the main incentive for the players is financial profit, not environmental or social awareness. The biggest drawback of the current Indian system was stated as uncontrolled emission of hazardous toxics into air, water and soil. It concluded that the growing quantity of e-waste necessitates the development of systems which can handle the waste in such a way that minimizes negative social and environmental impacts while maximizing the positive impacts.

Sinha-Khetriwal et al. (2005) discussed the disposal of end-of-life electronic appliances in the countries of India and Switzerland, including appliance collection and the financing of recycling systems as well as the social and environmental aspects of the current practices.

From the above literature review we can conclude that, the studies on e-waste till now have focused mainly on the impacts of its various toxic components, actual management practice and recycling options for a few particular waste components. Though the need for minimization of risk from the management of computer waste has been stressed in the literature above, no methodology has been proposed and implemented for its assessment.

2.2. Material Flow Analysis in Waste Management

In the past many researchers and environmental engineers have attempted to address the material flow of solid waste management through various mathematical models. Hasit and Warner (1981) presented an application of regional solid waste management with WRAP (waste resource allocation program).

Peirce and Davidson (1982) applied linear programming technique to identify a cost effective configuration of transportation routes, transfer stations, processing facilities and secure long term storage impoundments. Mohan (1983) proposed an integer programming based model for disposal management of municipal solid waste (MSW) economically. The example problem considered was optimal waste allocation from two cities to three management alternatives namely incineration, recycling and sanitary landfill. Jennings and Sholar (1984) formulated the regional hazardous waste management system as a transportation routing problem, with sources generating multiple types of wastes.

Zografos and Davis (1989) suggested a multi-objective formulation of hazardous waste routing problem using goal programming approach to address population at risk, risk imposed to special population categories, travel time and property damages. Zografos and Samara (1990) proposed a combined location-routing model examining trade-offs between hazardous waste transportation and disposal risks, routing risk and travel time.

Lund (1990) proposed a linear programming method that both evaluated and scheduled adoption of each of several possible recycling efforts, minimizing total present value cost and considering the effect of recycling on landfill exhaustion and future costs.

List et al. (1991) surveyed methodological research on hazardous materials transportation in the areas of risk analysis, routing/ scheduling and facility location. The review traced the evolution of models from single-criterion optimizations to multi-objective analyses.

ReVelle et al. (1991) suggested a model based on the method of shortest path, a zero-one mathematical program for siting, and the weighting method based multi-objective programming for simultaneous siting and routing for the disposal of hazardous waste.

Jacobs and Everett (1992) presented a linear optimization model that could suggest the times at which the landfills should be closed or opened and the amount of waste that should be diverted to waste recycling programs. Everett et al. (1993) improved upon the study of Jacobs and Everett (1992) and proposed a model that could schedule landfill, recycling and composting operations in an integrated solid waste management system. Stowers and Palekar (1993) proposed a model that simultaneously considered the risk posed by location and transportation, while searching for an optimal location of a single obnoxious facility on a network.

Ramu and Kennedy (1994) demonstrated with an example a heuristic technique, to locate a solid waste facility with a minimum cost based on map distances. Jacobs and Warmerdam (1994) presented a linear programming model to aid decision makers in the simultaneous routing and siting of hazardous waste transport, storage and disposal operations. Mirchandani et al. (1995) described a model based on heuristics, for optimally locating a number of inspection stations along a road network plying trucks carrying hazardous waste, with the objective of intercepting maximum number of trucks to prevent hazardous material transportation (HAZMAT) violations.

Chang and Wang (1996) analyzed the potential conflict between environmental and economic goals using multi-objective, mixed integer programming technique, and, evaluated sustainable strategies for waste management in a metropolitan region. The information incorporated into the optimization objectives included economic impacts, characterized by operational income and cost for waste management, air quality impacts from discharges of target pollutants due to waste incineration, noise impacts from various types of facilities operation, and traffic flow increments by garbage truck fleets.

Everett and Modak (1996a) proposed a linear programming based cost minimization model that could assist decision makers in the long term scheduling of disposal and other management options such as recycling, incineration and composting. A companion paper (Everett and Modak, 1996b) demonstrated the usefulness of the model by its application on a hypothetical problem of regional integrated solid waste management system.

Anex et al. (1996) presented GIGO, a spreadsheet based model for MSW management, comprising of various modules for processes such as waste generation, collection etc with integrated cost estimation. Nozick et al. (1997) suggested an integrated routing/ scheduling approach based on time-varying patterns of accident rates and exposure parameters to reduce overall risk, and, find preferred solutions in multi-objective context.

Giannikos (1998) presented a goal programming model for locating disposal and treatment centers and routing hazardous wastes through an underlying transportation network. Four objectives were considered: (1) minimization of total operating cost, (2) minimization of total perceived risk, (3) minimization of maximum individual risk, and (4) minimizetion of maximum individual disutility.

Nema and Gupta (1999) proposed a model based on multi-objective integer programming approach to suggest optimal configuration of waste management facilities. Utility function approach was used to address multiple objectives of cost and environmental risk.

Leonelli et al. (2000) formulated the problem of selection of best route for transportation of dangerous goods as a “minimum cost flow problem”, which consisted of determining, for a specific hazardous substance, the cheapest flow distribution, honoring the arc capacities from origin to destination nodes. They also stated that both historical evidence and provisional calculations have shown that, the risks arising from the transportation of hazardous materials are often of the same magnitude of those due to fixed installations.

Solano et al. (2002a) presented a linear programming mathematical model for integrated solid waste management (ISWM) that accounted for cost, energy and environmental emissions. A life cycle analysis (LCA) was used to compute energy consumption and environmental emissions. A companion paper (Solano et al., 2002b) described the application of the model to several solid waste management scenarios for a hypothetical case study.

Hu et al. (2002) presented a multi-time-step, multi-waste type, and reverse logistics cost-minimization model for hazardous waste. The total reverse logistics cost considered in the objective function included total collection cost, total storage cost, total treatment cost, total transportation cost for reusing processed wastes, and total transportation cost for disposing processed wastes.

Shih and Lin (2003) presented a multiple criteria optimization approach that considered minimization of the cost, risk and workload for collection system planning for infectious medical waste. A compromise programming method was used to integrate the three objectives and an example of infectious waste collection in Taiwan city was presented. The location of medical institutions, actual road map & population density were provided using geographical information system (GIS).

Nema and Gupta (2003) improved upon their suggested model based on utility function approach, by basing the model on integer goal programming technique. The model was able to address practical issues such as multiple objectives, compatibility between waste types, compatibility between waste and waste technologies and the waste residue generation associated with treatment technologies.

Wang et al. (2004) developed a spreadsheet based systems analysis model, based on the mass balance principle, to assist the cost-benefit evaluation for various construction and demolition (C&D) waste management scenarios. The model was designed to track a C&D waste stream through the various stages of a waste management system, i.e. generation, source separation, processing, recycling and final disposal.

Costi et al. (2004) presented the structure and application of a decision support system (DSS) designed to help decision makers of a municipality in the development of incineration, disposal, treatment and recycling integrated programs. The main goal was to plan the MSW management, defining the refuse flows that have to be sent to recycling or to different treatment or disposal plants, and to suggest the optimal number, the types and location of such plants.

Najm and El-Fadel (2004) presented an interface developed using excel in visual basic environment for ISWM optimization. A linear programming model was formulated with mass balance, capacity, material limitations and policy implementation constraints, whose results were expressed as entries in an excel worksheet.

Ghose et al. (2006) proposed a GIS based optimal routing model, to determine the minimum cost/ distance-efficient collection paths for transporting the solid wastes to the landfills, based on the population density, waste generation capacity, road network and the types of road, storage bins and available collection vehicles.

Klang et al. (2006) investigated various aspects of system analysis and its usefulness as a decision support tool as perceived by local municipal officers and politicians. The respondents considered the most important aspects in evaluating scenarios to be: possibilities for municipal co-operation to minimize cost and negative environmental influence; sound working conditions for refuse disposal personnel; low emissions of greenhouse gases; keeping household economy in mind; and using technologies that are known and reliable.

Badran and El-Haggar (2006) proposed a model for MSW management for Port Said, which minimized the municipal solid waste management system cost using mixed integer programming, by selecting the best location for collection stations from the given candidate locations.

Sharma et al. (2007) presented a mixed integer linear program-ming model with a single objective of minimization of cost, aimed at facilitating better leasing and logistics decisions (including end-of-life disposal options), from the perspective of an electronic equipment leasing company.

As is evident from the literature review, several OMFA models have been developed for municipal solid waste and hazardous wastes. However, none of these can be applied to the management of computer waste without significant additions, because of the issues related to the reverse flow of computer waste in terms of its reuse and reappearance as waste after secondary or tertiary use in future years. Moreover, it can be seen that cost is the most widely addressed objective, although several researches have proposed multi-objective optimal material flow models, addressing both cost and risk. It is to be noted that the management of computer waste has significant issues of risk associated with it, owing to its toxic nature.

2.3. Data Uncertainty in Waste Management

The success of a planning critically depends on the accuracy of parameters. The parameter values are likely to deviate from estimated ones during implementation of planning. In an optimization model the uncertainty can be incorporated using grey technique, fuzzy systems and/or stochastic modelling. A number of researchers have applied these techniques to consider the effect of uncertainty in the integrated solid waste management (ISWM) models.

Grey programming has been widely used by researchers to incorporate uncertainty in ISWM (e.g. Huang et al., 1994; Huang et al., 1995a, 1995b; Huang et al., 1997; Huang et al., 2005). The output of grey programming method/ technique is within upper and lower bounds and does not reflect the distribution of output within these bounds.

Fuzzy techniques have also been used for addressing the uncertainties due to human impreciseness. Various decision support models have addressed uncertainty in the input parameters using fuzzy techniques. A combination of grey programming with fuzzy linear programming has been used by Chang et al. (1997). Chang and Wang (1997) applied fuzzy goal programming for considering the impreciseness of the decision maker's preferences associated with multiple goals.

Stochastic modelling is another way for addressing uncertainty and is dependent on the probability range of parameter values. Abundance of stochastic uncertainty within any solid waste management system renders many optimization approaches relatively unsuitable for practical implementation purposes, since they provide no effective mechanism for directly incorporating system uncertainties into their solution construction (Coyle, 1973; Brown et al., 1974; Liebman, 1975; Gottinger, 1986; Tchobanoglous et al., 1993; MacDonald, 1996). Consequently, Monte Carlo simulation methods (Kalos, 1986) have been used in attempts to circumvent these uncertainty shortcomings (Bodner et al., 1970; Openshaw & Whitehead, 1985; Baetz, 1990; Wang et al., 1994). Monte Carlo simulation has been stated as one of the most effective quantification method for uncertainties and variability among the environmental system analysis tools available (LaGrega et al., 1994). The method makes all the parameters vary at random in a given range. The randomly selected values from all the parameter are inserted as parameter input. Model calculations produce output values reflecting the combined parameter uncertainties. Although, it does not provide a formal mechanism for producing best solutions, simulation contributes an effective means for comparing stochastic system performance.

2.4. Need for the Present Study

Management of computer waste has significant issues of risk associated with it. Although several studies have addressed the issue of risk during the management of hazardous waste, they have not been specifically implemented to computer waste categories. Also computer waste has significant reuse and the dilemma to either send it to a reuse facility (which will make it reappear in future years as waste) or recover the recyclables by sending it to processing facilities can only be resolved by a multi-time step model. It is to be noted that the multi-time step model should consider the reappearance of the waste after its secondary or tertiary uses. Also, there is a need to simultaneously address uncertainty in waste generation quantities while analyzing the tradeoffs between cost and associated risks.

3. Methodology for Relative Risk Assessment

The term "risk" has different meanings depending on different contexts. When used in the process of risk assessment, it has specific definitions; the most commonly accepted is "the combination of the probability, or frequency, of occurrence of a definite hazard and the magnitude of the conesquence of the occurrence" (Royal Society, 1992). On the other hand, hazard can be defined as "the potential to cause harm" and also as "a property or situation that in particular circumstances could lead to harm" (Royal Society, 1992).

Computer waste has several significant issues of risk associated with it owing to its hazardous nature. The risk can be risk to the environment as a whole, which would include risk posed to human beings and the environment during the management of computer waste in case of an accident.

Quantification of accidental risk to the environment in absolute terms is a complex and difficult exercise due to lack of data regarding the probability of accident and/or its consequences (Kirchsteiger, 1999). Several researchers have attempted to quantify this risk in relative terms. Jennings and Suresh (1986) presented an algorithm that uses an analytical solution of the fuzzy decision alternative ratio evaluation analysis to generate risk penalty functions for hazardous waste management planning. The procedure was based on a series of ratio evaluations that could be made using any existing hazardous waste ranking or rating procedure, or any combination of existing methods and the required input could be purely subjective, facilitating assessment of relative risk.

Nema and Gupta (1999) proposed a function for addressing risk to the environment in relative terms. Risk was considered as the function of waste quantity, hazard potential (HP) of the waste, probability of accident, and receptor population impacted in case of accident. Similar to the parameter HP proposed by Nema and Gupta (1999), Talinli et al. (2005) proposed an overall rating value for hazardous waste by using variables such as ecological effect (ignitability, reactivity, corrosivity, toxicity) and combined potential risk (carcinogenic effect, toxic characteristics, infectious characteristics, persistency).

The above literature forms the basis of assessment of relative environmental risk in this study. Hazard Potential (HP) of each waste type was arrived at which can be defined as an index that ranks the various categories of a waste depending upon the various chronic and acute risks (reactivity, corrosivity, environmental persistence, toxicity, flammability, abatement potential, potential subsurface mobility, potential for airborne hazards release, potential for waterborne hazard release, bioconcentration potential, explosivity, direct skin contact hazard) associated with its management. The potential hazards of important constituents of various types of waste (Source: Exporting Harm, 2002) were identified. Expert opinion was utilized to rank the various categories of waste for each identified hazard and also to rank the various hazards attributes in terms of their damage potential. A set of 60 experts were approached to estimate the relative risk of various categories of computer waste for different management options, out of which 43 responded. A consensus was reached using Delphi technique. The HP of a waste was then arrived at by combining the results of the Delphi Technique using AHP (Saaty, 1980).

4. Proposed Integer Goal Programming Model Formulation

Linear programming has been stated as one of the strongest method currently available that can work 'out of the box' on large optimization problems. The important advantage of linear programming is that the method can deal with hundreds of decision variables, and within this huge space identify and set the values of the variables that are critical in the problem. Simplex method in Linear Programming gives important sensitivity information, or information about what happens when data values are changed. Goal programming (Ignizio, 1976) like linear programming is a linear mathematical model, but there are several significant differences between goal programming and linear programming. In goal programming, unlike linear programming, the objective function may be comprised of multiple, incommensurable, and conflicting goals. Rather than minimizing or maximizing the objective criterion directly through structural variables, the deviations from these set goals are minimized, based on priority factors assigned to each goal or sub goal. One of the most appealing characteristics of goal programming concerns the data inputs. That is, the model is not limited by the necessity for an accurate quantification of the relationship among the variables in cardinal numbers. Instead, management need establish only upper or lower limits for their goals and rank them in an ordinal sequence. This is an appealing feature because it is often infeasible to obtain accurate information on the cost or value of a goal. The proposed model has been formulated using goal-programming approach.

The proposed model can be applied to any regional network of source nodes; processing/ recycling/ treatment facilities reuse facilities and disposal facilities. The model considers varying quantities of waste generation in various time steps. The waste going for reuse in a certain time step is again analyzed in future time steps depending upon the assumed/ known reuse time range for that particular waste type. This feature of the model is particularly useful for waste streams such as that of computers, because, while analyzing the trade-offs between various management options (reuse, recycle and landfilling) for a single time step, it may seem beneficial to reuse as much as possible. However if we take into account its reappearance as waste in future, it may not be the most optimum option from economic point of view, as cost of landfilling would increase with each time step not to mention the constraint of availability of landfill space. The selection of various facilities and allocation of waste to these facilities is decided keeping in mind the achievement of a certain objecttive over all the time steps.

The decision variables in this mathematical formulation are: i) waste quantities traveling on a set of transportation routes; ii) decision variables for location of a set of facilities; and iii) the quantities being processed/stored/disposed at various facilities.

The next step is the formulation of objectives. The objectives can be classified as absolute and non-absolute objectives. Absolute objective can be: 'the total of all the waste quantities transported for treatment and disposal from the generation node must be equal to the waste quantity generated at that node'. Fulfillment of the absolute objective can only generate a feasible solution. Hence, the absolute objectives are given the top priority. An example of non-absolute objective can be minimization of cost or the minimization of risk. All the non-absolute objectives are assigned priorities. These objectives are expressed as an equality constraint the right hand side of which represents the desired attainment level of the objective. Two deviational variables are assigned to each objective constraint to measure the over-attainment and the under-attainment of the objective. As stated earlier, the absolute objectives are given the top priority and should be satisfied to the fullest. The non-absolute objectives, on the other hand, should be grouped on the basis of the weightages awarded to them. The decision maker himself normally does this prioritization. Equal weightage can be awarded to analogous objectives.

The problem is subjected to following absolute objectives (constraints): a) mass balance of wastes at each node (source nodes and facilities), b) allowable capacities at various facilities; and c) logical constraints at various facilities to be sited.

The non-absolute objectives (goals) addressed are:

• Minimization of total cost, which includes storage, segregation, processing, disposal, transportation cost; and cost recovered from the sale of reusable and recycled portion of waste.

• Minimization of relative environmental and health risk, which includes waste transportation risk as well as risk at various nodes due to storage, segregation, processing and disposal of waste.

• The goal programming approach strives to minimize the deviations from achievement of a goal based on the priority assigned to it by the decision maker.

5. Equations of the Proposed Mathematical Model

5.1. Non Absolute Objectives

5.1.1. Total Cost (TC)

$$TC = SEG\_C + STO\_C + TR\_C + PRO\_C + DIS\_C + CAP\_C - REC\_C + n_c - p_c$$

(in the achievement function, minimize p_c) (1)

where:
TC = desired attainment level for the total cost;
SEG_C = cost of segregation at source nodes;
STO_C = cost of storage at source nodes;
TR_C = cost of transportation;
PRO_C = cost of processing waste at processing facilities;
DIS_C = cost of disposal;
CAP_C = capital cost for locating processing and disposal facilities;
REC_C = cost recovered from the sale of reusable and recyclable portion of generated waste;
n_c = negative deviation from the desired attainment level for the total cost;
p_c = positive deviation from the desired attainment level for the total cost.

$$SEG\_C = \sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{s=1}^{S} Bsgk \cdot \left\{ Ask_{(g)} - \sum_{d'=1}^{D'} Ask_{(g-d')} - \sum_{g'=1}^{G'} Ask_{(g-g')} \right\} \quad (2)$$

where:
$Ask_{(g)}$ = amount of primary waste (s) generated at source node (g) in time step (k);
$Ask_{(g-d')}$ = amount of primary waste (s) at source node (g) in time step (k) allocated to disposal facility (d');
$Ask_{(g-g')}$ = amount of primary waste (s) generated at source node (g) in time step (k) allocated to reuse facility (g');
$Bsgk$ = Cost of segregation per unit quantity of primary waste (s) in time step (k).

Cost of segregation at source nodes has been arrived at multiplying the quantity of waste arriving at source node minus waste directly going for reuse and disposal, with the cost of segregation per unit weight of waste.

$$STO\_C = \sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{s=1}^{S} Ask_{(g)} \cdot Bstk \cdot Rstk_{(g)} \quad (3)$$

where:
$Bstk$ = cost of storage per unit quantity of primary waste (s) in time step (k);
$Rstk_{(g)}$ = ratio of stored primary waste (s) to waste arriving at source node (g) in time step (k).

Cost of storage at source nodes is the quantity of waste arriving at source node multiplied by the cost of storage per unit weight of waste and ratio of stored waste to incoming waste.

$$\begin{aligned} \mathrm{TR\_C} = & \sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{s'=1}^{S'}\sum_{sr'=1}^{SR'} As'k_{(g-sr')} \cdot Ts'k \cdot \sum_{r=1}^{R} D_{r(g-sr')} \\ & + \sum_{k=1}^{K}\sum_{sr'=1}^{SR'}\sum_{s'=1}^{S'}\sum_{d'=1}^{D'} As'k_{(sr'-d')} \cdot Ts'k \cdot \sum_{r=1}^{R} D_{r(sr'-d')} \\ & + \sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{g'=1}^{G'} \left[\left\{ \sum_{s=1}^{S} Ask_{(g-g')} \cdot Tsk + \sum_{s''=1}^{S''} As''k_{(g-g')} \cdot Ts''k \right\} \cdot \sum_{r=1}^{R} D_{r(g-g')} \right] \\ & + \sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{d'=1}^{D'} \left[\left\{ \sum_{s=1}^{S} Ask_{(g-d')} \cdot Tsk + \sum_{s''=1}^{S''} As''k_{(g-d')} \cdot Ts''k \right\} \cdot \sum_{r=1}^{R} D_{r(g-d')} \right] \\ & + \sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{d'=1}^{D'} \left[\left\{ \sum_{s'=1}^{S'} As'k_{(g-d')} \cdot Ts'k + \sum_{s^*=1}^{S^*} As^*k_{(g-d')} \cdot Ts^*k \right\} \cdot \sum_{r=1}^{R} D_{r(g-d')} \right] \end{aligned} \quad (4)$$

where:
$As'k_{(g-sr')}$ = amount of processable waste (s') (generated after segregation of primary waste types) at source node (g) in time step (k) allocated to processing facility (sr');
$Ts'k$ = cost of transportation of processable waste (s') per unit weight per unit distance in time step (k);
$D_{r(g-sr')}$ = distance between the source node (g) and processing facility (sr') via route (r);
$As'k_{(sr'-d')}$ = amount of processable waste (s') left as residue at processing facility (sr') in time step (k) going to disposal facility (d');
$D_{r(sr'-d')}$ = distance between the processing facility (sr') and disposal facility (d') via route (r);
Tsk = Cost of transportation of primary waste (s) per unit weight per unit distance in time step (k);
$As''k_{(g-g')}$ = amount of reusable secondary waste (s'') (generated after segregation of primary waste types) at source node (g) in time step (k) allocated to reuse facility (g');
$Ts''k$ = Cost of transportation of secondary reusable waste (s'') per unit weight per unit distance in time step (k);
$D_{r(g-g')}$ = Distance between the source node (g) and reuse facility (g') via route (r);
$As''k_{(g-d')}$ = amount of reusable secondary waste (s'') (generated after segregation of primary waste types) at source node (g) in time step (k) allocated to disposal facility (d');
$D_{r(g-d')}$ = distance between the source node (g) and disposal facility (d') via route (r);
$As'k_{(g-d')}$ = amount of processable waste (s') (generated after segregation of primary waste types) at source node (g) in

time step (k) allocated to disposal facility (d');

$As^{*}k_{(g-d')}$ = amount of non-reusable, non-processable secondary waste (s^{*}) (generated after segregation of primary waste types) at source node (g) in time step (k) allocated to disposal facility (d');

$Ts^{*}k$ = cost of transportation of non-processable, non- reusable waste (s^{*}) per unit weight per unit distance in time step (k).

Cost of transportation of waste from one node to other is the quantity of waste traveling from origin node to 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 destination node along a particular route.

$$\text{PRO\_C} = \sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{s'=1}^{S'}\sum_{sr'=1}^{SR'} As'k_{(g-sr')} \cdot Bsr'\_s'k \quad (5)$$

where:

$Bsr'\_s'k$ = cost of processing per unit quantity of waste (s') at processing facility (sr') in time step (k).

$$\text{DIS\_C} = \sum_{k=1}^{K}\sum_{d'=1}^{D'}\sum_{g=1}^{G} Bd'k \cdot \left\{ \sum_{s^{*}=1}^{S^{*}} As^{*}k_{(g-d')} + \sum_{s=1}^{S} Ask_{(g-d')} + \sum_{s''=1}^{S''} As''k_{(g-d')} \right\}$$
$$+ \sum_{k=1}^{K}\sum_{d'=1}^{D'}\sum_{s'=1}^{S'} Bd'k \cdot \left\{ \sum_{g=1}^{G} As'k_{(g-d')} + \sum_{sr'=1}^{SR'} As'k_{(sr'-d')} \right\} \quad (6)$$

where:

$Bd'k$ = Cost of disposal per unit quantity of waste at disposal facility (d') in time step (k).

Cost of processing or disposal at any facility is the quantity of waste reaching the facility at any time step multiplied by the cost of processing/disposal per unit weight at the facility.

$$\text{CAP\_C} = \sum_{sr'=1}^{SR'}\sum_{k=1}^{K} CPsr'k \cdot \alpha\_sr' + \sum_{d'=1}^{D'}\sum_{k=1}^{K} CPd'k \cdot \alpha\_d' \quad (7)$$

where:

$CPsr'k$ = equitable capital cost per time step for locating processing facility (sr');

α_sr' = logical variable associated with the processing facility (sr'), which would be 1, if the facility is sited, else 0;

$CPd'k$ = equitable capital cost per time step for locating disposal facility (d');

α_d' = logical variable associated with the disposal facility (d'), which would be 1, if the facility is sited, else 0.

Capital cost for locating facilities 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.

$$\text{REC\_C} = \sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{g'=1}^{G'} \left[\sum_{s=1}^{S} Ask_{(g-g')} \cdot Brsk + \sum_{s''=1}^{S''} As''k_{(g-g')} \cdot Brs''k \right] +$$
$$\sum_{k=1}^{K}\sum_{s'=1}^{S'}\sum_{g=1}^{G}\sum_{sr'=1}^{SR'} As'k_{(g-sr')} \cdot Brs'k \cdot Rs'k \quad (8)$$

where:

$Brsk$ = cost recovered from the sale of unit quantity of primary reusable waste (s) in time step (k);

$Brs''k$ = cost recovered from the sale of unit quantity of secondary reusable waste (s'') in time step (k);

$Brs'k$ = cost recovered from the sale of unit quantity of waste (s') after processing in time step (k);

$Rs'k$ = ratio of waste (s') that could be processed w.r.t. its total quantity in time step (k).

Cost recovered from the sale of recyclable portion of waste is the quantity of a waste type reaching the processing facility at any time step, multiplied by the cost recovered by sale of processed waste per unit weight at any time step and the ratio of processed/recycled waste to incoming waste coming 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 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.

5.1.2. Risk

Risk being addressed in this formulation is relative risk. It is being assumed that the minimization of relative risk leads to the minimization of actual risk.

$$\text{TOR} = \text{Rt} + \text{Rs} + n_R - p_R$$
(in the achievement function, minimize p_R) (9)

where:

TOR = desired attainment level for the total risk;

Rt = transportation risk;

Rs = site risk;

n_R = negative deviation from the desired attainment level for the total risk;

p_R = positive deviation from the desired attainment level for the total risk.

$$\text{Rs} = \text{R\_source} + \text{R\_pro\_r} + \text{R\_dis} \quad (10)$$

where:

R_source = site risk at source nodes due to segregation and storage;

R_pro_r = site risk at processing and reuse facilities;

R_dis = site risk at disposal facilities.

$$\text{Rt} = \sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{d'=1}^{D'}\sum_{r=1}^{R} PAk_{r(g-d')} \cdot PIk_{r(g-d')} \cdot \Bigg[\sum_{s=1}^{S} Ask_{(g-d')} \cdot HPs + \sum_{s'=1}^{S'} As'k_{(g-d')} \cdot HPs' + \sum_{s''=1}^{S''} As''k_{(g-d')} \cdot HPs'' + \sum_{s^*=1}^{S^*} As^*k_{(g-d')} \cdot HPs^*\Bigg] + \sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{s'=1}^{S'}\sum_{sr'=1}^{SR'} As'k_{(g-sr')} \cdot HPs' \cdot \sum_{r=1}^{R} PAk_{r(g-sr')} \cdot PIk_{r(g-sr')} + \sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{g'=1}^{G'}\Bigg[\sum_{s=1}^{S} Ask_{(g-g')} \cdot HPs + \sum_{s''=1}^{S''} As''k_{(g-g')} \cdot HPs''\Bigg] \cdot \sum_{r=1}^{R} PAk_{r(g-g')} \cdot PIk_{r(g-g')} + \sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{sr'=1}^{SR'}\sum_{d'=1}^{D'} As'k_{(sr'-d')} \cdot HPs' \cdot MF\_HPs' \cdot \sum_{r=1}^{R} PAk_{r(sr'-d')} \cdot PIk_{r(sr'-d')} \tag{11}$$

where:

$PAk_{r(g-d')}$ = probability of accident during transportation on route (r) from source node (g) to disposal facility (d') in time step (k);

$PIk_{r(g-d')}$ = population impacted during transportation on route (r) from source node (g) to disposal facility (d') in time step (k);

HPs = hazard potential of primary waste (s);

HPs' = hazard potential of processable waste (s');

HPs'' = hazard potential of secondary reusable waste (s'');

HPs^* = hazard potential of non-processable, non-reusable waste (s^*);

$PAk_{r(g-sr')}$ = probability of accident during transportation on route (r) from source node (g) to processing facility (sr') in time step (k);

$PIk_{r(g-sr')}$ = population impacted during transportation on route (r) from source node (g) to processing facility (sr') in time step (k);

$PAk_{r(g-g')}$ = probability of accident during transportation on route (r) from source node (g) to reuse facility (g') in time step (k);

$PIk_{r(g-g')}$ = population impacted during transportation on route (r) from source node (g) to reuse facility (g') in time step (k);

MF_HPs' = factor by which hazard potential of the residue left after processing of waste (s') is greater than the waste itself;

$PAk_{r(sr'-d')}$ = probability of accident during transportation on route (r) from processing facility (sr') to disposal facility (d') in time step (k);

$PIk_{r(sr'-d')}$ = population impacted during transportation on route (r) from processing facility (sr') to disposal facility (d') in time step (k).

$$\text{R\_source} = \sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{s=1}^{S} HPs \cdot PAk_{(g)} \cdot PIk_{(g)} \cdot \Bigg\{Ask_{(g)} - \sum_{d'=1}^{D'} Ask_{(g-d')} - \sum_{g'=1}^{G'} Ask_{(g-g')}\Bigg\} + \sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{s=1}^{S} Ask_{(g)} \cdot Rstk_{(g)} \cdot HPs \cdot PAk_{(g)} \cdot PIk_{(g)} \tag{12}$$

where:

$PAk_{(g)}$ = probability of accident on source node (g) in time step (k);

$PIk_{(g)}$ = population impacted on source node (g) in time step (k).

$$\text{R\_pro\_r} = \sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{s'=1}^{S'}\sum_{sr'=1}^{SR'} As'k_{(g-sr')} \cdot HPs' \cdot PAk_{(sr')} \cdot PIk_{(sr')} + \sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{g'=1}^{G'} PAk_{(g')} \cdot PIk_{(g')} \cdot \Bigg[\sum_{s=1}^{S} Ask_{(g-g')} \cdot HPs + \sum_{s''=1}^{S''} As''k_{(g-g')} \cdot HPs''\Bigg] \tag{13}$$

where:

$PAk_{(sr')}$ = probability of accident on processing facility (sr') in time step (k);

$PIk_{(sr')}$ = population impacted on processing facility (sr') in time step (k);

$PAk_{(g')}$ = probability of accident on reuse facility (g') in time step (k);

$PIk_{(g')}$ = population impacted on reuse facility (g') in time step (k).

$$\text{R\_dis} = \sum_{k=1}^{K}\sum_{d'=1}^{D'} PAk_{(d')} \cdot PIk_{(d')} \cdot \Bigg\{\sum_{g=1}^{G}\Bigg[\sum_{s^*=1}^{S^*} As^*k_{(g-d')} \cdot HPs^* + \sum_{s=1}^{S} Ask_{(g-d')} \cdot HPs + \sum_{s''=1}^{S''} As''k_{(g-d')} \cdot HPs''\Bigg] + \sum_{s'=1}^{S'} HPs' \cdot \Bigg[\sum_{g=1}^{G} As'k_{(g-d')} + \sum_{sr'=1}^{SR'} As'k_{(sr'-d')} \cdot MF\_HPs'\Bigg]\Bigg\} \tag{14}$$

where:

$PAk_{(d')}$ = probability of accident on disposal facility (d') in time step (k);

$PIk_{(d')}$ = population impacted on disposal facility (d') in time step (k).

5.2. Absolute Objectives

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

$$\sum_{g=1}^{G}\sum_{g'=1}^{G'} Ask_{(g-g')} = \sum_{k'=1}^{K'}\sum_{g=1}^{G} Ask'_{(g)} \quad \forall\, k, s \tag{15}$$

which transforms in the goal programming approach to:

$$\sum_{g=1}^{G}\sum_{g'=1}^{G'} Ask_{(g-g')} - \sum_{k'=1}^{K'}\sum_{g=1}^{G} Ask'_{(g)} + n_1 - p_1 = 0 \quad \forall\, k, s$$

(in the achievement function, minimize $(n_1 + p_1)$) (15a)

where:

k' = time step in which primary waste (s) going for reuse in time step (k) is discarded back as waste, where k' = 1 to K';

$Ask'_{(g)}$ = amount of primary waste (s) coming after a cycle of reuse in time step (k') at source node (g);

n_1 = negative deviation from the difference of waste quantity going for reuse in time (k) and discarded back as waste in future time steps;

p_1 = positive deviation from the difference of waste quantity going for reuse in time (k) and discarded back as waste in future time steps.

Mass balance for waste arriving at source nodes

$$AGsk_{(g)} + \sum_{k'=1}^{K'} Ask'_{(g)} = Ask_{(g)} \quad \forall\ k'=k,\ \forall\ k, s \tag{16}$$

which transforms in the goal programming approach to:

$$AGsk_{(g)} + \sum_{k'=1}^{K'} Ask'_{(g)} - Ask_{(g)} + n_2 - p_2 = 0 \quad \forall\ k'=k,\ \forall\ k, s$$

(in the achievement function, minimize $(n_2 + p_2)$) (16a)

where:

$AGsk_{(g)}$ = amount of primary waste (s) discarded by the first user in time step (k) and arriving at source node (g);

n_2 = negative deviation from the difference of waste quantity discarded and being managed in time step (k);

p_2 = positive deviation from the difference of waste quantity discarded and being managed in time step (k).

Mass balance at source nodes

$$\sum_{s=1}^{S} Ask_{(g)} - \sum_{s''=1}^{S''}\left[\sum_{g'=1}^{G'} As''k_{(g-g')} + \sum_{d'=1}^{D'} As''k_{(g-d')}\right] - \sum_{d'=1}^{D'}\left[\sum_{s^*=1}^{S^*} As^*k_{(g-d')} + \sum_{s=1}^{S} Ask_{(g-d')}\right] - \sum_{s'=1}^{S'}\left[\sum_{sr'=1}^{SR'} As'k_{(g-sr')} + \sum_{d'=1}^{D'} As'k_{(g-d')}\right] - \sum_{g'=1}^{G}\sum_{s=1}^{S} Ask_{(g-g')} = 0 \quad \forall\ g, k \tag{17}$$

which transforms in the goal programming approach to:

$$\sum_{s=1}^{S} Ask_{(g)} - \sum_{d'=1}^{D'}\left[\sum_{s^*=1}^{S^*} As^*k_{(g-d')} + \sum_{s=1}^{S} Ask_{(g-d')}\right] - \sum_{s''=1}^{S''}\left[\sum_{g'=1}^{G'} As''k_{(g-g')} + \sum_{d'=1}^{D'} As''k_{(g-d')}\right] - \sum_{s'=1}^{S'}\left[\sum_{sr'=1}^{SR'} As'k_{(g-sr')} + \sum_{d'=1}^{D'} As'k_{(g-d')}\right] - \sum_{g'=1}^{G}\sum_{s=1}^{S} Ask_{(g-g')} + n_3 - p_3 = 0 \quad \forall\ g, k$$

(in the achievement function, minimize $(n_3 + p_3)$) (17a)

where:

n_3 = negative deviation from the difference of waste quantity arriving at source node (g) and allocated to various management options in time step (k);

p_3 = positive deviation from the difference of waste quantity arriving at source node (g) and allocated to various management options in time step (k).

Mass balance at processing facilities

$$\sum_{g=1}^{G} As'k_{(g-sr')} \cdot (1 - Rs'k) - \sum_{d'=1}^{D'} As'k_{(sr'-d')} = 0 \quad \forall\ sr', k, s' \tag{18}$$

which transforms in the goal programming approach to:

$$\sum_{g=1}^{G} As'k_{(g-sr')} \cdot (1 - Rs'k) - \sum_{d'=1}^{D'} As'k_{(sr'-d')} + n_4 - p_4 = 0 \quad \forall\ sr', k, s'$$

(in the achievement function, minimize $(n_4 + p_4)$) (18a)

where:

n_4 = negative deviation from the difference of waste quantity arriving at processing facility (sr') and being processed in time step (k);

p_4 = positive deviation from the difference of waste quantity arriving at processing facility (sr') and being processed in time step (k).

Capacity constraint at processing facilities

$$\sum_{g=1}^{G}\sum_{s'=1}^{S'} As'k_{(g-sr')} \le Cap.sr'.k \times \alpha\_sr' \quad \forall\ sr', k \tag{19}$$

which transforms in the goal programming approach to:

$$\sum_{g=1}^{G}\sum_{s'=1}^{S'} As'k_{(g-sr')} + n_5 - p_5 = Cap.sr'.k \times \alpha\_sr' \quad \forall\ sr', k$$

(in the achievement function, minimize p_5) (19a)

where:

$Cap.sr'.k$ = capacity available at processing facility (sr') in time step (k);

n_5 = negative deviation from the product of binary variable associated with processing facility and its capacity at time step (k);

p_5 = positive deviation from the product of binary variable associated with processing facility and its capacity at time step (k).

Logical constraint at processing facilities

$$\sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{s'=1}^{S'} As'k_{(g-sr')} / \sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{g=1}^{G} Ask_{(g)} \le \alpha\_sr' \quad \forall\ sr' \tag{20}$$

which transforms in the goal programming approach to:

$$\sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{s'=1}^{S'} As'k_{(g-sr')} / \sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{g=1}^{G} Ask_{(g)} + n_6 - p_6 = \alpha\_sr' \quad \forall\ sr'$$

(in the achievement function, minimize p_6) (20a)

where:

n_6 = negative deviation from the binary variable associated with processing facility;

p_6 = positive deviation from the binary variable associated with processing facility.

$$\sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{s'=1}^{S'} As'k_{(g-sr')} \geq \alpha\_sr' \quad \forall\ sr' \tag{21}$$

which transforms in the goal programming approach to:

$$\sum_{k=1}^{K}\sum_{g=1}^{G}\sum_{s'=1}^{S'} As'k_{(g-sr')} + n_7 - p_7 = \alpha\_sr' \quad \forall\ sr'$$

(in the achievement function, minimize n_7) (21a)

where:

n_7 = negative deviation from the binary variable associated with processing facility;

p_7 = positive deviation from the binary variable associated with processing facility.

Capacity Constraint at disposal facilities

$$\sum_{sr'=1}^{SR'}\sum_{s'=1}^{S'} As'k_{(sr'-d')} + \sum_{g=1}^{G}\left[\sum_{s=1}^{S} Ask_{(g-d')} + \sum_{s^*=1}^{S^*} As^*k_{(g-d')} + \sum_{s'=1}^{S'} As'k_{(g-d')} + \sum_{s''=1}^{S''} As''k_{(g-d')}\right] \leq Cap.d'.k \times \alpha\_d' \quad \forall\ d', k \tag{22}$$

which transforms in the goal programming approach to:

$$\sum_{sr'=1}^{SR'}\sum_{s'=1}^{S'} As'k_{(sr'-d')} + \sum_{g=1}^{G}\left[\sum_{s=1}^{S} Ask_{(g-d')} + \sum_{s*=1}^{S*} As^*k_{(g-d')} + \sum_{s'=1}^{S'} As'k_{(g-d')} + \sum_{s''=1}^{S''} As''k_{(g-d')}\right] + n_8 - p_8 = Cap.d'.k \times \alpha\_d' \quad \forall\ d', k$$

(in the achievement function, minimize p_8) (22a)

where:

$Cap.d'.k$ = capacity available at disposal facility (d') in time step (k);

n_8 = negative deviation from the product of binary variable associated with disposal facility and its capacity at time step (k);

p_8 = positive deviation from the product of binary variable associated with disposal facility and its capacity at time step (k).

Logical constraints at disposal facilities

$$\sum_{k=1}^{K}\left[\sum_{sr'=1}^{SR'}\sum_{s'=1}^{S'} As'k_{(sr'-d')} + \sum_{g=1}^{G}\left[\sum_{s=1}^{S} Ask_{(g-d')} + \sum_{s^*=1}^{S^*} As^*k_{(g-d')} + \sum_{s'=1}^{S'} As'k_{(g-d')} + \sum_{s''=1}^{S''} As''k_{(g-d')}\right]\right] / \sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{g=1}^{G} Ask_{(g)} \leq \alpha\_d' \quad \forall\ d' \tag{23}$$

which transforms in the goal programming approach to:

$$\sum_{k=1}^{K}\left[\sum_{sr'=1}^{SR'}\sum_{s'=1}^{S'} As'k_{(sr'-d')} + \sum_{g=1}^{G}\left[\sum_{s=1}^{S} Ask_{(g-d')} + \sum_{s^*=1}^{S^*} As^*k_{(g-d')} + \sum_{s'=1}^{S'} As'k_{(g-d')} + \sum_{s''=1}^{S''} As''k_{(g-d')}\right]\right] / \sum_{k=1}^{K}\sum_{s=1}^{S}\sum_{g=1}^{G} Ask_{(g)} + n_9 - p_9 = \alpha\_d' \quad \forall\ d'$$

(in the achievement function, minimize p_9) (23a)

where:

n_9 = negative deviation from the binary variable associated with disposal facility;

p_9 = positive deviation from the binary variable associated with disposal facility.

$$\sum_{k=1}^{K}\left[\sum_{sr'=1}^{SR'}\sum_{s'=1}^{S'} As'k_{(sr'-d')} + \sum_{g=1}^{G}\left\{\sum_{s'=1}^{S'} As'k_{(g-d')} + \sum_{s''=1}^{S''} As''k_{(g-d')}\right\} + \sum_{g=1}^{G}\left\{\sum_{s=1}^{S} Ask_{(g-d')} + \sum_{s^*=1}^{S^*} As^*k_{(g-d')}\right\}\right] \geq \alpha\_d' \quad \forall\ d' \tag{24}$$

which transforms in the goal programming approach to:

$$\sum_{k=1}^{K}\left[\sum_{sr'=1}^{SR'}\sum_{s'=1}^{S'} As'k_{(sr'-d')} + \sum_{g=1}^{G}\left\{\sum_{s'=1}^{S'} As'k_{(g-d')} + \sum_{s''=1}^{S''} As''k_{(g-d')}\right\} + \sum_{g=1}^{G}\left\{\sum_{s=1}^{S} Ask_{(g-d')} + \sum_{s^*=1}^{S^*} As^*k_{(g-d')}\right\}\right] + n_{10} - p_{10} = \alpha\_d' \quad \forall\ d'$$

(in the achievement function, minimize n_{10}) (24a)

where:

n_{10} = negative deviation from the binary variable associated with disposal facility;

p_{10} = positive deviation from the binary variable associated with disposal facility.

Capacity constraint at reuse facilities

$$\sum_{g=1}^{G}\sum_{s''=1}^{S''} As''k_{(g-g')} \leq Cap.g'.k \quad \forall\ g', k \tag{25}$$

which transforms in the goal programming approach to:

$$\sum_{g=1}^{G}\sum_{s''=1}^{S''} As''k_{(g-g')} + n_{11} - p_{11} = Cap.g'.k \quad \forall\ g', k$$

(in the achievement function, minimize p_{11}) (25a)

where:

n_{11} = negative deviation from the capacity of the reuse facility;

p_{11} = positive deviation from the capacity of the reuse facility.

Waste going for reuse in a particular time step is again analyzed in future time steps depending upon the reuse time span for that waste (refer eqn. 15 and 16). Mass balance at various nodes ensures that waste quantity arriving at a node (source node/ facility) is equal to the waste present at the node and waste leaving the node (refer eqn. 17 and 18). 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 (refer eqn. 19 and 22). Logical constraints (refer eqn. 20, 21, 23 and 24) 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). The logical constraint will be satisfied when value of binary value associated with the facility is forced to be one by the capacity constraint equation when waste arriving at that facility is greater than zero.

5.3. Achievement Function

Minimimize

$$\left[\Pr i\_1\{(n_1+p_1),(n_2+p_2),(n_3+p_3),(n_4+p_4),p_5,p_6,n_7,p_8,p_9,n_{10},p_{11}\},\ \Pr i\_2\{p_R\},\ \Pr i\_3\{p_C\}\right] \quad (26)$$

The deviation variables (n_a, p_a) are used to formulate the achievement function [Equation (26)], which is an order vector. The priority (x) attached with the linear function $\Pr i\_x$ (n_a, p_a) governs the order in which the deviations are minimized.

6. Example Problem

The example problem taken is a hypothetical problem of computer waste (personal computers (PCs), printers and computer peripherals) generation based on a study of computer waste generation in Delhi (Agarwal et al., 2003). The network considered is as shown in Figure 1. The network consists of 16 links, the details of which are given in Table 1.

Proposed Waste Types of the example problem are explained as follows- WA (Computer/PC); WB (Dot matrix Printers); WC (Deskjet Printers); W1 (Cathode Ray tube (CRT)); W2 (Processor chip, Reusable floppy drive, hard disk); W3 (Printer motor); W4 (Printer cartridge); W5 (Brominated or ABS (Acrylonitrile-butadiene styrene) Plastic); 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); W7 (Metal Casings and scrap metal).

The problem is analyzed for a total of three time steps; each time step of being four months. The waste generation varies at each source node with time step. The details of length, probability of accident and population impacted for each link are given in Table 2. The probability of accidents has been assumed on the basis of accident data published in a leading newspaper in India (Times of India, 2003). Waste generation rates at various source nodes are given in Table 3. Further details of various facilities such as probability of accident, population impacted, capacity, capital and running costs are given in Table 4. Recovered Cost from various waste types and their weightwise fractions are given in Table 5.

A schematic showing various management options available for each type of waste is shown in Figure 2. Each waste can either go to reuse facilities (if reusable), or can go to recycling facilities (from where the recycling residue would go to either of the disposal facility) or can go to either of the disposal facilities. The model decides how much of waste should

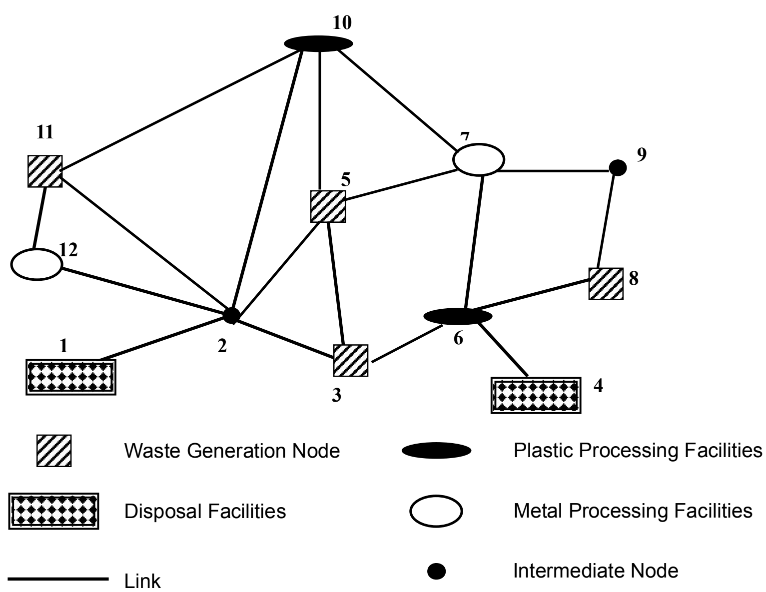

Figure 1. Network drawing.

be allocated to each management option and where the facility

Table 1. Proposed Waste Types of the Example Problem, their Description, Hazard Potential and Unit Cost of Transportation

Waste type	Description	Hazard potential*	Unit cost of transportation ($/tonne/km)
WA	Computer / PC	0.07	1
WB	Dot matrix printers	0.04	1
WC	Deskjet printers	0.04	1
W1	Cathode ray tube (CRT)	0.14	2
W2	Processor chip, Reusable floppy drive, Hard disk	0.08	2
W3	Printer motor	0.05	2
W4	Printer cartridge	0.08	2
W5	Brominated or ABS (acrylonitrile-butadiene styrene) plastic	0.11	1
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	0.26	2
W7	Metal Casings and scrap metal	0.13	1

* Hazard potential of the waste arrived at after analysis of feedback by experts using Analytical Hierarchy Process (Saaty, 1980)

Table 2. Information about Links in the Network

Link no.	From node	To node	Length (km)	Probability of accident × 10^{-6}	Population impacted × 1000
1	1	2	100	4.0	0.75
2	2	3	50	1.0	0.50
3	2	5	50	6.0	0.75
4	2	10	50	1.0	0.50
5	2	11	60	4.0	0.50
6	2	12	50	8.0	0.75
7	3	5	50	2.0	0.50
8	3	6	50	4.0	0.75
9	4	6	150	4.0	0.75
10	5	7	50	6.0	0.75
11	6	7	50	4.0	0.75
12	6	8	50	6.0	0.75
13	7	9	50	1.0	0.25
14	7	10	50	1.0	0.25
15	8	9	50	1.0	0.25
16	10	11	50	1.0	0.25
17	11	12	50	6.0	0.75

Table 3. Waste Generation Rates at Various Source Nodes (Tonnes per Four Month Time Step)

S.no.	Node no.	Type of waste	Time step		
			1 (Jan-Apr)	2 (May-Aug)	3 (Sept-Dec)
1	3	WA	300	320	300
2	3	WB	80	85	80
3	5 & 8	WA	350	360	350
4	11	WB	120	125	120
5	11	WC	130	135	130

Table 4a. Segregation and Storage Costs at Various Source Nodes

Node no.	Segregation cost (US $/tonne)	Storage cost (US $/tonne)	Probability of accident × 10^{-6}	Population impacted × 1000
3, 5, 8, 11	220	60	2.0	3.5

Table 4b. Capacities and Running Costs for Various Facility Options

Node no.	Capital cost for locating facility (US $/time step)	Running/ processing/ disposal cost ($/tonne)	Probability of accident × 10^{-6}	Population impacted × 1000
1	120000	30	2.0	4
4	480000	32	1.5	2
6	44000	20	2.5	3
10	22000	20	2.0	2
7	44000	18	2.5	3
12	22000	18	2.0	2

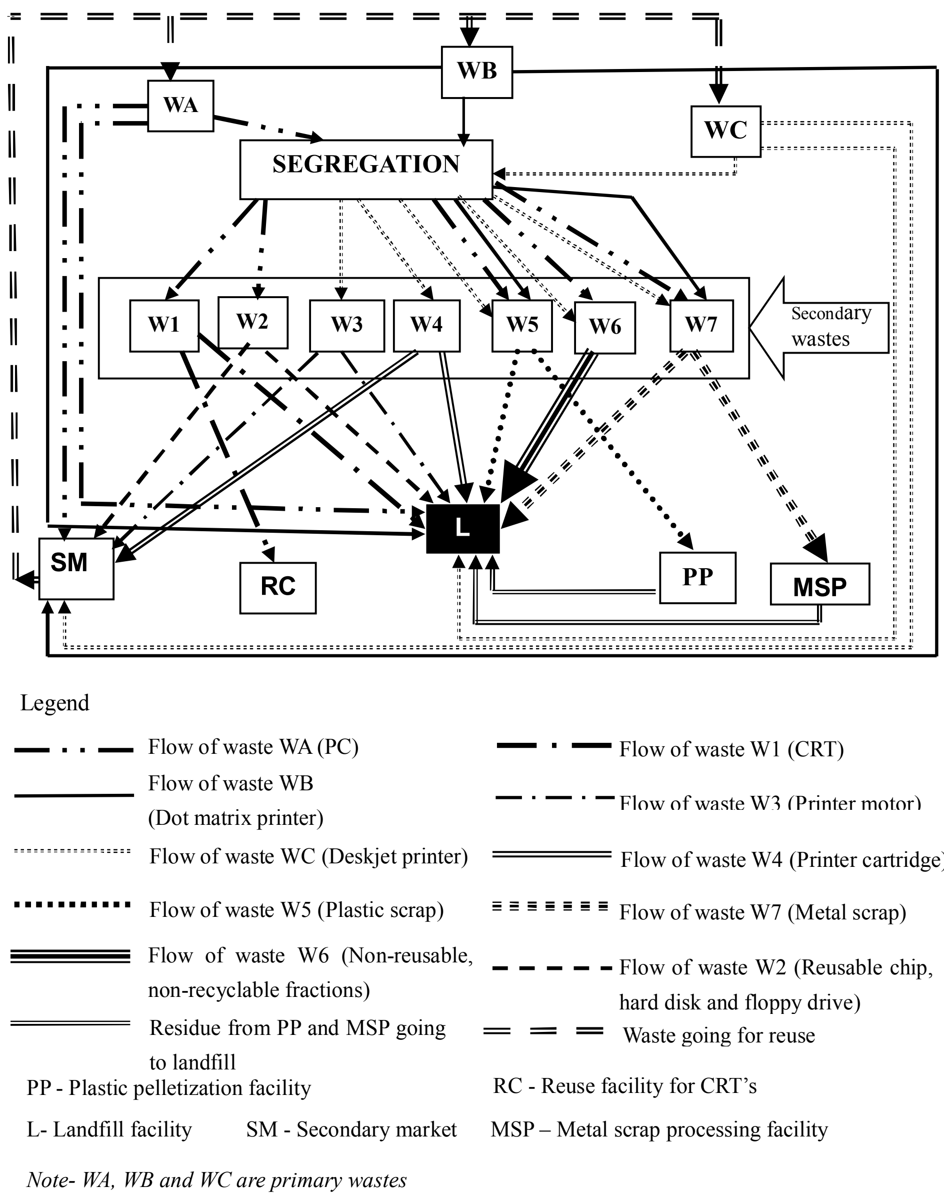

Figure 2. Typical diagram showing management options available for various categories of computer waste (source: Ahluwalia, P. K., Nema, A. K., 2006).

Table 5. Recovered Cost from Various Waste Types and their Weight Wise Fractions

Waste type	Recovered cost (US $/tonne)*	Weight wise fractions of primary waste*
Re-usable Primary Waste		
WA	900.00	= 0.1WA**
WB	450.00	= 0.2WB**
WC	400.00	= 0.2WC**
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 + 0.35WB + 0.35 WC
W6	0.0***	= 0.30996 WA + 0.339 WC + 0.35 WB + 0.15 (W5 + W7)
W7	150.00	= 0.15 WA + 0.1WC + 0.1 WB

*Source: Data collected through personal survey during the period- April to July, 2006 from various Computer Vendors in Delhi. Recovered Cost is assumed same for all the time steps;
**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;
***W6 waste type cannot be recycled or reused, hence the recovered cost = 0.

Table 6. Results of Example Problem

S. no.	Priority to cost	Priority to relative risk	Total cost for all time steps ($)	Relative risk for all time steps ($\times 10^{-3}$)	Facilities Sited
1	2	3	9,456,021	46175.11	1, 6, 7, 10, 12
2	2 (5% Compromise)	3	9,928,822	44342.64	1, 6, 7, 12
3	2 (10% Compromise)	3	10,401,620	35348.89	1, 4, 6, 7, 12
4	2 (15% Compromise)	3	10652320	35133.86	1, 4, 6, 7, 12
5	3	2	10,652,320	35133.86	1, 4, 6, 7, 12
6	3	2 (5% Compromise)	10,012,130	36890.55	1, 4, 6, 7, 10, 12
7	3	2 (10% Compromise)	10,001,040	37007.38	1, 4, 6, 7, 10, 12
8	3	2 (15% Compromise)	10,001,040	37007.38	1, 4, 6, 7, 10, 12

*Priority 1 is given to absolute objectives

should be located. The waste going for reuse is analyzed again in the future time steps. The model decides how much of the reusable waste should be sent for reuse keeping in mind the present recovered and the future management costs as well as capacity constraints.

7. Solution of the Model: Results and Discussion

The formulated example problem had 491 non-integer decision variables and 24 integer decision variables. Total number of formulated equations was 346. The example problem was solved after assigning different priorities to each objective. Absolute objectives were always assigned first priority. Non-absolute objectives of cost and risk were assigned second and third priorities by turn. Scenario of a 10% compromise for each objective having second priority was also analyzed. The results are summarized in Table 6 and Figure 3.

As is observed by the results, the relationship between cost and risk though inverse may not be linear in nature. The ratio of total risk for the scenario of low priority (risk priority-3, cost priority-2) to that of high priority (risk priority-2, cost priority-3) was observed to be approximately 1.3. The cost incurred increased by approximately 12% when the priority shifted from minimization of cost to minimization of risk. The decision regarding facilities being sited also varied with different priorities to each objective. Plastic processing facility at node number '6', metal processing facility at node number '12' and landfill facility at node number '1' was always sited irrespective of the priorities to cost and risk. The results are specific to the example problem presented in this paper and may vary from problem to problem. However, the analyses of these results give an insight to the decision maker for efficient planning.

In a real life situation, the generation of waste at any node is not constant, even within the same time frame. It fluctuates around a certain mean value. To study the effect of such fluctuations on each solution, a sensitivity analysis was required on the waste quantities generated using Monte Carlo

Simulation. Ten scenarios each for random 5%, and 10% variation in the waste quantities for each time step were considered to evaluate their sensitivity on the decisions (regarding selection of facilities) reported by the model. Two of the scenarios considered for each case were for extreme minimum and maximum variation. The above reported decisions had 100% reliability for 5% variation in the waste quantities for all scenarios of different priorities to cost and risk. This implies that for up to ±5% variations in the quantities, the reported decisions (sited facilities) would remain the same for all the analyzed scenarios. The reported decisions remained same for eight out of the total ten cases studied for 10% variation in the waste quantities for higher priority to cost; reported decisions remained the same for six out of the ten scenarios for 10% compromise to the objective of cost and risk; and, the reported decisions remained the same for four out of the ten scenarios for higher priority to risk. Hence it is evident that a large error in data collection may result in altogether different solution.

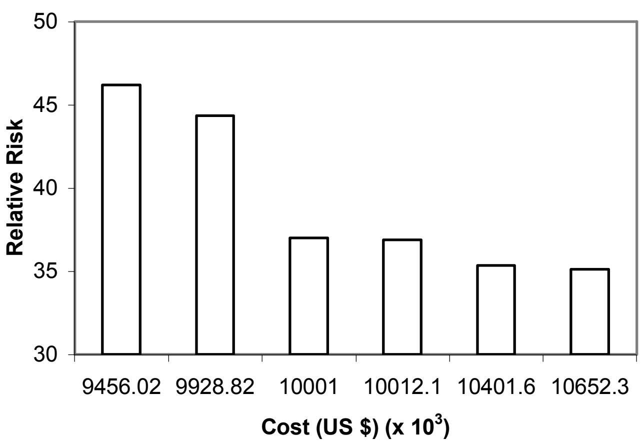

Figure 3. Tradeoffs between risk and cost.

From the post optimality analysis it was observed that disposal of waste type W1 (CRT) in a landfill was the most critical during higher priority to cost and disposal of waste type W6 was found to affect the solution under higher priority to risk the most. Siting plastic processing facility at node number 10 was observed to affect the solution under higher priority to risk the most and siting of landfill at node number 4 was found to affect the solution of higher priority to cost the most.

8. Summary and Conclusion

In summary this paper presents a multi-objective goal-programming model for a multi-time step, multi waste system. A methodology for assessing relative risk from the management of computer waste has been proposed and implemented. Uncertainty in waste generation quantities has been addressed using Monte Carlo simulation.

The proposed approach facilitates the decision-making process by giving the choice of priority to minimize cost or risk and the opportunity to specify constraints as truly absolute or non-absolute. The model can be used as a decision support tool for optimum configuration for integrated waste management for diverse waste streams with more than one option available for management. For the present study the environmental and health risk were considered directly proportional to waste quantity. However, one can consider it as a non-linear function. Threshold quantities for each waste type may be identified below which risk from that waste quantity could be zero.

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