Integrated Modelling of Solid Waste in India

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Abstract

Solid waste management (SWM) in developing countries has traditionally focused on organisational and technical concerns. However, this approach neglects the many activities and actors that waste management comprises. We propose a new paradigm of SWM which extends the technical model to tackle a range of problems associated with waste management in order to achieve socially and environmentally responsible waste management. This includes a range of activities, issues and processes such as the types of waste generated, the number of stakeholders and economic activities involved, and the various economic, social and environmental effects of SWM and may include legitimisation of the informal system, public participation and possibly partial privatisation.

Such an approach must therefore adopt a more comprehensive and broader perspective, and, because of this complexity, it is necessary to incorporate insights from several disciplines to develop effective management of solid waste. This paper attempts to offer such an approach by incorporating these issues in an economic framework.

To evaluate the effectiveness of different SWM alternatives, a linear programming model has been developed. The main objective of the model is to minimise overall system costs and to identify low cost alternatives to manage household, institutional and industrial waste. Although it has been developed as a classic single objective model, ie to minimise costs, it does incorporate social and environmental objectives associated with SWM; thus, it may be regarded as one which aims to find sustainable solutions. The set up of the model is comparable with input-output modelling with additional objectives embedded as side constraints.

To demonstrate its relevance, the model is applied to the Indian city Bangalore. Various scenario runs are presented. This empirical exercise does not only reveal the model’s strengths such as revealing important interdependencies in the waste management sector, but also highlights its weaknesses such as the demand for high quality data. Nevertheless, this model may be considered a valuable first step in evaluating integrated SWM in developing countries.

Resumen

La Gestión de Desechos Sólidos (GDS) en países en desarrollo se ha concentrado tradicionalmente en aspectos organizativos y técnicos. Este enfoque, sin embargo, descuida las múltiples actividades y actores que participan en la gestión de desechos. Con el objetivo de lograr una gestión de desechos sólidos que sea social y ambientalmente responsable, estamos proponiendo un nuevo paradigma de GDS que aplique el modelo técnico a otro rango de problemas asociados con la gestión de desechos. Dicho paradigma comprende una serie de actividades, temas y procesos tales como el tipo de desechos que se generan, el número de intereses (stakeholders) y de actividades económicas que se crean al igual que los muchos efectos económicos, sociales y ambientales de la GDS. Puede también involucrar la legitimización del sistema informal, procesos de participación y posiblemente privatización parcial.

La complejidad del tema hace necesario que se adopte una perspectiva más completa y amplia, incorporando aportes de muchas disciplinas con el objeto de desarrollar una efectiva gestión de desechos sólidos. Este ensayo propone este tipo de enfoque incorporando dichos asuntos dentro de un marco económico.

Para evaluar la efectividad de varias alternativas de GDS se ha desarrollado un modelo de programación lineal. El principal objetivo del modelo es minimizar costos del sistema en general e identificar alternativas de bajo costo para la gestión de desechos domésticos, institucionales e industriales. Aunque el modelo ha sido desarrollado como un modelo clásico, de objetivo único (minimizar costos), también incorpora objetivos sociales y ambientales asociados con la GDS. Es por esto que puede considerarse como un modelo cuyo objetivo es encontrar soluciones sustentables. El esquema del modelo es comparable a un modelo insumo-producto al cual se le han añadido objetivos adicionales como restricciones secundarias.

Para demostrar su importancia, el modelo se ha aplicado a la ciudad de Bangalore en India. En este ejercicio empírico se proponen varios escenarios en donde se muestran tanto las ventajas del modelo (como el revelar interdependencias importantes en el sector de gestión de desechos) como sus debilidades (v.g. la necesidad de contar con datos de alta calidad). Este modelo, sin embargo, puede considerarse como un primer paso valioso en la evaluación integrada de GDS en países en desarrollo.

Abrégé

La gestion des déchets solides (GDS) a eu coutume de se focaliser, dans les pays en développement, sur des questions organisationnelles et techniques. Or cette démarche néglige les nombreux intervenants et activités qui font partie de la gestion des déchets. Nous proposons donc un nouveau paradigme de GDS qui repousse les limites du modèle technique afin d'aborder toute une gamme de problèmes liés à la gestion des déchets, avec pour but de rendre cette dernière socialement et écologiquement responsable. Cela implique que l'on prenne en compte tout un éventail d'activités, de problèmes et de processus - comme les types de déchets produits, le nombre de parties prenantes et d'activités économiques impliquées et les différents effets économiques, sociaux et écologiques de la GDS - et cela peut amener la légitimisation du système informel, la participation du public et la possibilité d'une privatisation partielle.

Une telle approche doit donc se doter d'une perspective bien plus complète et plus ample. Il est par ailleurs nécessaire, à cause de cette complexité, de l'enrichir des points de vue de plusieurs disciplines si l'on veut élaborer une gestion efficace des déchets solides. Ce document tente de suggérer une approche de ce genre, en procédant dans le contexte d'un cadre économique, à l'intégration de ces questions.

Pour évaluer l'efficacité de différentes alternatives de GDS, on a élaboré un modèle de programmation linéaire, dont le principal objectif est la minimisation du coût global du système et l'identification d'alternatives peu coûteuses envisageables pour la gestion des déchets domestiques, institutionnels et industriels. Bien qu'il ait été développé sous forme de modèle classique à objectif unique (pour coûter le moins cher possible) il intègre les objectifs sociaux et écologiques afférents à la GDS et peut donc être perçu comme modèle visant à découvrir des solutions durables. Sa structure est comparable à celle d'une modélisation entrée/sortie, avec inclusion d'objectifs supplémentaires comme autant de contraintes afférentes.

Pour en démontrer la pertinence, le modèle est appliqué à la ville de Bangalore, en Inde. On présente le déroulemet de divers scenarii. Cet exercice empirique n'aboutit pas seulement à la révélation des forces du modèle, comme la mise à jour d'interdépendances cruciales au sein même du champ d'activités qu'est la gestion des déchets, mais à la mise en lumière de ses faiblesses, telle que son besoin de données de grande qualité. On peut néanmoins le considérer comme un très utile premier pas por l'évaluation d'une GDS intégrée dans les pays en développement.

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Introduction

Population growth and the rapid pace of urbanisation pose many environmental challenges for large cities. One of these is solid waste management (SWM). Since the early 1970s SWM in developing countries has received increasing attention from researchers and policy makers concerned to establish a sustainable management system. In India the responsibility for SWM rests largely with municipal authorities who, for the most part, focus primarily on organisational aspects such as improvement of municipal management quality, cost recovery from users, privatised collection and transportation system, as well as technical aspects such upgrading of waste management equipment. The fact that waste management is a fairly extended economic sector, comprising a range of interlinked actors, activities, and commodities, has been neglected since decades. Instead, much emphasis has been put on minimising the costs of collection through transport route optimisation as nearly 90% within the municipal SMW budget goes in waste collection and transportation (De Souza,1991). Other important economic goals like waste reduction, source segregation, and local recycling have not received much attention. Similarly, social goals such as employment generation, and environmental goals such as litter avoidance, and the care for a healthy and sustainable environment have not been an integral part of the analysis.

Due to price and policy distortions, economic, social and environmental externalities are generated in waste generation and management. These, if neglected, may have serious environmental and social impacts. Thus, efforts should aim to internalise the externalities along with the financial constraints. To achieve “socially and environmentally sound solid waste management”, it is essential to put forward a new paradigm for SWM that involves source separation, recovery of waste, legitimisation of the informal system, partial privatisation and public participation. Such an integrated approach to SWM seems to be the best option and could well hold the key to effective and sustainable waste management system in India. This approach must take account of a range of issues, since solid waste management in developing cities is a rather complex issue. For example,

- the types of waste generated varies widely;
- the number of stakeholders involved is substantial;
- the range of related economic activities is extensive;
- the boundaries of an analysis of the “waste problem” are difficult to define;
- the impacts can be environmental, economic and social.

Because of this complexity, contributions from several disciplines are necessary for developing a sound management of solid waste. A comprehensive approach is needed to tackle various problems and issues at the same time. The concept of integrated solid waste management (ISWM) in this paper incorporates these issues in an economic framework, and provides us with such a comprehensive framework. More generally, ISWM does not need to be based on an economic framework since it is a very broad concept. Essentially it implies that decisions about waste handling should take into account economic, environmental, social and institutional aspects not only in the waste production stage but also in its up and downstream stages. The integration can take place at various levels: 1) the use of a range of different collection and treatment options, 2) the involvement and participation of all the stakeholders,

and 3) the interactions between the waste system and other relevant systems such as industry (Lardinios and Klundert 1997).
To evaluate the effectiveness of different ISWM alternatives, a linear programming model has been developed. The main objective of the model is to minimise the overall systems cost and to identify the low cost alternatives for managing household, institutional and industrial waste. Although the model is developed as a classic single objective model, ie, minimising costs, it does include social and environmental objectives associated with solid waste management. Thus it may be regarded as a model which aims to find sustainable solutions.

A model of a waste sector in a developing country should be different from a comparable model of a developed country, for various reasons. First, the two regions have different forms of waste generation, collection and processing. For example, while most recyclable goods in Northern countries are supplied by households on a voluntary basis, the main source of these materials in the South are the waste pickers and itinerant waste buyers who collect these materials for living. A second major distinction is different priorities. Collection and proper disposal of municipal waste are the main problems in developing countries. Despite the high costs involved, the collection of disposable waste is mostly well organised in Northern cities. Priorities in this region lie more in the area of finding ways of increasing recycling or improving the safety of incineration. These differences should be reflected in the model, either in its structure or in the scenarios which are run. For example, the model developed in this paper takes into account some typical characteristics of the informal sector and the specific technological conditions.

An often heard critique of economic models is the high level of abstraction of the analysis. By representing the waste management system in a model structure, certain detailed relations may be omitted. This critique is to a certain extend also valid for this model. In this paper, we describe the set up of the model and a limited application to the city of Bangalore, India. The model has, to a certain level, ignored detailed aspects. For example, to indicate its recyclability, solid waste is specified in terms of qualities. The model does however not categorise the specific material composition of the waste as is common in most alternative models. This part of the model will be improved upon in future work. At this point in time, we succeeded to develop a highly flexible framework that is easily extended and is capable of analysing various policy issues. Although this may have an impact on the exact levels of the solutions of the model, some abstraction is unavoidable, given the data and time constraints.

A clear advantage of an economic model is that it takes into account the linkages between the various actors and activities, something which even an experienced expert would have difficulties with. Moreover, since the model is operated from a computer, it is possible to assess the efficiency of various policy options in a very limited time. To a certain extent the model is capable of testing the validity of certain presumptions in relation to solid waste management. For example, it is often claimed that recycling is the most effective way to deal with the problem of excess waste. The model may demonstrate how an increase in recycling could be achieved most effectively and whether indeed it has the desired effects.

The paper is structured as follows. In Chapter 2, the most important issues are outlined. In Chapter 3 a summary is given of modelling efforts in the waste management sector. Chapter 4 presents a model with agents and commodities. In Chapter 5, it is shown how the model can be applied to specific cities in various ways such as simulation and optimisation. In Chapter 6, the process of calibration is explained as well as the resulting outcomes such as the hidden costs and the capacities. The results of the application to Bangalore are presented in Chapter 7. Conclusions are presented in Chapter 8. The full model, including equations and data sets, are illustrated in the Annexes.

Solid Waste Management in India

Before going into detail about the modelling aspects of the waste sector, it is important to present the state-of-the-art of urban solid waste in India. The empirical background of SWM in India has been explained extensively in another paper (Sehker and Beukering, 1999). Therefore the description that follows in this chapter is based mainly on the salient points raised in the study together with limited additional literature. Special mention is made of Bangalore since this is the city for which the model will be developed.

Low per capita levels, high aggregate levels

On the basis of available data, it is estimated that the nine major metropolitan centres in India are presently producing 23,000 tonnes of solid waste per day. Bangalore, the capital of the southern state Karnataka, with an estimated population of 5 million and one of the largest cities of India, is estimated to generate around 3000 to 3600 tonnes of municipal waste per day, out of which 80-85 per cent is collected, and the rest left unattended. Table 1 provides details about the garbage generated, cleared and the annual municipal budget in nine major Indian cities.

Table 1. Urban Waste Situation in Some Major Indian Cities

Major Cities	Garbage Generated (Tonnes Per Day)	Garbage Cleared (Tonnes Per Day)	Annual Municipal Budget (Rs. In Crores)
Delhi	3,880	2,420	1016.28
Calcutta	3,500	3,150	250.00
Bombay	5,800	5,000	2436.00
Bangalore	**2,130**	**1,800**	**237.00**
Madras	2,675	2,140	145.00
Lucknow	1,500	1,000	48.00
Patna	1,000	300	15.00
Ahmedabad	1,500	1,200	270.00
Surat	1,250	1,000	170.00

Source : India Today, 31st October, 1994
Note : 1 Crore = 10 millions; $ 1 = about Rs.36/-

A high organic content

Solid waste may be defined as the organic and inorganic waste materials, produced by households, commercial, institutional and industrial activities, which have lost their value in the eyes of the first owner (Cointreau, 1982). While another actor may find the material useful, if the owner does not want it, it is waste. The quantities and characteristics of solid waste produced vary from country to country, and from city to city. Factors influencing the quantities and composition include the average level of income, the sources, the population, social behaviour, climate, industrial production and the existence of markets for waste materials (Baldisimo 1988). Waste densities and moisture contents are much higher in developing countries, which require different technology and management systems (Cointreau et al. 1984). Generally refuse from Indian cities contains a high organic and low combustible matter (Table 2), hence incineration is a less appropriate option compared to industrialised countries.

Table 2 Composition of urban solid waste in Indian cities (percentage by weight)

City	Paper	Metals	Glass	Textiles	Plastic*	Ash & dust	Organic	Others**
Madras	5.90	0.70	-	7.07	-	16.35	56.24	13.74
Delhi	5.88	0.59	0.31	3.56	1.46	22.95	57.71	7.52
Calcutta	0.14	0.66	0.24	0.28	1.54	33.58	46.58	16.98
Bangalore	1.50	0.10	0.20	3.10	0.90	12.00	75.00	7.20
Ahmedabad	5.15	0.80	0.93	4.08	0.69	29.01	48.95	10.39
Bombay	3.20	0.13	0.52	3.26	-	15.45	59.37	18.07

Source: Planning Commission on "Urban Solid Waste Management in India", GOI (1995)
* includes rubber and leather
** includes bones, stones and wooden matter

Extensive informal activities

In parallel to the formal system of waste management, there is an active informal network in Indian cities. This sector consists of waste pickers, Itinerant Waste Buyers (IWB's), waste dealers and wholesalers, and small recycling enterprises. The sector is driven primarily by market forces, and makes a significant contribution to the overall waste management process in Indian cities. Moreover, since the sector is labour intensive, it provides employment opportunities to a large group of people, accounting for an estimated 1-2% of the workforce in large cities (Furedy 1992). Sudhir et al. (1997) estimate the maximum number of waste pickers, IWBs and waste dealers in Madras at respectively 40,000, 3000 and 2700. Although the role of the informal sector in waste collection is quite significant, the problem of SWM still lies in the partial collection of waste and inability of municipalities to handle the problem efficiently (Ravindra 1993).

Poor performance of the formal sector

In most Indian cities, the municipal service for the collection and transportation of urban solid wastes comprises three separate functions: (a) sweeping and kerbside collection; (b) transportation by hand-carts to large or road collection points, which may be open dumps, vats (masonry enclosures) or storage chambers; and (c) transportation by vehicles to the disposal sites.

It is broadly estimated that between 10 to 40 per cent of the total municipal budget is used for SWM (Bhide, 1990). However, despite this large share, it is argued that the Indian waste management system is starved of resources when account is taken of the increasing demands associated with growing urbanisation (Shekdar, *et. al.*, 1992). Due to budgetary constraints, inadequate equipment and poor planning, house- to- house collection is very rare in India, particularly in certain low-income areas where waste is not collected at all (Baud and Schenk 1994). It is estimated that up to 30 per cent of disposed solid waste (public dustbins and street garbage) are left uncollected. The areas which are not serviced are left with clogged sewers and litter which creates serious health problems for the resident population (NIUA, 1993; India Today, 1994).

What happens to the waste?

Waste collected by the formal and informal sectors is delivered mainly to three destinations. First, high quality materials and used products are cleaned or transformed for reuse. A well-known example is the re-use of old newspapers for packaging material. Second, recyclable materials are traded for recycling purposes. As a result, a wide range of products are generated. Third, organic waste can be converted into compost, which, when used as manure instead of chemical fertiliser contributes to improved fertility of the soil. The remaining waste goes for disposal. Table 3 illustrates the composition of SWM options identified in Bangalore.

Table 3 Composition of SWM options in Bangalore (1998)

SWM option	%
reuse	19
recycling	43
composting	7
disposal	31

source: Sekher and Beukering, 1999

The final destination of solid waste in India is disposal. Most urban solid waste in Indian cities and towns is landfilled or dumped. Incineration of solid waste is generally limited to hospital waste. As already mentioned, because of its low calorific value, high moisture content, and high quantity of non-combustibles, Indian city refuse is generally not suitable for incineration. However, Bangalore's waste is mainly dumped along public highways and in open fields which is extremely hazardous to both the environment and health. Although various public landfills have been earmarked, local opposition has hindered landfill operations. The only place where BCC may legally send garbage is Karnataka Compost Development Corporation (KCDC).

Conclusions

Municipalities are unable to cope with the growing problem of increasing solid waste generation. Two main causes are identified:

- financial constraints: municipal agencies in India spend 10 to 40 per cent of their total budget on solid waste management. This is approximately Rs.100 per capita per year (approximately US$ 20 based on PPP[1]). Due to inadequate financial resources, the municipal agencies are mostly interested in collection and transportation of the solid waste out of the city limits with not much attention is given to proper disposal of the waste.

- organisational and technical aspects: no single organisational model may be considered as *the best* for India, where situations vary from city to city along with population, collection system, etc. Suggestions for improvement should include aspects such as the quality of municipal services, systems of cost recovery from users, and privatisation of collection systems (Bernstein 1991; Schetenleib and Meyer 1992). Attention should also be given to technical aspects; upgrading of equipment used for waste collection, developing environmentally safer methods of disposal (ie, composting, sanitary landfill), while noting that large-scale solutions may not be feasible in areas with inadequate infrastructure.

The classical approach to SWM, which considers it a responsibility of municipal body, ignores several socio-economic aspects of most existing solid waste systems, thereby contributing to the problems of inefficiency and ineffectiveness of the system. It does not recognise the fact that solid waste separation, re-use and recycling by the informal sector may be part of the solution to improved management. Venkateswaran (1994) points out that the constraints and inefficiencies experienced in SWM are mainly due to an undue emphasis of on technology, while ignoring SWM's social, ecological and economic characteristics.

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[1] Relative prices of goods and services not traded on international markets tend to vary substantially from one country to another, leading to large differences in the relative purchasing power of currencies. The purchasing power of one dollar in India is higher than in the United States. Purchasing Power Parity (PPP) estimates are calculated by converting local currencies to US dollars by using purchasing power parities (PPP) instead of exchange rates as conversion factors. The conclusion of the PPP conversion is that spending US$ 20 for waste management every year, in US purchasing power conditions is not much.

Modelling Solid Waste Management

The former chapter identified the main practices and problems in the waste management sector in India. In order to find effective solutions, comprehensive scientific tools are required. This chapter discusses various tools which are examined in the derived from the literature are discussed.

Trend analysis

Several sophisticated quantitative models have been developed to address different important aspects of SWM such as allocation of waste over disposal sites, routing of collection vehicles, waste estimation and prediction, rankings of disposal alternatives and location of SWM facilities such as transfer stations, processing plants and disposal sites.

Planning for solid waste management requires an assessment of many complex interactions, eg among transportation systems, land use patterns, public health considerations, etc., and interdependencies in the system, eg disposal methods can influence collection and vice versa. Because of these interactions and interdependencies, attention has focused on systems analysis and mathematical modelling techniques. Modelling serves three purposes. First, it is a means for ensuring an orderly interpretation of the data and a consistent representation of the system. Second, it may provide a quantitative indicator of the efficiency of resource use when these are limited. Third, models can be used to anticipate the response of a system when the context changes, including both ‘autonomous’ changes such as demographic and economic growth, and changes bound to policy measures. As such, models may assist with assessing alternative policies, optimising the total system costs, and in assessing operative actions in order to determine their impacts on the system. In the literature, many models have been developed, some of which are listed briefly below.

Successful solid waste management frequently depends on accurate predictions of waste generation. Conventional prediction models frequently use socio-economic and demographic factors on a per-capita basis which may be fixed over time or projected to change with time. An example is given by Chang *et.al.* (1997), who apply ‘Time Series Intervention Modelling’ to evaluate recycling impacts on solid waste generation; they demonstrate the use of forecasting information for evaluating the capacity of incinerators in Taipei city, Taiwan. However, extrapolation of past data should be constrained to a limited time interval. Time series data analysis may help to identify trends embedded in SWM over time, but results are inaccurate when significant changes in determining variables occur in the future.

Trend analysis may be further improved by a material flow analysis such as Life Cycle Analysis or Substance Flow Analysis, and by Input-Output Modelling, to generate consistent relations between consumption, production, and flows of various materials in the economy. The approaches rely heavily on industry and trade statistics which are usually available at national level. In a study by Iwai *et.al.* (1980), the analysis was used to calculate households materials consumption, which was assumed to equate to household waste generation and waste storage. Whereas in input-output modelling, relative flows are constant, a more advanced ‘Multi-sector Equilibrium Model’ allows for several substitution possibilities. Bruvoll and Ibenholt (1997) use an economic model to forecast production and material input, and in a second stage use these to explain future waste generation in Norwegian manufacturing industry. The Multi-sector Equilibrium Model is used to estimate changes and determine total production growth by technological change, growth in real capital, labour and the supply of raw materials and natural resources. Compared to a straightforward input-output model, this is more sophisticated, but also depends more heavily on assumptions regarding technological progress and price mechanism of substitution in the production process.

Optimality Analysis

In the last few decades, the financial, environmental and social costs related to the disposal of solid waste, have been increasing. Since then, various attempts have been made to build models with the objective of selecting least cost waste management options and thus minimising costs. Cost effective models are a way of finding cost minimisation for a given policy.

Linear programming is one of the most widely used decision making tools in quantitative analysis. It is used essentially to determine the most efficient allocation of scarce resources to obtain the optimum results. Many studies have investigated the problem of SWM transportation between supply regions and demand regions using linear programming. Some of these studies have investigated the problem of locating intermediate transfer stations between suppliers and demand regions. Balinski (1961) developed a method with which to approximate the optimal solution to the transportation problem when fixed charges were presented. Khan (1987) developed a method with which to optimise solid waste disposal costs by trading off transportation costs against the capital and the operating costs of introducing stations. Shekdar *et.al* (1991) dealt with an application of a transportation model designed to minimise solid waste handling costs over several developmental plans of an urban area. An optimal mixed-integer linear model has been developed by Wang *et.al.* (1995), to determine suitable sites as intermediate processing stations to minimise the cost of recovered paper transportation for the state of Iowa, USA. Transportation models can be used to evaluate relevant resource location-allocation decisions.

For the optimal design of a municipal solid recycling system, Diamadopoulous *et.al.* (1994) developed an Integer Linear Programming Model. This takes into account all the costs related to the collection, transportation and promotion of recycled products, those related to the disposal of solid wastes at the landfill as well as those related to the closure and monitoring of the exhausted landfills, and opening of a new one. An important aspect of this model is the discrete element which is necessary to take account of the high set up costs for infrastructure. The model was applied to the city of Chania, Greece, for the recycling of paper, glass, aluminium and organic residues. The results showed that recycling produces a significant reduction in the mean annual cost of SWM by 35%, as well as an increase in the life of the landfill by six years. The optimal recycling scheme depends on the characteristics of the areas of the city. The model may consider unfavourable market conditions, such as future reduction of recovered material prices or limited absorption of these materials in the market.

Sundberg, Gipperth and Wene (1994) applied the existing model MIMES (a Model description and optimisation of Integrated Material flows and Energy Systems) to the solid waste sector. MIMES/WASTE is a one time step model and is designed to find new solutions to future waste management systems that are cost effective and environmentally acceptable. It can be used for short term planning by focusing on variable costs only and long term planning by also incorporating fixed costs. It can also be used to analyse the consequences of specific changes in the system environments, that are for instance initiated by proposed waste management plans. A pilot study was undertaken for the region of Götheborg and for the city of Böras in Sweden.

Sudhir, Muraleedharan and Srinivasan (1996) developed a non-linear lexicographic goal programming (NLGP) model to provide an approach by which planners can analyse an integrated waste management system. It defines six objectives that incorporate the interests of various actors involved in waste management. These objectives vary from meeting the collection and disposal targets to meeting employment targets. A planning period of 5 years was considered. The model is solved by splitting the waste problem into sub-problems. It is thus not fully clear whether the solutions are solved in a truly integrated manner, and environmental effects have not been explicitly taken into account. The merit of this model, which is tested for the city of Madras (India), is that it highlights the limitations of techno-managerial solutions often adopted in waste management and the scope of the informal sector in urban SWM in developing countries. The same authors also developed a dynamic version of a SWM planning model (Sudhir et al. 1997). This captures the dynamic nature of interactions among the various components of the urban SWM system in Madras, a typical metropolitan city in India. It considers a time horizon of 1980-2020. Its merit lies in its capacity to capture the dynamics of interactions among the formal waste collection, informal recycling, and the waste generating system.

A cost-benefit model has been developed for Madras, the capital city of the southern Indian state of Tamilnadu by Srinivasan (1985), to select the optimal allocation of solid waste to different methods of disposal. The costs and benefits of different methods such as sanitary landfill, composting and bio-gas production are considered and different combinations are attempted in this study. Benefit to cost ratios are formulated for each combination with the maximum ratio as the optimal. Sanitary landfill was found to be the ideal method for large scale disposal of waste, provided the land is available at a reasonable cost and biogas production is preferred over composting for the city.

Palmer *et al*. (1996) use a simple partial equilibrium model for waste generation and recycling to evaluate the cost effectiveness of various policies for reducing solid waste disposal. The calibrated model analyses the intervention level necessary for waste disposal reduction through three price based policies : deposit/refunds, Advance Disposal Fees (ADF) and recycling subsidy, with deposit/ refund found to be the most cost effective. However, high administration costs may alter this conclusion making an ADF appear more attractive. But there may be greater uncertainty about the social benefits of waste reduction than its marginal costs. Thus the study highlights the need for more research on the social benefits of the waste reduction.

It is often considered a main weakness of cost-benefit studies that they only account for those factors which are measured in money terms, neglecting the socio-environmental costs which are not expressed in monetary units, such as health impacts due to pollution. Qualitative information/data on environmental variables need to be incorporated with quantitative variables to achieve sustainable results. If an emphasis is put on the incorporation of many criteria, a technique like Multi-Criteria Analysis (MCA) is used to select the preferred waste disposal options.

In order to assess the suitability of this methodology, two studies were undertaken by Powell (1992) to evaluate waste disposal options and scenarios. In the studies, a multi-criteria model was developed to evaluate six waste disposal options (incineration, Refuse Derived Fuel (RDF) and landfill, each with and without recycling) which were judged against 16 criteria. The conclusion was drawn that in the absence of sufficient cardinal (quantitative data) information, the available criteria can be incorporated by the use of ordinal data using a ranking system, in order to arrive at better decisions. MCA has proved to be a useful tool as it permits a comparison of the criteria in the units that they occur. Chung and Poon (1996) made use of MCA to establish the preferred waste management option for Hong Kong. Land filling, waste to energy, composting and source of separation were analysed and source separation was found to be the most preferred option. A similar study, to choose the best SWM system out of existing alternatives was undertaken by Hokkanen and Salminen (1993) for the Oulu region in Finland.

MCA may serve as an important tool for environmental decision making by accommodating both technical information in its original form as well as evaluative criteria. However, there are several problems associated with MCA such as the selection of suitable criteria, appropriate weights, which if may lead to biased results. Buckley (1988) argues that the method which depends on the weighting procedure will produce meaningless results. It is suggested that MCA may be used as a supporting method, in addition to cost minimisation models for SWM.

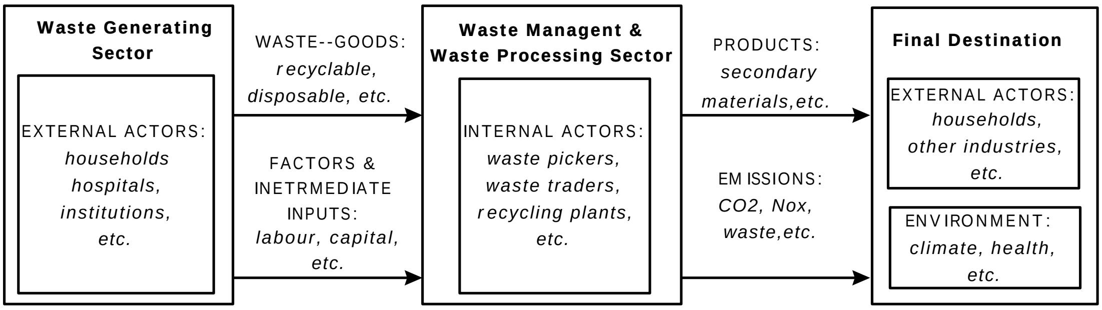
An Integrated Waste Assessment Model

In this section we develop a new model whose prime objective is to minimise the overall systems cost and to identify the low cost alternatives to manage the generated waste effectively. Although it is developed as a classical single objective model, within its single objective structure, it does incorporate other important social and environmental objectives associated with solid waste management. The model distinguishes between the waste management sector, which consist of actors and commodities, and the rest of the economy.

Model set up

The model describes the activities of the waste management sector resulting from the demands in other parts of the economy for the processing of waste and for the production processes of output. These activities require the supply of production factors such as labour and capital. In certain scenarios the supply of emission permits may also be considered a necessary production factor. An important subdivision in the model can be made between actors and commodities. Figure 1 gives an overview of the main categories of actors and commodities relevant in the model.

Figure 1. Schematic overview of waste management sector



Actors (households, hospitals, waste pickers, composting plants, etc.) are denoted by $j \in \mathbf{J}=\{1,..,J\}$. We can follow the standard distinction of actors in a households sector, a public sector, and a business sector, but this distinction does not reflect the different functions of the actors in the model. What matters is the distinction between ‘internal’ agents that only process waste, and ‘external’ agents that also produce waste, buy recycled products, provide production factors, etc.. Many agents, such as households, are both internal and external, since they dispose of waste and offer labour for the processing, but they are also capable of separating their waste at the source. For convenience, we will denote the group of ‘external actors’ by $i \in \mathbf{I}=\{1,\ldots,I\}$, $\mathbf{I} \subseteq \mathbf{J}$, and explicitly state that the model also includes the waste processing of these external actors, e.g., treating the processing by households on equal footing with processing by others. In other words, external actors also account for part of the processing.

Goods are grouped as ‘factors and intermediate inputs’ and ‘waste-goods’. Factors and intermediate inputs are a necessary input for the processing, eg., labour, capital, petrol, vehicles, and other inputs from other industries. These are denoted by $k \in \mathbf{K}=\{1,\dots,K\}$. The supply of production factors and intermediate inputs used in the process such as labour and capital is external to the model.

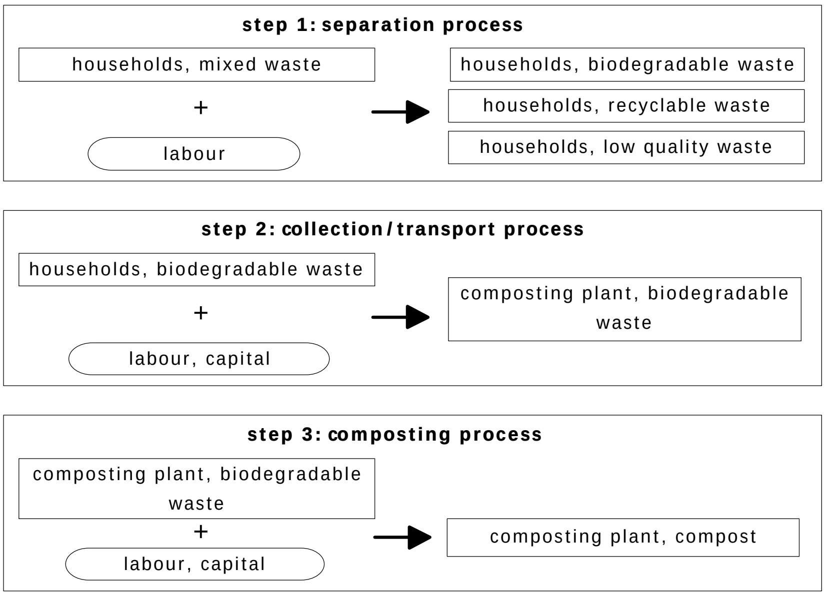
Waste-goods consist of biodegradable waste, disposed waste, recycled products, etc.. Let there be H waste-goods, $h \in \mathbf{H}=\{1,\dots,H\}$. The first version of the model contains only a brief list of waste types. The model does not specify the material types such as paper, glass, plastics. This is a major shortcoming of the model should be improved. Nonetheless, the model explicitly recognises that the same waste-good will have a different price at different stages of its processing. A full characterisation of a waste-good therefore includes its point within the chain of transaction between original generation and final disposal. This is captured by including the actor that processes the waste-good, so that the characterisation consists of a pair: the waste-good type and the actor. In this way, the model can distinguish between mixed waste before collection, say the pair (‘mixed waste’, ‘households’), and after collection, say (‘mixed waste’, ‘small enterprises’). In formal notation, the waste-good characterisation is denoted by $(j,h) \in \mathbf{J} \times \mathbf{H}$. We will sometimes use an apostrophe ' for the actor, j', to refer to the waste-good pair.

Using the term ‘waste-good’, another issue emerges: whether the ‘good’ is valuable, that is, has a positive price, or is a ‘bad’, that is a negative price. The sign of the price is not determined in advance. If composting becomes a profitable venture, then biodegradable waste may become a valuable good. On the other hand, if there is a processing capacity constraint, then this will decrease the price of biodegradable waste, and probably even make it negative. We thus choose to use the term ‘waste-good’ without interpreting it as a valuable or non-valuable good.

In addition to processing and supplying waste-goods, the internal actors also generate emissions or other causes of environmental impacts. These may include damage to human health, global warming or eco-toxicity. The environmental dimension of the model is explained in more detail later.

In Figure 2, we give a simple specification of a composting process in which the waste-goods are represented by pairs.

Figure 2 Representation of a chain of processes



The first step in the composting process is household separation of mixed waste flow. This process requires some labour input, and generates three categories of waste: biodegradable, recyclable and low quality waste. The second step involves the collection and the transportation of the waste. In addition to labour, capital is used in the form of a truck and intermediate inputs are required in the form of fuel. The quality stays the same, but the biodegradable waste is now with a different actor, and it may have a different price. Finally, the biodegradable waste will be composted in the plant using the factors labour and capital. The final product of this sequence of activities is compost which can be sold to consumers (external actors).

To complete the general description of the model, we introduce in the sequel the impact of scarcity in demand and factor supply, the integration of environment, actors, the physical constraints formulated as commodity balances, and finally the costs minimisation program.

Demand and scarcity

Let $d_i^{j',h}$, $(i,j',h)\in\mathbf{I}\times\mathbf{J}\times\mathbf{H}$, denote demand of waste-good (j',h) by actor i, e.g. demand for recycled products. As regards the supply of waste, the vector $d_i^{j',h}$ has negative sign and represents the waste generation at the source. The model includes household separation as a process, and if, say, the price paid by IWBs increases, this might induce households to undertake enhanced separation of their mixed waste to extract more metals, glass, etc.. However, this does not affect the vector $d_i^{j',h}$ which represents the source of mixed waste. We reiterate that separation by households is explicitly included in the model as a potential activity. Other waste-goods are demanded but substitutable with economic commodities from other sectors, e.g., recycled plastics which can be substituted by primary plastics. Thus, the supply of these goods is of a variable nature. In our framework, this is represented by lower and upper bounds.

$$\underline{d}_i^{j',h} \leq d_i^{j',h} \leq \overline{d}_i^{j',h} \qquad 1$$

Demand is aggregated over external actors (consumers), and denoted by a tilde.

$$\tilde{d}^{j',h} = \sum_{i \in \mathbf{I}} d_i^{j',h} \qquad 2$$

In the model, 'external' prices, 'constraint' margins and 'internal' prices are represented. The internal prices, denoted by $q^{j',h}$, $(j',h) \in \mathbf{J} \times \mathbf{H}$, are the most important, since they reflect the value of the waste-goods for the actors in the waste sector. The 'external' prices, denoted by $p^{j',h}$, $(j',h) \in \mathbf{J} \times \mathbf{H}$, describe the value of goods to external actors outside the waste sector, such as the value of recycled paper for printers. These prices are derived from market information and are fed into the model as exogenous values. We may say that the external price reflects the value of the waste-goods at the boundary of the waste-sector. However, this may cause confusion. The model does not exclude the possibility that observed prices for waste-goods within the waste-sector, say the price of bottles before recycling, enter the model via the parameter p. If the model is well calibrated, internal and external prices coincide, at least at the 'boundary' of the waste sector. However, it is possible that certain data are not available, that data are inconsistent, or that different scenarios are run for which the original prices do not satisfy. In these cases, a 'constraint margin' arises, denoted by $s^{j',h}$, $(j',h) \in \mathbf{J} \times \mathbf{H}$, which describes the added value of goods for internal actors within the waste sector taking into account its scarcity. These 'constraint' margins are calculated within the model as shadow prices for the constraint that demand for waste management services has to be met by the waste management sector, and that the supply of intermediate waste-goods has to match its demand. Prices satisfy:

$$q^{j',h} = p^{j',h} + s^{j',h} \qquad 3$$

Factor and intermediate inputs supply and scarcity

External actors also supply the internal actors with required production factors and intermediate inputs, denoted by ω_i^k, $(i,k) \in \mathbf{I} \times \mathbf{K}$. Aggregated supply of production factors is defined by analogy to demand.

$$\tilde{\omega}^k = \sum_{i \in \mathbf{I}} \omega_i^k \qquad 4$$

As for goods, actors demand a price p^k, $k \in \mathbf{K}$ for the use of their endowments. This can be seen as the 'external' price of endowments. Also, there is an 'constraint' margin for endowments that reflects its scarcity as a result of bounded supply, denoted by μ^k, $k \in \mathbf{K}$. Similar to the goods, the external prices and the constraint margins are combined, giving the 'internal' price λ^k, $k \in \mathbf{K}$, for which production is optimised:

$$\lambda^k = p^k + \mu^k \qquad 5$$

We reiterate that, if the model is well calibrated, the constraint margins μ^k are zero in the reference scenario.

Environment and scarcity

Waste processing does not only require factors and intermediate inputs, but also the use of environmental resources. In principle, these enter the model in the same way as factor use. For land on which plants are build, this is an obvious handling of its use, but it can usefully be extended for other environmental externalities. For example, we may say that incineration uses a certain amount of the absorption capacity of the atmosphere. For this purpose, we specify environmental goods such as 'GHG emission units', that enter the processes similar to production factors. Landfilling also requires land (sites), that can be said to be supplied by the government. It is assumed that the public sector is endowed with the initial emission permits, that is, revenues from emission taxes flow to the government. In this version of the model we specify three environmental goods: global warming impact, human toxicity impact and land use. Although this list is far from complete, we consider this a relatively sound first attempt to represent the environmental impact of waste related processes.

Prices for the environment are difficult to derive, especially when we consider the social price of using the environment, eg., for disposal of solid waste, fluid and gaseous emissions. In this project we will use two ways of valuing the environment. In the monetary approach, fixed values on a per unit basis for the various categories of environmental impacts will be derived from existing literature. In the physical approach, the shadow prices for the environment impacts will be based on the upper levels of acceptable environmental pollution for a specific geographic system.

In the first approach, the method of economic valuation (EVA) of the externalities is applied (Beukering *et al.* 1998). In EVA the importance of environmental quality (like that of any other scarce good) is determined by individual preferences and expressed in monetary units. These environmental prices will be entered in the model as exogenous values. A more elaborate explanation is provided in the Appendix.

The EVA method enables the direct translation of emissions and environmental effects into costs. For example, the development of a landfill site may cause a temporary or even permanent reduction in the real-estate prices in the neighbouring area. This negative value can be used as an indicator of the inconvenience of visual, odour and health effects. The advantage of the EVA approach is that it enables the combination of the derived external values with internal "financial" costs. Thereby a full cost-benefit analysis can be performed. Also, economic valuation, albeit conducted under strong assumptions, bypasses the problem of determining sustainable levels of emissions.

Although, the EVA approach has the advantage of not having to set upper limits of environmental pollution, the limited availability of monetary values for these impacts in developing countries can certainly be considered a disadvantage. Therefore, the physical approach is also applied in this model. In this approach the values will be derived in the model itself, based on the scarcity of the environmental resource. Formally, the scarcity level of the resource is based on the potential damage which an emission may cause. Usually, standards of the World Health Organisation (WHO) are applied in analyses. Yet, since the units in which these values are provided are not compatible with the model, the values are derived in an artificial manner. First, the emission levels are determined based on the current situation.

These levels are used as a reference scenario. Now, it is possible to reduce the emission levels, that is, to constrain the available endowments of emission units, which will cause a positive constraint margin, and thus the ‘internal’ costs of the environment, will increase.

Applying both approaches and evaluating differences in the outcomes, will improve our understanding of the impact of the choice of these methods. Moreover, researchers and policy makers who are sceptical of one particular approach will be served by the other.

Internal actors and activity levels

On the production side, $y_j^{j',h}$, $(j,j',h)\in \mathbf{J}\times\mathbf{J}\times\mathbf{H}$, denotes supply of good (j',h) by internal actor j. Note that external actors can also be part of the production process, e.g., in the case of waste separation by households, such that the set of external actors is considered a subset of the set of internal actors. Production is distinguished in different processes, $m\in\mathbf{M}$. As for the goods, it is the pair of a internal actor and a process together that specifies the activity. For example, (j,m) = (’final waste management’, ‘dumping site’) refers to dumping whereas (j,m) = (’final waste management’, ‘incineration’) refers to the incineration process. Every internal actor-process pair has fixed input/output ratios for goods and factors, denoted by $\bar{y}_{j,m}^{j',h}$ and $\bar{r}_{j,m}^{k}$ respectively (where the subscripts denote the process, and the superscripts denote the goods/factors), implying that only the activity level, say the total throughput of an activity, is variable, denoted by $x_{j,m}$, $(j,m)\in\mathbf{J}\times\mathbf{M}$. Therefore, production of goods is equal to the activity level times the fixed production vector $x_{j,m}\,\bar{y}_{j,m}^{j',h}$, $(j,m,j',h)\in\mathbf{J}\times\mathbf{M}\times\mathbf{J}\times\mathbf{H}$, whereas factor, intermediate inputs, and environmental resource use is equal to the activity level times the fixed resource vector $x_{j,m}\,\bar{r}_{j,m}^{k}$, $(j,m,k)\in\mathbf{J}\times\mathbf{M}\times\mathbf{K}$. A simplified example of this linear relation is given in Table 4.

Table 4 Simplified example of a production vector

	separation	separation
Activity level	1	20
inputs		
mixed waste	1 ton	20 tons
labour	5 man hours	100 man hours
outputs		
biodegradable waste	0.25 ton	5 tons
recyclable waste	0.25 ton	5 tons
low quality waste	0.5 ton	10 tons

Production is aggregated over all processes within every internal actor:

$$y_j^{j',h} = \sum_{m\in\mathbf{M}} x_{j,m}\,\bar{y}_{j,m}^{j',h} \tag{6}$$

The same can be written for factors, intermediate inputs, and environmental resources.

$$r_j^k = \sum_{m \in \mathbf{M}} x_{j,m} \, \bar{\mathrm{r}}_{j,m}^k \qquad 7$$

As for demand, production and factor, intermediate inputs, and environmental resource use is aggregated, and denoted by a tilde.

$$\tilde{y}^{j',h} = \sum_{j \in \mathbf{J}} y_j^{j',h} \qquad 8$$

and

$$\tilde{r}^k = \sum_{j \in \mathbf{J}} r_j^k \qquad 9$$

Good balances and cost minimisation program

There are two commodity balances to hold. First, production should match demand.

$$\tilde{d}^{j',h} = \tilde{y}^{j',h} \qquad 10$$

and second, factor use, intermediate inputs, and resource use cannot exceed their supply.

$$\tilde{r}^k \le \tilde{\omega}^k \qquad 11$$

Taking all equations together, we derive the following cost minimisation program.

PROGRAM 1. *Cost minimisation*

$$min \, \mathrm{c} = \sum_{k \in \mathbf{K}} \mathrm{p}^k \, \tilde{r}^k - \sum_{h \in \mathbf{H}} \sum_{j' \in \mathbf{J}} \tilde{\mathrm{p}}^{j',h} \, \tilde{y}^{j',h}$$

$$x_{j,m} \ge 0, \; y_j^{j',h}, \; \tilde{y}^{j',h}, \; r_j^k \ge 0, \; \tilde{r}^k \ge 0, \; \underline{d}_i^{j',h} \le d_i^{j',h} \le \bar{d}_i^{j',h}, \; \tilde{d}^{j',h}, \; \tilde{\omega}^k$$

subject to the good balances

$$\tilde{d}^{j',h} = \tilde{y}^{j',h} \qquad (s^{j',h})$$

$$\tilde{r}^k \le \tilde{\omega}^k \qquad (\mu^k)$$

and given the production equivalencies

$$y_j^{j',h} = \sum_{m \in \mathbf{M}} x_{j,m} \, \bar{\mathrm{y}}_{j,m}^{j',h} \qquad (q_j^{j',h})$$

$$\sum_{m\in\mathbf{M}} x_{j,m}\,\bar{\mathrm{r}}^{k}_{j,m} = r^{k}_{j} \qquad (\lambda^{k}_{j})$$

and given the aggregation equivalencies

$$\sum_{i\in\mathbf{I}} d_i^{j',h} = \tilde{d}^{\,j',h}\;(\hat{s}^{\,j',h})$$

$$\tilde{\omega}^{k} = \sum_{i\in\mathbf{I}} \omega_i^{k} \qquad (\hat{\mu}^{k})$$

$$\tilde{y}^{\,j',h} = \sum_{j\in\mathbf{J}} y_j^{j',h} \qquad (\hat{q}^{\,j',h})$$

$$\sum_{j} r_j^{k} = \tilde{r}^{\,k} \qquad (\hat{\lambda}^{k})$$

The objective of the model is to minimise costs, *c*. Positive prices denote valuable goods, and positive flow variables denote output, so that $\sum_{h\in\mathbf{H}}\sum_{j'\in\mathbf{J}} \tilde{p}^{\,j',h}\tilde{y}^{\,j',h}$ is the value of output, which is subtracted from the costs. Tildes denote variables on an aggregate level. The hat denotes auxiliary shadow-prices.

Despite the single objective function, the model can address multiple objectives, eg. employment or recycling rates. Some of these objectives enter the cost function, while others can be specified as variable constraints. A brief discussion of this issue is given in above (factor and intermediate inputs).

The second line of the program describes all variables and their domain. The lower and upper bounds for the demand (1) are included in this part of the program. Dual variables for the constraints are given in brackets, and they are used to derive and interpret the ‘internal’ prices *q* and λ used for production optimisation. Note that the last aggregation identity, summing factor use, is reverted with no other reason than to ensure a positive dual Lagrange variable. Taking the Lagrange derivatives, we find the Lagrange variables for the aggregation identities to be equal to the associated Lagrange variables for the commodity balances and production identities: $s^{\,j',h} = \hat{s}^{\,j',h}$, $\mu^{k} = \hat{\mu}^{k}$, $q^{\,j',h} = \hat{q}_{j}^{\,j',h}$, and $\lambda^{k} = \hat{\lambda}^{k}_{j}$ for all $j\in\mathbf{J}$. The Lagrange dual variables for the commodity balances can be interpreted as the shadow variables for resource constraints. Taking the Lagrange derivatives for the production variables, we find that production is optimised with respect to the ‘internal’ prices *q* and λ, which satisfy 3 and 5. Because of the linear production structure, at these prices, *q* and λ, firms make neither excess profits nor losses, treating the rents for capital as a cost of a production factor.

$$\left[\sum_{(j',h)\in\mathbf{J}\times\mathbf{H}} q^{\,j',h}\,\bar{\mathrm{y}}^{\,j',h}_{j,m} - \sum_{k\in\mathbf{K}} \lambda^{k}\,\bar{\mathrm{r}}^{k}_{j,m}\right] \le 0 \;\perp\; x_{j,m} \ge 0 \qquad 12$$

The ‘⊥’ symbol denotes that either the left or right constraint is binding. In other words, there are no activities generating profits (if x>0, then the left side is equal to zero), and only activities with no losses are executed (if the left side is strict lower than zero, the right side is binding, x=0). We reiterate, if the ‘constraint’ margins for physical constraints are fully incorporated in the external prices, exogenous prices *p* (for both factors and goods) and internal prices *q* (goods), λ (factors) coincide.

Model Use

In this section we discuss the working of the model and how it addresses other objectives associated with SWM.

A Waste Account Matrix (WAM)

The Waste Account Matrix (WAM) organises commodity flows through the economy so that balances can easily be checked. Moreover, the WAM can be used to provide a clear picture of the different interests in the waste management sector. In this way, it can be a useful tool for interpretation of scenario outcomes. Both a physical and monetary WAM can be defined. Let us start with the physical WAM (Table 5).

Table 5. Physical Waste Account Matrix

	Goods (*j’*,*h*)	Factors, Intermediates, and Resources (*k*)
External actors	$-d_i^{j',h}$	ω_i^k
External and internal actors and processes (*j*,*m*)	$x_{j,m}\,\bar{y}_{j,m}^{j',h}$	$-x_{j,m}\,\bar{r}_{j,m}^{k}$

The physical WAM can be interpreted in various ways. First, columns for goods sum to zero, i.e., demand equals supply:

$$\sum_{i\in\mathbf{I}} d_i^{j',h} = \tilde{d}^{\,j',h} = \tilde{y}^{\,j',h} = \sum_{j\in\mathbf{J}} y_j^{j',h} = \sum_{j\in\mathbf{J}}\sum_{m\in\mathbf{M}} x_{j,m}\,\bar{y}_{j,m}^{j',h} \quad \text{for all } (j',h) \qquad 13$$

Note that the first row gives the demand at the source, whereas the second row includes all processes carried out by households. Second, actors’ endowments of factors, intermediate inputs and environmental resources (second column) might exceed their use by internal actors if the constraint is not binding. We notice that the accounting matrix represents the *ex post* model results, and we may scale endowments such that supply matches demand. Of course, this would not be possible for the *ex ante* accounting matrix, but then, the activity values $x_{j,m}$ are unknown as well.

It is possible to include a material balance which secures the physical consistency of the material flows (what goes in, must come out somewhere). To detect leakages which do not belong to the main material flows such as recyclable or disposable waste, an auxiliary ‘waste-good’, for example labelled ‘mass gone’, measuring mass leaving the waste sector, is used. An obvious destination of this disappearing mass is for example environmental sinks. The auxiliary waste-good will ensure that rows sum to zero over the set of goods:

$$\sum_{j'\in\mathbf{J}}\sum_{h\in\mathbf{H}} x_{j,m}\,\bar{y}_{j,m}^{j',h} = 0 \quad \text{for all } (j,m) \qquad 14$$

This is a useful consistency check.

The monetary WAM can easily be derived from the physical WAM by multiplying the variables with the associated internal prices (Table 6).

Table 6 Monetary Waste Account Matrix

	Goods (*j'*,*h*)	Factors, Intermediates, and Resources (*k*)
External actors	$-q^{j'h}\ d_i^{j',h}$	$\lambda^k\ \omega_i^k$
External and internal actors and processes (*j*,*m*)	$q^{j'h}\,(x_{j,m}\ \bar{y}_{j,m}^{j',h})$	$-\lambda^k\,(x_{j,m}\ \bar{r}_{j,m}^{k})$

Again, columns sum to zero. However, as shown in equation 12, there are no excess profits so that rows sum to the net value of demand and factor supply, that is to net revenues from waste management by external actors.

Integrating social optimum and decentralised equilibrium

The model minimises the aggregate costs. However, from competitive equilibrium theory, we know that optimisation at the individual level, which is referred to as the equilibrium allocation, is compatible with optimisation at the aggregate level, which is referred to as the optimal allocation. More precisely, if all externalities (eg the environment) are reflected in prices, and if all individual agents are subject to these prices, and if we abstract from distortions caused eg by taxes, then cost minimisation at the aggregate level is equivalent to cost minimisation at the individual level.

Of course, one of the reasons for the use of an assessment model is the divergence between market prices which individuals confront, and social costs at the aggregate level. To take account of this divergence, we may think of two scenarios. The first uses the market prices, and thereby the cost minimisation program will find the market equilibrium which is not the social optimum. As an alternative scenario, we may reflect social costs in external prices of the model, and thereby the model calculates the social optimum. The activities of the individual agents will not be optimal from their point of view if market prices differ from marginal social costs. If one does not succeed in decentralising the optimum through prices, then one may search for alternative policy scenarios that bring the optimum as close to the equilibrium as possible.

Serving multiple objectives

The model described here seems to have a single objective - minimising overall costs. This may invite criticism as solid waste management is intended to meet several objectives. That is the reason why so many analysis in the waste sector apply multi-criteria analysis (Powell 1992, Chung and Poon 1996). However, we argue that many of the differences between single-objective and multiple-objective models are artificial. We restrict ourselves to multiple-objective models that aim to provide a complete ordering or ranking of a set of alternative allocations (ie, all mutual pairs of allocations can be compared on their quality). In this setting, multi-objectives typically reduce to summed weighted objectives, in which the ordering is determined by relative weights and side-constraints. To show that the distinction between single-objective and multiple-objective models is artificial, we give several examples of multiple-objectives that can be incorporated straightforwardly in the single-objective model specified above.

We distinguish two types of objectives, the first being described as a constraint (examples 1-3), the second type being described as a maximisation or minimisation of some goal variable (example 4,5). At the end of this section, we briefly discuss consistency of multi-objectives.

EXAMPLE 1. The institutional objective is to collect at least 70 per cent of generated waste of say 100 tons. This objective can easily be translated in terms of the model, using the lower and upper bounds for the demand variables appropriately. Set the lower bound to -100 tons, and the upper bound to -70 tons (negative signs because the supply of waste is treated as negative demand). Now, the model demands a solution with a collection rate of at least 70 per cent. Thus, a constraint is used to meet the institutional objective, while at the same time the overall objective (minimising costs) is met.

EXAMPLE 2. The objective is to protect the environment and thus incinerate not more than 100 tons of waste. This objective is met by defining an auxiliary factor, describing the emissions of burned waste. The burning process uses this factor. In other words, these potential emissions are in demand (by the incinerator) and in supply (by the exposed public). In this case, the objective for proper environmental management is met limiting the supply by the public agent of a quantity of the factor sufficient for incineration to not more than 100 tons. Again, multiple objectives are met by setting a constraint. The constraint margin can also be understood as the required tax level to meet the objective.

EXAMPLE 3. The objective is to use at least 80 per cent of capacity of an existing composting plant. This objective presumes a specific time perspective in the model. Usually, the model is used either as a static device, where costs of physical capital are reduced to its depreciation, or as a dynamic device, where building time for plants is an explicit constraint. For convenience, we restrict the analysis here to the static case. Let us assume that the model calculates a (static) optimum in which the plant is not required; this means that it is optimal not to build the plant. However, the plant is built, and it is a waste not to use it. One circumvents this difficulty by taking the opportunity costs for not using the plant into the model as follows. In case the plant has already been built, these opportunity costs are represented by the variable costs of the composting plant. In the case where a decision has to be made to built the plant or not, the opportunity costs are represented by the productivity of the capital in another type of project. We give a numerical example to clarify.

Let us assume the building of the plant costs a million rupees, and its lifetime is 10 years, resulting in a depreciation of 100,000 (1 lakh) rupees a year. Moreover, assume the variable costs of the plant amount to 50,000 rupees a year. If the plant is not profitable at the costs of 150,000 rupees a year, it should not have been built. However, given the plant is built, its opportunity costs are 50,000 rupees, so that this number is entered in the model. We now define an auxiliary factor that represents the plant, with limited supply (endowment) of unity. If the constraint margin of this factor is less then the depreciation costs of the plant, the conclusion from the model would be the plant should not be rebuilt after it has fully been depreciated. If the constraint margin is equal to or exceeds the depreciation costs, then the plant is profitable.

It is possible that the plant is essential, for example for processing biodegradable waste. However, in that case, the model would reveal its profitability, if necessary by (internal) shadow prices if not by market prices. It is also possible that policy has other reasons to promote a composting plant. In that case, there seems to be no other solution than an explicit subsidy on the use of the plant.
EXAMPLE 4. The objective is to maximise employment in the informal sector or to support other income policies in order to reduce income inequity. Such a policy can be restated as the presumption that the actual costs of labour are below market labour earnings (one could use the term wages also for the informal market, although there are no formal wages in this market segment), even if earnings are just sufficient to reach a subsistence level. If there is no alternative employment for the informal employees, the actual costs of labour might be very low. In other words, if for example, waste pickers are unable to find alternative livelihood as a street vendor or in the construction industry, they will continue to recover waste, even if the compensation is below minimum wages.

Thus maximising employment, can be incorporated in the model if one runs the model with zero prices for labour endowments. To prevent an unrealistic solution in which the only factor use is labour and total factors costs are zero, the processing activities have to be specified carefully to make sure that other production factors are essential as well. However, the implementation of the optimal solution found by the model requires a subsidy on labour that would not be realistic. An alternative is to stimulate labour use by taxing other factor use, a ‘second best’ solution because it causes distortions in the economy. One should be careful with such an exercise, as the distortion increases the costs of the waste management and might disable the fulfilment of other objectives.

EXAMPLE 5. The objective is to maximise recycling. Usually, promoting recycling is a derivative of some other objective, e.g., decreasing dumps and incineration, and decreasing imports of raw materials. Preferably, the original objective itself should be treated by the model, leading to increased recycling for the optimal allocation. If one attempts to decrease dumping and incineration, one can restrict the supply of land necessary for dumping in the model, and restrict the supply of emission permits (see other example above). The optimal allocation calculated by the model will ‘automatically’ increase the recycling rate.

To summarise, objectives formulated as constraints can relatively easily be incorporated in the model. Objectives stated in terms of maximising or minimising some goal variables are more difficult to include, though it is in general not impossible.

Simulation

After calibration, the model can be used for several simulation exercises. Similar to the discussion of multi-objectives analysis, examples are used to present the general principles.

EXAMPLE 1. Analysing profitability of new waste management activities. The pilot projects, executed by the UWEP will reveal waste management options for improving the present situation. These new activities can be translated into processes, demanding factors and goods, delivering other goods. Formally, the activity is converted into a process characterised by the vectors $\bar{y}_{j,m}^{j',h}$ and $\bar{r}_{j,m}^{k}$. If such a new process is profitable, i.e., if $\sum\limits_{(j',h)\in\mathbf{J}\times\mathbf{H}} q^{j',h}\,\bar{y}_{j,m}^{j',h} - \sum\limits_{k\in\mathbf{K}} \lambda^{k}\,\bar{r}_{j,m}^{k} > 0$, the process can be included in the model, and the model is rerun. After the model has calculated the new optimum, we have both the maximal scale and overall benefit of the new activity, and its effects on other waste management processes. For example, the process of a community based recovery may be incorporated in the model. It is likely that this process will substitute other processes, such as disposal of mixed waste, and therefore reduce the availability of recyclables for waste pickers. On the other hand, the overall quantity of recyclable materials will reduce because the separation will take place at an earlier stage. In this example, a trade-off between environmental and social objectives will emerge.

EXAMPLE 2. Analysis of ‘growth scenarios’ in which the capacity of the waste management sector to deal with population growth and economic growth is demonstrated. Such a scenario is consistently worked out in terms of changes in supply and demand, as well as prices for factors and goods. The calculations need to make a thorough analysis of expected by-effects of economic growth. For example, if one assumes economic development to provide opportunities in the formal economy for waste-pickers, their reference (or opportunity) wage will increase. Economic growth can lead to both increased and decreased demand for recycled products, depending on the assumptions regarding the composition of economic growth. For the development of a consistent scenario, one would need a model of its own to consistently represent the set of assumptions and its consequences on the variables that are external to the waste processing sector. The scenarios can then be fed into the waste model, which will indicate, through ‘constraint’ margins, which segments in the waste sector will be most attractive to expand in order to find a effective solution for the increasing burden of waste.

EXAMPLE 3. Analysing possibilities and consequences of environmental policy. This example has already been touched in the section on multi-objectives. One can formulated auxiliary variables representing the used ‘resource’ if degrading the environment. Environmental policy is then implemented by limiting the supply of the resource. In line with the previous example, one can make assumption about the development of societal preferences in the case of income growth. Since the demand for a cleaner environment is most likely to become stronger with economic growth, the ‘constraint’ margin and thus the internal price for the environmental resources, will also increase. We notice that the model developed in this paper can only calculate consequences of using different environmental objectives. It provides no guide as to which environmental constraints should be met.

Calibration

Hidden costs

Before we can use the model, we need to calibrate it to a benchmark data set that represents the actual situation in the city. In this section, we turn our attention to some practical problems that may arise. These problems may require specific adjustments of the model. As part of the calibration process, two problems appear. First, the cost minimisation program can reveal that the benchmark data set are sub-optimal. Second, it is possible that there exists a set of solutions that has the same total costs. The latter implies that the cost minimisation programme can return any solution out of this set, producing a kind of indeterminacy. This section addresses the first problem.

The general procedure for calibration is as follows. One initialises the model with an estimate of demand, endowments use and supply, and waste management processes. Using the physical WAM, one checks whether the allocation is feasible. Secondly, one adds a first estimate of prices for goods that are produced by the WMS and factors that are used. Now, if these data are put in the model, it can be run, and in most cases, the program will show that there exists an alternative solution with lower costs. This is the first problem we address.

We proceed as follows. One uses the benchmark activities of the processes as an upper bound for their level and runs the model. This constraint prevents the model from increasing processes that seem more profitable given the data input. In terms of the model, this amounts to adding an auxiliary constraint to the cost minimisation programme:

$$x_{j,m} \le \bar{x}_{j,m}. \quad (\eta_{j,m}) \qquad 15$$

which implies that 12 changes into:

$$\sum_{(j',h)\in \mathbf{J}\times\mathbf{H}} q^{j',h}\, \bar{\mathrm{y}}^{j',h}_{j,m} - \sum_{k\in \mathbf{K}} \lambda^k\, \bar{\mathrm{r}}^k_{j,m} - \eta_{j,m} \le 0 \;\perp\; x_{j,m} \ge 0. \qquad 16$$

It is possible that the data specified some superfluous processes so that the associated activity levels are below their benchmark level. Otherwise, as there is no substitution possible because of the constraint, all activities will have their benchmark level and equation 16 suggests the following calibration procedure.

The ‘constraint’ margin $\eta_{j,m}$ may be understood as representing the hidden costs for the activity, that is, these are the costs that have to be added to the resource use costs, $\sum_{k\in \mathbf{K}} \lambda^k\, \bar{\mathrm{r}}^k_{j,m}$, to ensure non-profitability of the process. Recall that all processes are, in the formal sense of the analysis, non-profitable, that is, their value added to the goods is equal to the costs of factor use. In standard economic terms, we would say that there are no surplus profits.

In terms of the model, the hidden costs can also be considered an auxiliary production factor of quantity $\eta_{j,m}$ and price unity. Thus, we add

$$\bar{\mathrm{r}}_{j,m}^{'hidden\ \mathrm{cos}ts'} = \eta_{j,m}. \qquad 17$$

and set the price to unity:

$$p^{'hidden\ \mathrm{cos}ts'} = 1. \qquad 18$$

which ensures that 12 for the programme in which the hidden costs are included as resource use coincides with 16 for the programme with the activity constraint. Thus, after including the hidden costs, the benchmark allocation is a solution of the initial programme.

One has to bear in mind that hidden costs may represent types of costs that have not been captured by the model (the usual meaning of hidden costs, often referring to opportunity costs), but they can also point to inadequacies in the benchmark data.

Capacity constraints

Although the inclusion of hidden costs ensures that the benchmark data set minimises total costs, it does not ensure that the programme returns the benchmark allocation, since there may be a set of optimal solutions. To prevent this from happening, that is, to ensure the selection of the benchmark, we add soft capacity constraints in the programme. More precisely, we assume that for every process, extra costs are added to the resource use costs if the activity level exceeds the benchmark level. Say, the additional costs amount to α of the marginal resource use costs. This amounts to adding

$$x_{j,m} \le \bar{x}_{j,m} + \hat{x}_{j,m}. \qquad 19$$

to the programme and replacing 7 by:

$$r_j^k = \sum_{m\in\mathbf{M}} (x_{j,m} + \alpha\hat{x}_{j,m})\bar{\mathrm{r}}_{j,m}^k \qquad 20$$

where α is the relative cost increase if the activity increases above the benchmark level. It can now easily be seen that substitution between processes that were cost-neutral in the initial programme, will increase costs in the adjusted program, since a decrease of the activity level will not decrease the average costs, but an increase above the benchmark level for another process will indeed increase the average costs.

Taking the Lagrange derivative for *x*, 12 becomes:

$$\sum_{(j',h)\in\mathbf{J}\times\mathbf{H}} q^{j',h}\,\bar{\mathrm{y}}_{j,m}^{j',h} - (1+\alpha\eta_{j,m}) \sum_{k\in\mathbf{K}} \lambda^k\,\bar{\mathrm{r}}_{j,m}^k \le 0 \ \perp\ x_{j,m} \ge 0. \qquad 21$$

where $\eta_{j,m}$=1 in case that $x_{j,m} > \bar{x}_{j,m}$. That is, marginal factor costs increase if the activity level exceeds the benchmark level.

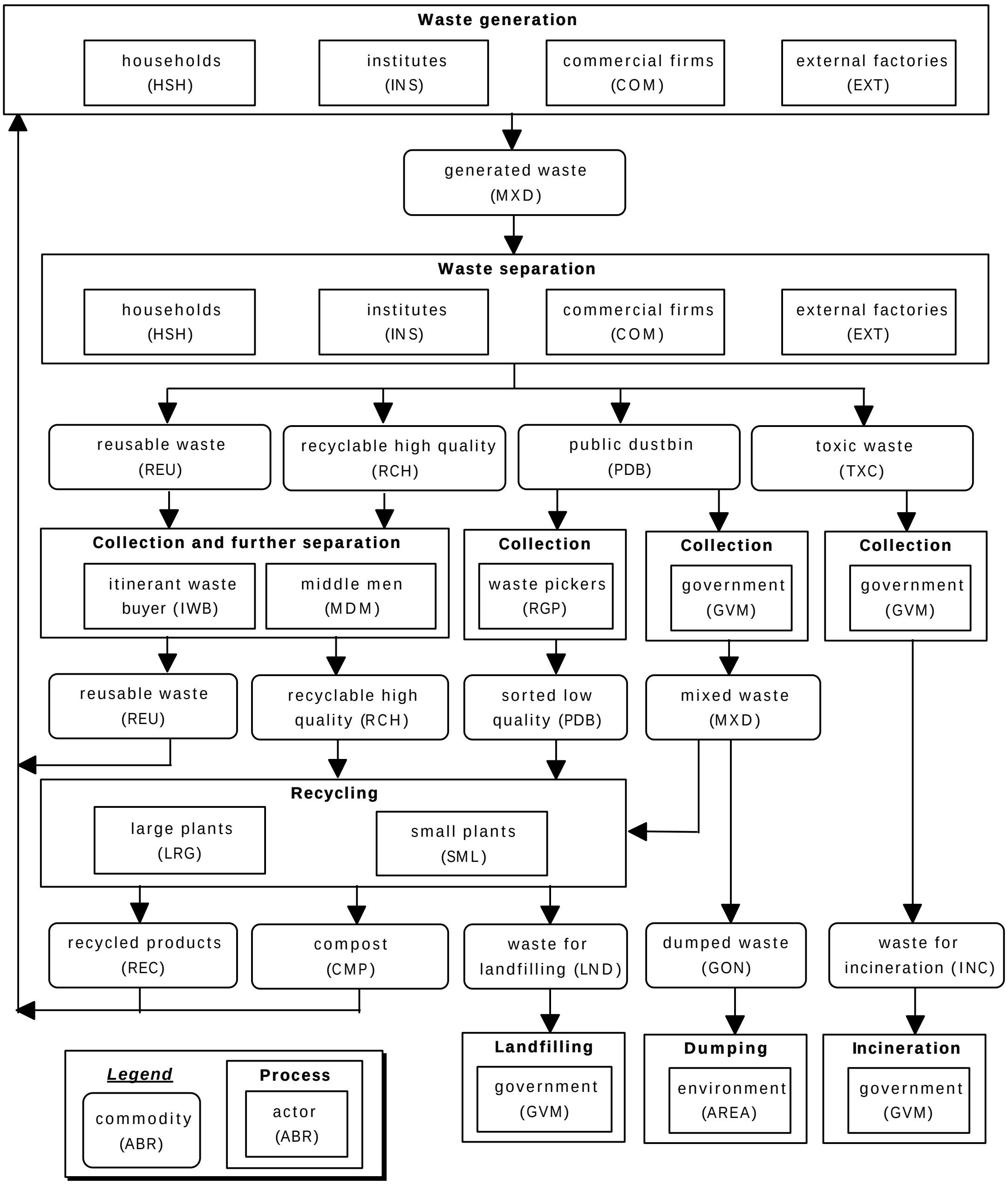
For example, assume we reach a benchmark situation in which 100 tons are incinerated at an initial price of 100 rupees per ton and the remaining 50 tons are landfilled at an initial price of 200 rupees per ton. The total costs of the benchmark situation is 20,000 rupees. We now consider the actual benchmark levels as soft constraints. Assume that the processing costs are the same for both alternatives. Yet, given the soft constraint, the costs of incineration will increase if the amount of waste incinerated increases, and as a result, thereby limiting the substitution between landfilling and incineration.

A Preliminary Application to Bangalore

Model Specification for Bangalore

In this section, the model structure described in preceding section is applied to the daily situation in Bangalore. Similar to the structure of the model, the subdivision of agents, commodities and processes, are identified for the city. These main parameters for the Bangalore city are represented in the flow diagram in Figure 3.

Figure 3. Flow diagram of the model of the waste sector in Bangalore



We notice that the figure does not contain all processes and relations, as this would increase the complexity. For example, waste pickers also supply middlemen with low quality sorted waste.

In operating the model, various simplifying assumptions have to be made:

i. It is assumed that all generated waste is processed.

ii. Although in the original situation, demand and supply of recycled and composted products may divert, price corrections will ultimately lead to a match in this market.

iii. Using the term ‘landfilling’ is a slight misnomer since there is no officially functional landfill site at Bangalore. The waste in fact is disposed in low lying areas.

iv. Construction and demolition debris are excluded from the analysis. Although this reduces the overall volume of solid waste, this type of waste is less important in terms of economic and environmental impacts. These materials can generally be used as filling material in, for example, road construction without harmful impacts.

v. Transportation costs are not dealt with exclusively but are included in the ‘intermediate inputs’ that denotes all variable costs.

vi. The interest rate over the value of land is used as a proxy of the cost of land. The idea behind this assumption is that the money which would be generated by selling the land would at least generate the existing interest rate: it is an opportunity cost.

vii. Incineration excludes open burning. It is used in a strict sense to include waste that is formally incinerated at high temperatures in closed incinerators.

viii. A waste to energy option has not been covered exclusively in the model.

ix. Above all the model assumes that all the agents work in a competitive setting with the objective to minimise their individual costs. Each agent’s activity is well defined and there exists no leakage in the system. For example, the waste thrown in the dustbins has to be either picked up by waste pickers or collected by government authorities.

Before demonstrating the results of the model runs, the agents, processes and commodities are specified for the conditions in Bangalore.

Agents

Agents are broadly classified into external and internal actors depending on their activities. Although we are aware that the existence of varying definitions of “formal” and “informal” labour may cause confusion, we do categorise according to this division in order to get a feeling for which categories of actors benefit or suffer from certain policies. However, this categorisation is of secondary importance. The impact on the individual actors is of more relevance, regardless whether they are labelled “formal” or “informal”:

External actors

External actors relate to the waste sector in terms of demand for services. Their prime concern is the provision of services by the waste management sector so that they can dispose of their waste in a sound manner. Yet external actors also have characteristics of internal actors, for example, households also separate their own waste and provide waste buyers with recyclable materials. The following external actors are identified in Bangalore:

Households - demand services from the waste sector in terms of waste collection and disposal but at the same time households are capable of separating their waste and sell it to itinerant or fixed waste buyers. They are considered informal.

Institutions - include governmental and private offices, schools and colleges, hospitals, religious institutions, universities, and recreational establishments (like parks, cinemas, etc.). Although these organisations are formal in their core activity, their waste related activities are considered to be informal. Usually, a care taker separates waste for recycling purposes.

Commercial establishments - include hotels, restaurants, and market places (daily, regular, weekly, etc.). Similar to institutions they belong to the informal segment of the waste sector.

“External” factories - includes all industries which generate waste residues, either recyclable or not, but who do not use waste inputs in their production.

Internal actors

The internal actors are assumed to be pure suppliers of waste services. Their responsibilities lie in processing and finally disposing of the waste generated by the external actors. They can further be classified into two groups: those concerned with sorting and upgrading and providing raw material to industry (waste picker, IWB, middlemen); the other is engaged in the production of goods and is responsible for disposing of waste (eg, small and large enterprises, government).

Waste pickers - include persons picking waste from street bins and dump sites (informal agents).

Itinerant Waste Buyers (IWBs) - include persons who purchase waste from households and commercial establishments (informal agents).

Middlemen - include purchasers of recyclable waste from households, waste pickers, IWBs, etc. These deliver the recyclable waste to recycling factories. They consist of both formal as well as informal agents depending on whether they are subject to taxation or not.

Small recycling enterprises- include small NGOs and CBOs involved in collection and processing of the waste on a small scale. These are generally located near the source of origin of waste (informal agents).

Large recycling enterprises - include medium and large recycling units which use recyclable waste as the main source of their inputs to produce recycled products. Given the fact that the scale of operation is relatively large compared to their suppliers and their formal obligation to pay tax, they are considered formal. This categorisation can be disputed because they often avoid taxation.

Government or Municipal - It has the responsibility to collect and dispose off the waste, left at end, in sound manner (formal agents).

Processes

The various stages involved in waste processing, from generation to disposal, are presented below:

Generation - the process by external and internal actors of creating solid waste of different composition. This autonomous process is determined by income level and type of actor involved. No production factors are applied in this stage.

Separation - the process in which an actor separates recyclable materials from disposable waste. The factor use in this process, especially capital, is rather limited.

Collection - collection of different types of mixed and recyclable waste by various actors from all the classes of external and internal actors. The main factors applied are unskilled labour, fuel and vehicles.

Reuse- Some of the waste is reused at the source itself while the remaining is traded via the collection actors (ie, IWB, middlemen).

Recycling - a process of transforming materials into secondary resources for manufacturing new products or into secondary products directly. Composting is included, although in some disciplines this process is considered a separate category. Although the various processes vary, recycling requires a relatively large input of capital.

Final waste management - if a mixed or separated material can no longer be reprocessed, a final waste management option has to be found. These options include landfilling and incineration. The latter is only used for toxic hospital waste. Dumping is a third category. Although it is not an officially recognised management option, it is widespread in Bangalore.

Commodities

Goods are grouped as ‘factors and intermediate inputs’ and ‘waste-goods’. In the following section these two categories will be specified for the waste sector in Bangalore.

Waste-goods

These include waste related materials such as recyclable and non-recyclable materials, but also contain primary products which can be substituted by recycled products. Also the quality of the goods (low, medium or high) may vary.

Mixed waste - waste which has not been separated or sorted and which is generally of little or no value. It may consist of a mixture of all kinds of recyclable and non-recyclable materials. Organic waste for large scale composting is also included in this category.

Separated waste - recyclable materials which are separated to be sold to IWBs or middlemen. This category may include metals, glass, paper, and plastics. The materials are of a medium or high quality.

Reusable materials - these are materials or goods which do not require reprocessing but may be reused after cleaning. This category includes bottles, newspapers, tyres and magazines.

Public Dustbin waste (PDB) - is the unseparated portion of waste in public dustbins disposed by various actors after separation. It may contain a variety of materials, even recyclable components. The energy value is generally low because of the high moisture content.

Composted waste - after the mixed waste is collected from the public dustbins, part of it is separated and composted in medium or large scale composting plants. A small portion of the compost in Bangalore is produced by community based organisations.

Hazardous and toxic waste - waste which exists in a separated form but is generally also mingled with mixed waste. This category contains aerosols, paints, pesticides, chemical drugs, explosives, etc. Formally the hazardous hospital waste is incinerated.

Dumped waste - consists of mixed waste which is dumped at the road site or other undesignated places, causing various environmental and health problems.

Incinerated waste - combustibles from hospitals. These materials are hazardous. Officially, and as assumed in the model, all hospital waste has to be burned. In reality, however, hospital waste is also disposed and sometimes even recycled.

Landfilled waste - after collection, part of the mixed waste is landfilled although in Bangalore the landfill space is very limited.

‘Gone waste’ - represents the waste that cannot be traced. It is an auxiliary waste-good that is used to check the mass-balances.

Factors, intermediate inputs, and resources

Factors, intermediate inputs, and resources are those valuable inputs that are not produced by the waste management sector. They may include labour, capital, natural resources and inputs from other industries. The following have been identified for the waste management sector in Bangalore.

Formal labour - workers and employees on regular wages, permanent payroll, contractual, etc.

Informal labour - workers employed in the informal sector. This group may be further classified into high paid and low paid labour. The former are supposed to skilled and semiskilled and are in short supply in the given time period whereas no such paucity exists for low paid labour.

Capital - the opportunity costs of the capital spent on machinery, building, equipment, and vehicles. These are reflected in the establishment and depreciation costs.

Intermediary inputs - inputs with a life span of less than one year (ie, broom, fuel). Therefore these goods are fully accounted for in the annual calculation without adding interest costs.

Natural Resources - These include Global Warming Impact (GWI), Human Toxicity Impact (HTI) and the area used for dumping.

Different Policy Options for Effective Waste Management

Several policy changes are introduced by altering key variables in the model. The positive or negative effects on employment, environment, etc. of these changes are recorded. The various policy options chosen for scenario runs are summarised in Table 7. To start with, the reference scenario is explained. It should be noted that the evaluation of the various scenarios presented in the following section, is a first attempt at interpreting the runs. Occasionally, extraordinary outcomes are revealed which may be the result of model or data irregularities which still need to be resolved. Therefore the model runs' value is mainly of a demonstrative nature. We are still too uncertain about the underlying data to consider this as a strong empirical proof.

Table 7. Different Scenarios Considered for the Policy Options

Scenarios	Policy options	Objectives
1	Decrease borrowing rate of interest to 11.5% per annum	To increase the capital availability to waste management sector
2	Reduce the area for landfilling by 30%	To discourage dumping so as to decrease social and environmental hazards
3	Reduce of the sales price of recycled products by 50%	To simulate a fall in the price of recycled products.
4	Reduce environmental ceiling by 20% i.e. to limit the use of environmental factors used for waste management in the model	To decrease environmental impacts.

Reference Scenario

The data on waste generation, actors involved, factors used, capital and labour costs of processes, etc., has been acquired through an elaborate field survey[2] for Bangalore. This represents the existing waste management situation in the city. Within the integrated framework of the model, the initial run is performed and possible options for financially effective waste management are obtained on an annual basis. This produces a list of a combination of factors needed to manage the generated solid waste in Bangalore on the basis

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[2] The results of this survey are summarised in the CREED Working Paper "Integrated Solid Waste Management: a Perspective on Bangalore (India)" by Madhushree Sehker and Pieter van Beukering (1998).

of costs minimisation. These factors include amount of capital (fixed and intermediary), number of labours (formal and informal) used in processing, and the amount of commodities (recycled, reused, dumped waste) produced. The initial cost to process the mixed waste of 1.3 million tonnes is 1.8 billion rupees (see Table 8). The physical account of different categories of commodities and factors is represented by the "Physical Waste Account Matrix (PWAM)" in Table 9 in the Appendix, which shows various combinations of the factors used and commodities produced. The commodities and factors used as input have a negative sign in the model results.

Table 8. Total Net Costs to Waste Management Sector

	REF	SCEN1	SCEN2	SCEN3	SCEN 4
% increase	0	-6	0	66	0
Costs (billion Rs.)	1.8	1.7	1.8	2.9	1.8

SCENARIO 1: REDUCTION IN INTEREST RATE

As mentioned earlier one of the problems of waste management in developing countries is shortage of capital and proper allocation of funds. Municipalities are expected to undertake a range of activities within a limited budget. Likewise, other actors, such as recycling enterprises, are faced with similar difficulties in accessing sufficient capital to operate efficiently (Beukering, 1994). This is partly due to their informal characteristics. As a result they often have to pay very high interest rates. Thus it is presumed that if capital is made available at a lower cost, the capital costs for their activities will decrease.

To illustrate the impact of this policy on the waste sector the scenario is run by decreasing the price of procuring capital to 11 percent. As seen from Table 8, the waste management costs decrease by 6 percent . Nevertheless, there is no significant change in the waste management configuration (see Table 9 in the Appendix). One might expect that due to the reduced price of capital, the capital intensive sectors such as recycling enterprises (in this case) would expand their production activities, as a result of which the quantity of recycled products would also increase. Various explanations can be found for this static response. First, recycling might not be as capital intensive as assumed. Although the direct use of capital for other waste management options (i.e. landfilling) may be less, their downstream activities such as waste collection may require relatively more capital such as trucks and transfer stations. Second, recycling may not be constrained by capital but by other bottlenecks such as the overall availability of high quality recyclable waste. This availability is only indirectly and thus weakly determined by their own operations. It is the separation and recovery processes which determine the availability of high quality recyclable materials. It is known that these are not very sensitive to capital costs. To find out whether other variables are more effective means for increasing recycling, the following scenarios were tested.

SCENARIO 2: REDUCING LANDFILL AREA

Although it is hazardous, waste dumping is standard practice in Bangalore since no penalties exist against it. Effectively this makes "landfill area" practically freely available. This scenario is introduced with the objective of decreasing the environmental and social hazards caused by waste dumping. If the area used for dumping waste is limited, then one might expect that this process will be substituted by others such as recycling, composting, etc.. Such a policy would require substantial control, since it could result instead in an increased level of illegal dumping. Therefore the feasibility of this scenario is doubtful. On the other hand, given increasing land scarcity, it may be useful to use this scenario as an illustration of the possible consequences of a tighter policy that may be needed.

As evident from the results, the production of recycled products and compost increases while that of dumped waste decreases (Table 9 in the Appendix). Increased recycling mainly results from enhanced efforts in composting organic waste and to some extent from recycling other materials as well. In factor use configuration, the amount of intermediate inputs as well as fixed capital goes up. It is interesting to see that employment is created for the informal sector, where labour use now increase by 58%.

As also illustrated by Table 9, the negative impact of global warming is significantly reduced. Dumping has a much larger impact on climate change because dumped waste is often burned in the open in order to reduce its volume. Even when carbon dioxide and methane emissions from composting, and the emissions of fossil fuels used in recycling are taken into account, both composting and recycling avoid more global warming intensive processes such as the production of fertiliser or the primary production of other raw materials. For the same reason, the human toxicity impact of this scenario is reduced. Moreover, the area usage is decreased by 31%. All in all, one can say that by discouraging dumping, one may significantly reduce the negative environmental and social impacts without incurring extra costs. As shown in Table 8, the initial costs are the same as in the reference scenario.

SCENARIO 3: DECREASING THE PRICE OF RECYCLED PRODUCTS

Because recycled materials and products are generally strong substitutes for primary materials and products, the economic feasibility of the recycling sector is partially dependent on general price trends on the Indian and even the global commodity market. Where the prices of primary products fall, the price of secondary products has to adapt and decrease. In general, one may expect that a price reduction in secondary products (recycled goods) will encourage external actors to buy more recycled products. However, this is not the case in this scenario because relative attractiveness compared to primary product remains the same.

To simulate an economic crisis, the price of recycled products was reduced by 50 percent. The results are predictable. The production of recycled products goes down by 8 percent. Only composting increases slightly by 3 percent. This may suggest that the recyclers facing losses will shift to a still profitable sector.[3] The dumped waste however increases as some of the materials that are earlier being recycled are now no longer recovered. As a result, area usage increases by 12 percent, which in turn increases environmental damage. Partly due to the reduced recycling activities, the overall waste management costs increase by 66 percent. Other reasons may be the increase in land use.

SCENARIO 4 : REDUCE "ENVIRONMENTAL CEILING"

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[3] It may be argued that since recycling is often considered the last resort for many underprivileged people, a shift from waste to other more profitable sectors is impossible. This is, however, only true for waste picking. Other activities in the recycling sector should certainly not be considered as "last resort" activities.

As with many industries, the solid waste sector is considered environmentally harmful. Basically all processes in the SWM sector are, to some extent, harmful to the environment, yet within the sector, one waste “route” is less harmful than another. Therefore, it would be useful to see which “route” becomes more popular if the scarcity of the environment is enhanced. This can be done in two ways. First, it is an option to introduce a price for environmental variables. This would restrict its use because at present goods are freely available. This approach has the advantage of producing a monetary indicator for the environment which thus allows for integration with the common financial optimisation. Yet, it is very complex to determine the exact values for environmental goods as these differ largely across space and time. Secondly, environment may be constrained by putting a physical boundary on its use. Hereby, we avoid the tricky exercise of finding a “price” for a complex commodity. In this model we can base these levels by simply taking the environmental usage levels from the reference scenario and reduce its availability by a certain amount.

In this scenario run, we choose to follow the second approach. First, we determined the levels of environmental usage in terms of global warming impacts (GWI), human toxicity impacts (HTI) and the use of scarce urban land (AREA). These levels were fixed as the available stock of environmental goods. Next, the availability of the stock of environmental variables was artificially reduced by 20 percent. The configuration of waste management option indeed changes as one would expect: the most environmental harmful processes such as dumping are substituted by less damaging activities such as composting. It also creates additional demand for informal labour, leading to an overall increase in employment (see Table 9 in the Appendix).

Conclusions

A linear programming model was developed with the prime objective of minimising the overall systems cost and identifying the low cost alternatives for managing waste effectively. The model describes the activities of the waste management sector resulting from the demands in other parts of the economy for the processing of waste and for secondary output. The costs related to these activities are determined by a combination of demand and supply of production factors such as labour and capital. In certain scenarios the supply of emission permits can also be considered a necessary production factor. Such an economically based framework is uncommon in waste modelling, which are generally based on more rigid methodologies such as input-output and transportation modelling.

Although the model developed as a single objective model, it integrates other important social and environmental objectives associated with solid waste management. Without this characteristic the model would be considerably less valuable for policy makers. The waste sector is one in which issues such as employment (i.e. waste pickers, itinerant waste buyers) and environment (i.e. air pollution, scarcity of natural resources), play an important role.

The model is flexible in the sense that it allows for analysis from multiple perspectives. Although the overall costs are minimised at an aggregate level, it is possible, through shadow prices and wages, to evaluate the consequences for various stakeholders in different scenarios. For example, promoting waste separation at the household level generates a higher demand for composting plants but waste pickers would be left with a minor to zero shadow wage and thus discontinue operations.

The generic set up of the model enables the incorporation of a large variety of waste types, number of stakeholders, and processing activities. The possibility to fine-tune the model to a local situation is a strength, but also a weakness. First, it requires an extensive set of data. This is especially difficult in developing countries, were the quality of the data varies significantly. Moreover, some types of data will be very difficult to generate such as information on the environment and on the informal sector. Second, the software which has been used for modelling is comprehensive but relatively user unfriendly at the same time. To operate or modify the model, a basic level of understanding on linear programming and economic principles is required. Therefore, it is unlikely that policy makers may operate this model without the support of economic researchers, or a user support system.

To demonstrate its applicability, the model was applied to the Indian city Bangalore and a range of scenario runs were presented. This empirical exercise not only reveals the model’s strengths such as highlighting important interdependencies in the waste management sector, but also its weaknesses such as its great demand for high quality data. Nevertheless, this model may be considered a valuable first step in evaluating integrated SWM in developing countries.

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Appendix I. Program files

I.1. The main GAMS programme file

```
SETS

 SCENS SCENARIOS
          /'INI'       'Reference initial situation'
           'REF'       'Reference optimal situation'
           'SCEN1' 'policy option 1: decrease landfill space'
           'SCEN2' 'policy option 2: lowering informal labour costs'
           'SCEN3' 'policy option 3: decrease environmental availability'
           'SCEN4' 'Policy option 4: increase environmental costs'
          /

 SCEN(SCENS)    running scenario

 J    AGENTS
          /'HSH'   'HSH'
          ,'INS'   'Govt. & pvt.offices, Schools, Hospitals,etc.'
          ,'COM'   'Commercial est, Hotels, Markets, etc.'
     ,'IWB'   'IWB'
          ,'RGP'   'RGP'
          ,'MDM'   'MDM'
          ,'GVM'   'Municipal'
          ,'SML'   'Small enterprises'
          ,'LRG'   'Large enterprises'
          ,'EXT'   'External Factories'
          ,'DUM'       'Auxiliary agent to fill data gaps'
          /

 HK   COMMODITIES
    /'MXD'     'MXD waste after collection'
          ,'RCH'     'Sorted recycling waste of high quality'
    ,'PDB'     'Sorted recycling waste of low quality'
    ,'TXC'     'Hazarduous waste'
    ,'REL'     'REUSABLE products'
    ,'REC'     'REC products'
          ,'CMP'         'Compost'
    ,'REU'     'REUSED products'
    ,'LND'     'Residuals of dumped waste'
    ,'INR'     'Residuals of burned waste'
    ,'GON'     'Non relevant residuals of burned and dumped waste'
    ,'LBF'     'Formal Labour'
    ,'LBI'     'Informal labour'
          ,'LBL'         'Low paid informal labour'
          ,'CAP'     'CAP, machinery, etc.'
          ,'IMD'         'Intermediate inputs'
          ,'GWI'         'Global Warming Impact'
          ,'HTI'         'Human Toxicity Impact'
          ,'AREA'        'Area Usage'
          ,'APF'         'Auxiliary production factors'
          /

 H(HK) GOODS
    /'MXD','RCH','PDB','REC','CMP','REL','REU','TXC',
          'LND','INR','GON'/

 K(HK) FACTORS
          /'LBF','LBI','LBL','CAP','IMD','GWI','HTI','AREA','APF'/

 M    PROCESSES
    /'COLL'   'Collection of waste'
    ,'SEP'    'Sorting of waste'
    ,'RECY'   'Recycling'
    ,'RE'     'Reuse'
    ,'INC'    'Incineration'
    ,'LAN'    'Landfilling'
          /

 MM   PROCES NUMBERS
    /1*6/

 I(J)  CONSUMERS
```

```
        /'HSH','INS','COM','SML','LRG','GVM','EXT'/

 ALIAS(J,JJ)
 ALIAS(I,II)
;

PARAMETERS
 CHECK1,CHECK2
 ACTIVITY(SCENS,J,M,MM)
 P(K)          prices for resources and production surplus
 PP(JJ,H)      prices for resources and production surplus
 ALPHA                 relative penalty for excess activity level

 MU(SCENS,K)      scarcity rents for factors
 S(SCENS,JJ,H)    demand scarcity rents for goods
 LAMBDA(SCENS,K)     shadow prices for factors
 Q(SCENS,JJ,H)    shadow prices for goods
 PROFITS(SCENS,J,M,MM) potential profits for activity
 XBAR(J,M,MM)              benchmark activity level
 YBAR(J,M,MM,JJ,H)         unit production
 RBAR(J,M,MM,K)            unit factor use
 OMEGA(I,K)       factor availability
 PWAM(SCENS,*,HK)     physical waste account matrix
 WAM(SCENS,*,*)     waste account matrix
 VA(SCENS,*)               value added per agent
 TCOSTS(SCENS,*) total costs

 DUMMY1                    one dimensional auxiliary parameter
;
VARIABLES
 COSTS
 MINCOSTS
 D(I,JJ,H)   demand
 X(J,M,MM)   activity
 Y(J,JJ,H)   net production within firm
 YY(JJ,H)    net production per good
 R(J,K)      net resource use within firm
 RR(K)       net resource use per factor
 XR(J,M,MM)  excess activity level relative to benchmark
;
POSITIVE VARIABLES X,XR;

EQUATIONS
 COSTSINV         costinversion
 COSTSEQ          cost equation
 PRODUCTION(J,JJ,H)   production by firm J of good JJ H
 NETPROD(JJ,H)        net production of good JJ H
 DEMANDEQ(JJ,H)       demand equation for good JJ H
 NETRES(K)         net resource use
 RESEQ(J,K)        resource use per firm
 EXCACTEQ(J,M,MM)          excess activity level equation
 ENDOW(K)          factor endowments equation
;

COSTSINV..
  MINCOSTS
=L= -COSTS;

COSTSEQ..
  COSTS
=G= SUM(K,P(K)*RR(K))
 -  SUM((JJ,H),PP(JJ,H)*YY(JJ,H))
 +  SUM((J,M,MM,K),ALPHA*XR(J,M,MM)*P(K)*RBAR(J,M,MM,K));

PRODUCTION(J,JJ,H)..
  Y(J,JJ,H)
=E= SUM((M,MM),X(J,M,MM)*YBAR(J,M,MM,JJ,H));

NETPROD(JJ,H)..
  YY(JJ,H)
=E= SUM(J,Y(J,JJ,H));

DEMANDEQ(JJ,H)..
  SUM(I,D(I,JJ,H))
=E= YY(JJ,H);
```

```
NETRES(K)..
   SUM(J, R(J,K))
=E= RR(K);

RESEQ(J,K)..
   SUM((M,MM),X(J,M,MM)*RBAR(J,M,MM,K))
  + ALPHA*SUM((M,MM),XR(J,M,MM)*RBAR(J,M,MM,K))
=E= R(J,K);

EXCACTEQ(J,M,MM)..
   X(J,M,MM)
=L= XBAR(J,M,MM)+XR(J,M,MM);

ENDOW(K)..
   RR(K)
=L= SUM(I,OMEGA(I,K));

MODEL IWAM /ALL/;

$INCLUDE 'DATA36.DAT';

D.FX(I,JJ,H)=DFX(I,JJ,H);
D.UP(I,JJ,H)$(DUP(I,JJ,H) NE 0)=DUP(I,JJ,H);
ALPHA=0.;

* check whether data fit if all activities are unity:

* Calibration process

SCEN(SCENS)=NO;
SCEN('INI')=YES;

* first check whether the base solution in DATA2.dat is feasible
X.FX(J,M,MM)=XBAR(J,M,MM);
SOLVE IWAM USING NLP MAXIMIZING MINCOSTS;

* then check whether there are costly unnecessary cycles
X.LO(J,M,MM)=0;
X.UP(J,M,MM)=INF;
XR.UP(J,M,MM)=0.00001*XBAR(J,M,MM);
SOLVE IWAM USING NLP MAXIMIZING MINCOSTS;

* and incorporate the auxiliary 'apf' to account for hidden costs
RBAR(J,M,MM,'APF')=MAX(0,EXCACTEQ.M(J,M,MM));
OMEGA('HSH','APF')=1.001*SUM((J,M,MM),RBAR(J,M,MM,'APF'));
X.M(J,M,MM)=0;
P('APF')=1;
DISPLAY P,RBAR;

SOLVE IWAM USING NLP MAXIMIZING MINCOSTS;
$INCLUDE 'acc33.INC';

* finally, check whether solution does not change if constraints are relaxed
* for the scenario analysis, we demand a 10 per cent increase in factor costs for extra use
* and a 10 per cent decrease of the good price for an increase in output
OMEGA(I,K)=OMEGA(I,K)+0.5*ABS(OMEGA(I,K));
XR.UP(J,M,MM)=100;
ALPHA=0.01;
SOLVE IWAM USING NLP MAXIMIZING MINCOSTS;

* the reference should give the same result as the base model.
SCEN(SCENS)=NO;
SCEN('REF')=YES;
SOLVE IWAM USING NLP MAXIMIZING MINCOSTS;
$INCLUDE 'acc33.INC';

* the first scenario FOR employment by lowering the CAPITAL costs
SCEN(SCENS)=NO;
SCEN('SCEN1')=YES;
P('CAP')=P('CAP')*0.9;
SOLVE IWAM USING NLP MAXIMIZING MINCOSTS;
$INCLUDE 'ACC33.INC';
P('CAP')=P('CAP')/0.9;

* the second alternative consists of a decrease of landfilly by 30 per cent.
SCEN(SCENS)=NO;
```

```
SCEN('SCEN2')=YES;
DUMMY1('OMEGA')=OMEGA('GVM','AREA');
OMEGA('GVM','AREA')=-0.8*PWAM('REF','COLSUM','AREA');
SOLVE IWAM USING NLP MAXIMIZING MINCOSTS;
$INCLUDE 'acc33.INC';
OMEGA('GVM','AREA')=DUMMY1('OMEGA');
DUMMY1('OMEGA')=0;

* the third scenario for by decreasing prices of recycled products 50%
SCEN(SCENS)=NO;
SCEN('SCEN3')=YES;
PP('SML','REC')=PP('SML','REC')*.50;
PP('LRG','REC')=PP('LRG','REC')*.50;
SOLVE IWAM USING NLP MAXIMIZING MINCOSTS;
$INCLUDE 'ACC33.INC';
PP('SML','REC')=PP('SML','REC')/.50;
PP('LRG','REC')=PP('LRG','REC')/.50;

* the fourth scenario for by increasing prices of recycled products 500%
SCEN(SCENS)=NO;
SCEN('SCEN4')=YES;
PP('SML','REC')=PP('SML','REC')*5;
PP('LRG','REC')=PP('LRG','REC')*5;
SOLVE IWAM USING NLP MAXIMIZING MINCOSTS;
$INCLUDE 'ACC33.INC';
PP('SML','REC')=PP('SML','REC')/5;
PP('LRG','REC')=PP('LRG','REC')/5;

$ONTEXT;
* the fourth scenario increases environmental damage by including the costs
SCEN(SCENS)=NO;
SCEN('SCEN4')=YES;
* adjusted, because it seemed too much
P('GWI')=250/1000;
P('HTI')=250/1000;
P('AREA')=1750/1000;
* but this is not to be done by too much increase in capital, or the costs will increase as well
ALPHA('CAP')=0.5;
SOLVE IWAM USING NLP MAXIMIZING MINCOSTS;
$INCLUDE 'acc33.INC';
P('GWI')=0;
P('HTI')=0;
P('AREA')=0;
ALPHA('CAP')=0.1;
$OFFTEXT;

DISPLAY ACTIVITY, PROFITS, PWAM, WAM;
DISPLAY R.L, Y.L, YY.L, RR.L;

CHECK1=SMAX((J,K,SCEN),LAMBDA(SCEN,K)-RESEQ.M(J,K));
CHECK2=SMAX((J,JJ,H,SCEN),Q(SCEN,JJ,H)-PRODUCTION.M(J,JJ,H));
DISPLAY CHECK1,CHECK2;
PARAMETERS DFX,DLO,DUP;
ALIAS (I,AI),(JJ,AJJ),(H,AH),(M,AM),(MM,AMM),(J,AJ);

FILE DATAFILE  /'DATA.OUT'/;
PUT DATAFILE;
DATAFILE.LW = 0;
DATAFILE.ND = 5;
DATAFILE.PW = 255;

DFX(I,JJ,H)=D.L(I,JJ,H)$(D.LO(I,JJ,H) EQ D.UP(I,JJ,H));
DLO(I,JJ,H)=D.LO(I,JJ,H)$(D.LO(I,JJ,H) LT D.UP(I,JJ,H));
DUP(I,JJ,H)=D.UP(I,JJ,H)$(D.LO(I,JJ,H) LT D.UP(I,JJ,H));

PUT / / 'PARAMETER P (K)' / /;
PUT @1 '/';
LOOP(K,
  IF(P(K) GT 0,
    PUT ',',K.TL:>8:0,'=',P(K):7:3;
  );
);

PUT '/'
PUT @1 '/ ';
PUT //;
```

```
PUT / / 'TABLE PP (J,H)' / /;
PUT @20;
LOOP(H,
  IF(SMAX(J,ABS(PP(J,H))) GT 0,
      PUT H.TL:>8:0
    );
);
PUT / /;
LOOP(J$(SMAX(H,ABS(PP(J,H))) GT 0),
  PUT J.TL:8:0,@20;
  LOOP(H$(SMAX(JJ,ABS(PP(JJ,H))) GT 0),
    IF(PP(J,H) NE 0,
      PUT ' ',PP(J,H):7:3;
    ELSE
      PUT ' ':8;
    );
  );
  PUT /;
);

PUT //;

PUT / / 'TABLE DFX (I,JJ,H)' / /;
PUT @20;
LOOP(H,
  LOOP(JJ,
    IF(SMAX(I,ABS(DFX(I,JJ,H))) GT 0,
      PUT JJ.TL:>4:0,'.',H.TL:<3:0
    );
););
PUT / /;
LOOP(I$(SMAX((JJ,H),ABS(DFX(I,JJ,H))) GT 0),
  PUT I.TL:8:0,@20;
  LOOP(H,
    LOOP(JJ,
      IF(SMAX(AI,ABS(DFX(AI,JJ,H))) GT 0,
        IF(DFX(I,JJ,H) NE 0,
          PUT ' ',DFX(I,JJ,H):7:2;
                  ELSE
          PUT ' ':8;
      ););
  ););
  PUT /;
);

PUT //;

PUT / / 'TABLE DUP (I,JJ,H)' / /;
PUT @20;
LOOP(H,
  LOOP(JJ,
    IF(SMAX(I,ABS(DUP(I,JJ,H))) GT 0,
      PUT JJ.TL:>4:0,'.',H.TL:<3:0
    );
););
PUT / /;
LOOP(I$(SMAX((JJ,H),ABS(DUP(I,JJ,H))) GT 0),
  PUT I.TL:8:0,@20;
  LOOP(H,
    LOOP(JJ,
      IF(SMAX(AI,ABS(DUP(AI,JJ,H))) GT 0,
        IF(DUP(I,JJ,H) NE 0,
          PUT ' ',DUP(I,JJ,H):7:2;
                  ELSE
          PUT ' ':8;
      ););
  ););
  PUT /;
);

PUT //;

PUT / / 'TABLE OMEGA (I,K)' / /;
PUT @20;
LOOP(K,
```

```
  IF(SMAX(I,ABS(OMEGA(I,K))) GT 0,
    PUT K.TL:>8:0;
););
PUT / /;
LOOP(I$(SMAX(K,ABS(OMEGA(I,K))) GT 0),
  PUT I.TL:3:0,@20;
  LOOP(K,
    IF(SMAX(AI,ABS(OMEGA(AI,K))) GT 0,
      IF(OMEGA(I,K) NE 0,
        PUT ' ',OMEGA(I,K):7:2;
                  ELSE
        PUT ' ':8;
      ););
  );
  PUT /;
);

PUT //;

PUT / / 'TABLE RBAR (J,M,MM,K)' / /;
PUT @20;
LOOP(K,
  IF(SMAX((AJ,AM,AMM),ABS(RBAR(AJ,AM,AMM,K))) GT 0,
    PUT K.TL:>8:0;
););
PUT / /;
LOOP((J,M,MM)$(SMAX(K,ABS(RBAR(J,M,MM,K))) GT 0),
  PUT J.TL:3:0,'.',M.TL:12:0,'.',MM.TL:2:0,@20;
  LOOP(K,
    IF(SMAX((AJ,AM,AMM),ABS(RBAR(AJ,AM,AMM,K))) GT 0,
      IF(RBAR(J,M,MM,K) NE 0,
        PUT ' ',RBAR(J,M,MM,K):7:2;
                  ELSE
        PUT ' ':8;
    ););
  );
  PUT /;
);

PUT //;

PUT / / 'TABLE YBAR (J,M,MM,JJ,H)' / /;
LOOP(H,
  PUT @20;
  LOOP(JJ,
    IF(SMAX((AJ,AM,AMM),ABS(YBAR(AJ,AM,AMM,JJ,H))) GT 0,
       PUT JJ.TL:>4:0,'.',H.TL:<3:0
  ););
  PUT / /;
  LOOP((J,M,MM)$(SMAX(JJ,ABS(YBAR(J,M,MM,JJ,H))) GT 0),
    PUT J.TL:3:0,'.',M.TL:12:0,'.',MM.TL:2:0,@20;
    LOOP(JJ,
      IF(SMAX((AJ,AM,AMM),ABS(YBAR(AJ,AM,AMM,JJ,H))) GT 0,
        IF(YBAR(J,M,MM,JJ,H) NE 0,
          PUT ' ',YBAR(J,M,MM,JJ,H):7:2;
                  ELSE
          PUT ' ':8;
      ););
    );
    PUT /;
  );
  PUT // @10,'+';
);
PUT @10,' ';

PUT / ';' /;

PUT 'ONTEXT;'/;

PUT / / 'TABLE YBAR (J,M,MM,JJ,H)' / /;
LOOP((J,M,MM),
  IF(SMAX((JJ,H),ABS(YBAR(J,M,MM,JJ,H))) GT 0,
    PUT J.TL:>4:0,'.',M.TL:>3:0,'.'MM.TL:<1:0,'.' @15;
    LOOP((JJ,H),
      IF(ABS(YBAR(J,M,MM,JJ,H)) GT 0,
                  PUT JJ.TL:>4:0,'.',H.TL:<3:0;
```

```
  ););
  PUT / @15;
  LOOP((JJ,H),
   IF(ABS(YBAR(J,M,MM,JJ,H)) GT 0,
    PUT YBAR(J,M,MM,JJ,H):8:2;
   ););
  PUT //;
););

PUT 'OFFTEXT;' /;

PUTCLOSE DATAFILE;

$ONTEXT;
$OFFTEXT;

FILE PWAMFILE /PWAM.OUT/;
PUT PWAMFILE;
PWAMFILE.PC = 6;
PWAMFILE.PW = 255;
PWAMFILE.PS = 130;
PWAMFILE.TW = 20;
PWAMFILE.NW = 15;
PWAMFILE.ND = 2;

PUT 'Date: ', system.date;
PUT 'Input file: ', system.ifile //;
PUT 'COLSUM';
LOOP(HK, PUT HK.TL);
PUT /;
LOOP(SCENS,
 PUT SCENS.TL;
 LOOP(HK, PUT PWAM(SCENS,'COLSUM',HK));
 PUT /;
);

LOOP(SCENS,
 PUT / SCENS.TL / ' ';
 LOOP(HK, PUT HK.TL);
 PUT /;
 LOOP(J,
  PUT J.TL;
  LOOP(HK, PUT PWAM(SCENS,J,HK));
  PUT /;
 );
 PUT 'COLSUM'
 LOOP(HK, PUT PWAM(SCENS,'COLSUM',HK));
 PUT /;
);
PUTCLOSE PWAMFILE;

DISPLAY TCOSTS;

FILE WAMFILE /WAM.OUT/;
PUT WAMFILE;
WAMFILE.PC = 6;
WAMFILE.PW = 255;
WAMFILE.PS = 130;
WAMFILE.TW = 20;
WAMFILE.NW = 15;
WAMFILE.ND = 2;

PUT 'Date: ', system.date;
PUT 'Input file: ', system.ifile /;

PUT / 'Total costs' /;
LOOP(SCENS, PUT SCENS.TL);
PUT /;
LOOP(SCENS, PUT TCOSTS(SCENS,'SCENPRICE'));

PUT / 'Total costs at reference price' /;
LOOP(SCENS, PUT SCENS.TL);
PUT /;
LOOP(SCENS, PUT TCOSTS(SCENS,'REFPRICE'));

PUT / /'COLSUM';
```

```
LOOP(HK, PUT HK.TL);
PUT /;
LOOP(SCENS,
  PUT SCENS.TL;
  LOOP(HK, PUT WAM(SCENS,'COLSUM',HK));
  PUT /;
);

PUT / 'Value added per agent' /;
PUT ' ';
LOOP(J, PUT J.TL);
PUT /;
LOOP(SCENS,
  PUT SCENS.TL;
  LOOP(J, PUT VA(SCENS,J));
  PUT /;
);

PUT / 'Value added per production factor' /;
PUT ' ';
LOOP(K, PUT K.TL);
PUT /;
LOOP(SCENS,
  PUT SCENS.TL;
  LOOP(K, PUT VA(SCENS,K));
  PUT /;
);

PUT / 'Waste account matrix in values' /;
LOOP(SCENS,
  PUT / SCENS.TL / ' ';
  LOOP(HK, PUT HK.TL);
  PUT /;
  LOOP(J,
    PUT J.TL;
    LOOP(HK, PUT WAM(SCENS,J,HK));
    PUT /;
  );
  PUT 'COLSUM'
  LOOP(HK, PUT WAM(SCENS,'COLSUM',HK));
  PUT /;
);

PUTCLOSE WAMFILE;

FILE PRICEFILE /PRICES.OUT/;
PUT PRICEFILE;
PRICEFILE.PC = 6;
PRICEFILE.PW = 255;
PRICEFILE.PS = 130;
PRICEFILE.TW = 20;
PRICEFILE.NW = 15;
PRICEFILE.ND = 2;

PUT 'Date: ', system.date;
PUT 'Input file: ', system.ifile //;
PUT 'MU';
LOOP(K, PUT K.TL);
PUT /;
LOOP(SCENS,
  PUT SCENS.TL;
  LOOP(K, PUT MU(SCENS,K));
  PUT /;
);

PUT / 'LAMBDA';
LOOP(K, PUT K.TL);
PUT /;
LOOP(SCENS,
  PUT SCENS.TL;
  LOOP(K, PUT LAMBDA(SCENS,K));
  PUT /;
);

PUT / 'PRICE FOR MIXED WASTE';
LOOP(I, PUT I.TL);
```

```
PUT /;
LOOP(SCENS,
  PUT SCENS.TL;
  LOOP(I, PUT Q(SCENS,I,'MXD'));
  PUT /;
);

PUTCLOSE PRICEFILE;
```

I.2. Data input file

```
PARAMETER P (K)      /      LBF= 36.000,
          LBI= 18.000,
          LBL= 10.000
          CAP= 0.575
          IMD=  1.000 /

TABLE PP (J,H)

          REC     CMP     REU     LND     INR

HSH                 0.002
COM                  0.0025
GVM                      -0.005  -0.005
SML          0.020   0.002
LRG          0.025   0.003
EXT                 0.003



TABLE DFX (I,JJ,H)

          HSH.MXD INS.MXD COM.MXD EXT.MXD GVM.INR

HSH         -234.17
INS             -45.91
COM                  -516.91
EXT                     -503.70
GVM                          0.10



TABLE DUP (I,JJ,H)

          SML.REC LRG.REC SML.CMP LRG.CMP HSH.REU COM.REU EXT.REU GVM.LND GVM.INR HSH.GON INS.GON
GVM.GON

HSH                           36.61                  +INF
INS                                                   +INF
COM                               126.27
GVM                                       +INF              +INF
SML          191.61
LRG              436.65
EXT                 13.00   65.00          96.96



TABLE OMEGA (I,K)

          LBF    LBI    LBL     CAP     IMD     GWI     HTI     AREA

HSH          54.81   51.41   69.94   1617.91 1020.10
GVM                      230.09         -119.18 56.72   40.72


TABLE RBAR (J,M,MM,K)
          LBF    LBI    LBL     CAP     IMD     GWI     HTI     AREA
*PRICES       36.00   18.00   10.00   0.58    1.00
* VALUES       1937.16 907.38  689.40  1062.02 1019.10 0.00    0.00    0.00

HSH.SEP     .1          68.90        4.40            0.23
HSH.RE      .1          0.04             -111.00 -110.00
INS.SEP    .1   13.40   5.10             9.34            0.05
INS.INC    .1               1.78         0.08    0.03    0.00
INS.LAN     .1                          0.75    2.30    0.15
```

```
COM.SEP        .1   18.90   6.60           50.50   0.20                 0.52
COM.RE         .1         0.70                         25.20   400.00
IWB.COLL        .1         0.58                          0.52    0.78
IWB.COLL        .2         0.02                          0.02    0.03
RGP.COLL        .1         5.53                          0.52    0.78
RGP.COLL        .2         0.72                          0.07    0.11
RGP.COLL        .3         17.31                          1.62    2.40
RGP.COLL        .4         0.48                          0.01    0.01
MDM.COLL        .1          0.07                          5.00    10.00
MDM.COLL        .2          0.07                          5.20    10.00
MDM.COLL        .3          0.02                          1.80    2.70
MDM.COLL        .4          1.05                          81.00   120.00
MDM.COLL        .5          0.20                          22.40   30.00
MDM.COLL        .6          0.05                          5.40    10.00
GVM.COLL        .1  1.78    1.46           52.26   1.82    19.60   30.00
GVM.COLL        .2  0.23    0.19           6.73    0.23    2.60    3.90
GVM.COLL        .3  5.41    4.45           159.16  5.54    59.60   90.00
GVM.COLL        .4  0.02    0.01           0.57    0.02    0.20    0.30
GVM.COLL        .5  0.38    0.32           11.36   0.40    4.20    6.30
GVM.LAN        .1   0.18    0.14                   190.00  570.00  38.00
SML.COLL        .1                     0.20          4.00    6.00
SML.COLL        .2                     0.23          38.60   60.00
SML.RECY        .1   5.35    5.35           7.25    985.00  -213.00 -340.00 0.21
LRG.COLL        .1                              14.40   20.00
LRG.COLL        .2                              60.00   90.00
LRG.RECY        .1   1.22                 447.47  4.43    -41.00  -660.00 0.04
LRG.RECY        .2   0.54                 888.00  7.73    -7.00   -10.00  0.01
EXT.SEP        .1   6.30                                         0.50
EXT.RE         .1   0.10                          -291.00 -290.00
EXT.LAN        .1                      221.50         0.03    0.08    0.01


TABLE YBAR (J,M,MM,JJ,H)

                  HSH.MXD INS.MXD COM.MXD EXT.MXD

HSH.SEP        .1   -234.17
INS.SEP        .1          -45.91
COM.SEP        .1                 -516.91
EXT.SEP        .1                         -503.70


+                 HSH.RCH INS.RCH COM.RCH IWB.RCH MDM.RCH SML.RCH LRG.RCH EXT.RCH

HSH.SEP        .1   71.51
INS.SEP        .1          26.60
COM.SEP        .1                 10.53
IWB.COLL        .1   -26.20               25.81
IWB.COLL        .2                 -1.16   1.16
MDM.COLL        .1   -25.06                       25.05
MDM.COLL        .2          -26.60                26.60
MDM.COLL        .3                 -9.37          9.37
MDM.COLL        .4                        405.33                 -405.32
MDM.COLL        .5                                        112.50
MDM.COLL        .6                 -26.97  26.97
SML.COLL        .1   -20.25                               20.25
SML.COLL        .2                        -192.65 192.65
SML.RECY        .1                                -212.90
LRG.COLL        .2                        -300.67         300.67
LRG.RECY        .1                                        -413.17
EXT.SEP        .1                                                405.32
*check           0.00    0.00    0.00    0.00    0.00    0.00    0.00    0.00

+                 HSH.PDB INS.PDB COM.PDB RGP.PDB GVM.PDB SML.PDB LRG.PDB EXT.PDB

HSH.SEP        .1   124.82
INS.SEP        .1          16.07
COM.SEP        .1                 380.11
RGP.COLL        .1   -26.88               26.89
RGP.COLL        .2          -3.46         3.46
RGP.COLL        .3                 -81.86  81.86
RGP.COLL        .4                        0.29                   -0.30
MDM.COLL        .5                        -112.50
GVM.COLL        .1  -97.94                        97.94
GVM.COLL        .2          -12.61                12.61
GVM.COLL        .3                 -298.25        298.25
```

```
GVM.COLL    .4              1.07        -1.07
GVM.COLL    .5              21.29  -21.29
GVM.LAN     .1             -400.48
SML.RECY    .1                 21.29
LRG.COLL    .1             -72.00    72.00
LRG.RECY    .1              41.32
LRG.RECY    .2                    -72.00
EXT.SEP     .1                       1.37
*check       0.00   0.00   0.00   0.00   0.00   0.00   0.00   0.00

+           INS.TXC EXT.TXC

INS.SEP     .1  1.57
INS.INC     .1  -0.11
INS.LAN     .1  -1.46
EXT.SEP     .1      0.05
EXT.LAN     .1      -0.05


+           HSH.REL COM.REL EXT.REL

HSH.SEP     .1  36.61
HSH.RE      .1  -36.61
COM.SEP     .1      126.27
COM.RE      .1      -126.27
EXT.SEP     .1             96.96
EXT.RE      .1             -96.96


+           SML.REC LRG.REC

SML.RECY    .1  178.61
LRG.RECY    .1      306.85
LRG.RECY    .2      64.80


+           SML.CMP LRG.CMP

SML.RECY    .1  13.00
LRG.RECY    .1      65.00


+           HSH.REU COM.REU EXT.REU

HSH.RE      .1  36.61
COM.RE      .1      126.27
EXT.RE      .1             96.96


+           GVM.LND

INS.LAN     .1  1.45
GVM.LAN     .1  400.48
EXT.LAN     .1  0.05


+           GVM.INR

INS.INC     .1  0.10


+           HSH.GON INS.GON GVM.GON

HSH.SEP     .1  1.23
INS.SEP     .1      1.66
INS.INC     .1             0.01
INS.LAN     .1             0.01
IWB.COLL    .1             0.39
LRG.RECY    .2             7.20


TABLE XBAR(J,M,MM)


        1     2     3     4     5   6
```

```
HSH.SEP       1.000
HSH.RE        1.000
INS.SEP       1.000
INS.LAN       1.000
INS.INC          1.000
COM.SEP       1.000
COM.RE        1.000
IWB.COLL      1.000      1.000
RGP.COLL      1.000      1.000      1.000      1.000
MDM.COLL      1.000      1.000      1.000      1.000      1.000         1.000
GVM.COLL      1.000      1.000      1.000      1.000      1.000
GVM.LAN       1.000
SML.COLL      1.000      1.000
SML.RECY      1.000
LRG.COLL      1.000      1.000
LRG.RECY      1.000      1.000
EXT.SEP       1.000
EXT.RE        1.000
EXT.LAN       1.000

;
```

I.2. Accounting

```
ACTIVITY(SCEN,J,M,MM)=X.L(J,M,MM);

MU(SCEN,K) = ENDOW.M(K)$(ABS(ENDOW.M(K)) GT 1E-6);
S(SCEN,JJ,H) = DEMANDEQ.M(JJ,H)$(ABS(DEMANDEQ.M(JJ,H)) GT 1E-6);

* shadow prices

Q(SCEN,JJ,H) = NETPROD.M(JJ,H)$(ABS(NETPROD.M(JJ,H)) GT 1E-6);
LAMBDA(SCEN,K) = NETRES.M(K)$(ABS(NETRES.M(K)) GT 1E-6);

DISPLAY PP,S,Q,P,MU,LAMBDA;

* physical waste account matrix

PWAM(SCEN,J,H)=0;
PWAM(SCEN,J,H)=PWAM(SCEN,J,H)+SUM(JJ,Y.L(J,JJ,H));
PWAM(SCEN,J,K)=PWAM(SCEN,J,K)-R.L(J,K);
PWAM(SCEN,J,HK)=PWAM(SCEN,J,HK)$(ABS(PWAM(SCEN,J,HK)) GT 1E-6);
PWAM(SCEN,'COLSUM',HK)=SUM(J,PWAM(SCEN,J,HK))$(ABS(SUM(J,PWAM(SCEN,J,HK))) GT 1E-6);

* waste account matrix

WAM(SCEN,J,H)=0;
WAM(SCEN,J,H)=WAM(SCEN,J,H)+SUM(JJ,Q(SCEN,JJ,H)*Y.L(J,JJ,H));
WAM(SCEN,J,K)=WAM(SCEN,J,K)-(LAMBDA(SCEN,K)*R.L(J,K));
WAM(SCEN,J,HK)=WAM(SCEN,J,HK)$(ABS(WAM(SCEN,J,HK)) GT 1E-6);
WAM(SCEN,'COLSUM',HK)=SUM(J,WAM(SCEN,J,HK))$(SUM(J,WAM(SCEN,J,HK)) GT 1E-6);
WAM(SCEN,J,'ROWSUM')=SUM(HK,WAM(SCEN,J,HK))$(SUM(HK,WAM(SCEN,J,HK)) GT 1E-6);

* potential profits

PROFITS(SCEN,J,M,MM)=SUM((JJ,H),Q(SCEN,JJ,H)*YBAR(J,M,MM,JJ,H))-SUM(K,LAMBDA(SCEN,K)*RBAR(J,M,MM,K))-
EXCCAP.M(J,M,MM);
PROFITS(SCEN,J,M,MM)=PROFITS(SCEN,J,M,MM)$(ABS(PROFITS(SCEN,J,M,MM)) GT 1E-6);

* value added per agent

VA(SCEN,J) = SUM(K,LAMBDA(SCEN,K)*R.L(J,K));
VA(SCEN,K) = SUM(J,LAMBDA(SCEN,K)*R.L(J,K));

* total costs at reference prices

TCOSTS(SCEN,'SCENPRICE') = SUM((J,K),(LAMBDA(SCEN,K)-MU(SCEN,K))*R.L(J,K))-SUM((J,JJ,H),(Q(SCEN,JJ,H)-
S(SCEN,JJ,H))*Y.L(J,JJ,H));
TCOSTS(SCEN,'REFPRICE') = SUM((J,K),(LAMBDA('REF',K)-MU('REF',K))*R.L(J,K))-SUM((J,JJ,H),(Q('REF',JJ,H)-
S('REF',JJ,H))*Y.L(J,JJ,H));
```

Appendix II Output files of the model runs

Table9 Physical Waste Account Matrix (PWAM) Showing Waste Configuration

Scenes	MXD	REC	CMP	REU	LND	INR	GON	LBF	LBI	LBL	CAP	IMD	GWI	HTI	AREA	APF
units	‘000 Tonnes							‘000 Manyear			‘000 Tonnes		indicator			‘000 Rs.
REF	-1300,69	550,25	78	259,84	401,98	0,1	10,52	-53,81	-50,42	-68,94	-1846,94	-1019,11	120,34	-55,72	-39,72	-1185,75
SCEN1	-1300,69	548,68	77,76	259,84	402,15	1,43	10,82	-53,79	-50,42	-68,94	-1895,84	-1001,29	120,18	-51,95	-39,72	-1185,75
SCEN2	-1300,68	660,47	94,89	259,84	272,72	1,43	11,39	-52,9	-79,73	-68,94	-1904,79	-1266,94	234,52	343,3	-27,5	-1185,75
SCEN3	-1300,69	505,03	80,34	259,84	451,06	1,43	3,03	-53,3	-53,87	-68,94	-981,29	-1082,75	129,8	-55,72	-44,37	-84,21
SCEN4	-1300,68	622,9	92,2	259,84	315,91	0,1	9,79	-52,61	-68,75	-68,94	-1847,03	-1089,55	193,92	248,13	-31,58	-1167,39

Table 10. Processing Options Relative to Total Waste Generated

Scenes	Mixed (MXD)	Recycled (REC)	Compost (CMP)	Reused (REU)	Dumped (LND)	Incinerated (INR)	Gone (GON)	Labour Formal (LBF)	High Paid Labour Informal (LBI)
REF	100%	42,3%	6,0%	20,0%	30,9%	0,0%	0,8%	52 %	48 %
SCENE 1	100%	42,2%	6,0%	20,0%	30,9%	0,1%	0,8%	52 %	48 %
SCENE 2	100%	50,8%	7,3%	20,0%	21,0%	0,1%	0,9%	40 %	60 %
SCENE 3	100%	38,8%	6,2%	20,0%	34,7%	0,1%	0,2%	50 %	50 %
SCENE 4	100%	47,9%	7,1%	20,0%	24,3%	0,0%	0,8%	43 %	57 %

Table 11 Processing Options Relative to Reference Scenario

Scenes	MXD	REC	CMP	REU	LND	INR	GON	LBF	LBI	LBL	CAP	IMD	GWI	HTI	AREA	APF
SCEN1	0 %	0 %	0 %	0 %	0 %	1330 %	3 %	0 %	0 %	0 %	-3 %	-2 %	0 %	-7%	0%	0%
SCEN2	0 %	20 %	22 %	0 %	-32 %	1330 %	8 %	-2 %	58 %	0 %	-3 %	24 %	95 %	-716%	-31%	0%
SCEN3	0 %	-8 %	3 %	0 %	12 %	1330 %	-71 %	-1 %	7 %	0 %	47 %	6 %	8 %	0%	12%	-93%
SCEN4	0 %	13 %	18 %	0 %	-21 %	0 %	-7 %	-2 %	36 %	0 %	0 %	7 %	61 %	-545%	-20%	-2%

Appendix III Economic Valuation

Most projects in the solid waste sector result in environmental and social effects which are external to their financial costs and benefits. Therefore, the economic implications of these external effects are seldom reflected in the prices used to asses the costs and benefits of these projects. However, due to increasing awareness in the industrial and financial sectors, externalities are receiving increasing attention. As a result, a need arises for a standard, transparent and simple methodology for monetary valuation of externalities and their inclusion in the conventional project appraisal.

The scope of the applied methodologies to assess external effects includes the full life-cycle of materials, projects and processes under investigation. This so-called *impact pathway approach* combines aspects of economic valuation (EVA) and life cycle assessment (LCA). In this section, the impact pathway will be described very briefly. A more elaborate explanation can be found in Beukering *et al*. (1998). The impact pathway approach is designed with the following principles in mind:

- Transparency: the methodology should create a clear understanding of how the result was achieved, which assumptions were made, and which data were used.

- Comprehensiveness: the methodology should include all relevant environmental impacts.

- It should address time and spatial dimensions.

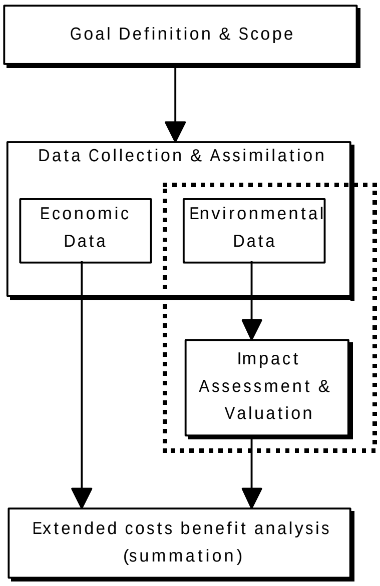
- It should be sufficiently flexible to allow the consideration of a wide range of water and waste management options.

- Practicality: the methodology should take into account the short appraisal period and the scarce professional resources available, and should thus be relatively simple and practical to apply. The various stages of the impact pathway approach are illustrated in Figure 4.

In the first step (goal definition and scope) the scope of the waste project is determined. The various project options are identified. For example, a municipality has the alternative to trade off various types of landfill (with or without gas recovery) against increased recycling efforts (kerbside collection, bring system). This stage is particularly important as it will be difficult to add other options in a later stage of the analysis.

The second stage consists of the collection of economic and environmental data relating to the project. Depending on whether these data are readily available, additional literature sources may have to be explored. The economic data mainly consist of financial details such as capital and labour costs. The environmental data are reported in physical units and contain predominantly process related emission levels.

Figure 4 The Impact pathway approach



The impact assessment and valuation stage is the third and probably most laborious. Given the requirement of applicability, only the most important externalities or effects are identified with reference to knowledge of the system under study and the goal of the study. For example, in the case of designing a waste collection scheme, traffic congestion should certainly be included while eutrophication is likely to be of less importance. Similarly, eutrophication, and not traffic congestion, will be the dominating impact category in the choice between a biological and chemical wastewater treatment. The ‘impact categories’ relevant for waste related projects may include: resource depletion, global warming, acidification, eutrophication, human health and eco-toxicity, traffic congestion, visual, noise and odour inconvenience and ground water pollution. This stage of the approach will be elaborated in the case study.

Next, the pathways to be used to relate the environmental pressure to the impact areas are described. The choice of pathway will be decided by considering such constraints as data availability and the requirements set by the goal of the study. In general, the closer the defined pathway can match the actual impact pathway, the greater the transparency and accuracy of the analysis but also the greater the data requirements. Since environmental appraisal is often performed under strict time constraints, more general pathways (or short cuts) will be developed through the use of rules-of-thumb and standard dose-response relationships. In this case, particular attention should be paid to the increased risk of double counting of impacts.

In order to value the impacts, the emission levels must be considered in the appropriate context. As a result, additional information needs to be recorded in the inventory. This may include description of the receiving environment - demographic factors, meteorological conditions and background emission levels. Where no information can be generated, standard data should be available to fill the gap. However, this reduces the quality of the estimates but still allows for an approximation of the impacts. If general data are not available, the impact cannot be quantified; this should be made explicit to the decision maker.