Domestic Solid Waste Management: the forgotten end of the urban goods movement chain.

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Abstract:

The urban goods movement chain consists of the various stages involved in the production, distribution and disposal of goods in urban areas. Starting with the raw materials, a variety of transport modes are involved in the manufacturing, inventory, wholesale and retail activities. It is at this stage, however, that many goods movement researchers stop their enquiries. Obviously, however, by the sheer conservation of matter, whatever goes into a retail site must also leave (usually in the boots of private cars), and most of what enters the household sooner or later also leaves via pipelines (the sewer) or in a garbage or recycling truck.

It is this latter part of the urban goods movement chain which is the subject of this paper. The paper describes the structure of the Solid Waste Integrated Management (SWIM) model, which considers the generation of domestic solid waste, the partitioning of this solid waste into various waste streams (e.g. garbage, recyclables, green waste etc.), the collection of this waste, sorting of the recyclables stream, transferral of waste to disposal sites, and the sale of recyclables in a variety of markets.

The SWIM model is then applied to consider the important question of the extent to which the collection, sorting and sale of recyclables makes sense from both an economic and environmental viewpoint. Does it cost more for the recycling process than can be obtained from the sale of recyclables or are there other ways of handling some of the components of domestic solid waste. Importantly, what are the environmental costs (e.g. fuel consumption, greenhouse gas emissions) of the recycling process? This paper presents some results, with respect to waste paper, which help to understand the economic and environmental trade-offs involved in the operation of the domestic solid waste management system.

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1. INTRODUCTION

The urban goods movement chain consists of the various stages involved in the production, distribution and disposal of goods in urban areas. Starting with the raw materials, a variety of transport modes are involved in the manufacturing, inventory, wholesale and retail activities, as shown in Figure 1. It is at this stage, however, that many goods movement researchers stop their enquires. Obviously, however, by the sheer conservation of matter, whatever goes into a retail site must also leave (usually in the boots of private cars), and most of what enters the household sooner or later also leaves via pipelines (the sewer) or in a garbage or recycling truck.

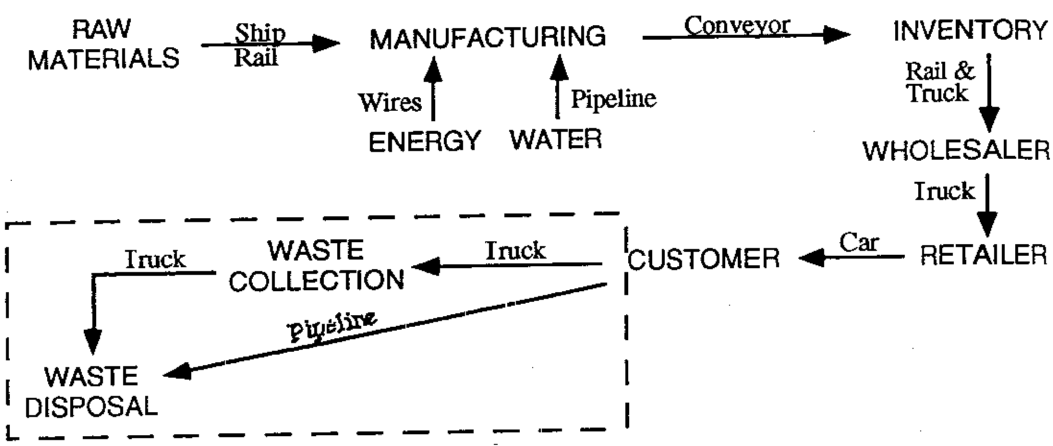

Figure 1: The Transport Chain

It is this latter part of the urban goods movement chain which has been the subject of investigation of a joint project between the Transport Research Centre at the University of Melbourne and the Faculty of Engineering at the Royal Melbourne Institute of Technology. This project has resulted in the development of a computer model of the solid waste management system. The Solid Waste Integrated Management (SWIM) model considers the generation of domestic solid waste, the partitioning of this solid waste into various waste streams (eg. garbage, recyclables, green waste etc.), the collection of this waste, sorting of the recyclables stream, transferral of waste to disposal sites, and the sale of recyclables in a variety of markets.

An important question is the extent to which the collection, sorting and sale of recyclables makes sense from both an economic and environmental viewpoint. Does it cost more for the recycling process than can be obtained from the sale of recyclables and, more importantly, what are the environmental costs (e.g. fuel consumption, greenhouse gas emissions) of the recycling process?

This paper investigates this question by reference to the operation of one part of the solid waste materials stream, that is, the generation and disposal of post-consumer paper products. The paper describes the background and structure of the SWIM model and will present some results, with respect to waste paper, which help to understand the economic and environmental trade-offs involved in the operation of the domestic solid waste management system.

. A FRAMEWORK FOR SOLID WASTE MANAGEMENT MODELLING

key feature of the transport decision-making process is the use of models to describe ie operation of the system. Conceptually, it would be possible to investigate the peration of the system by actually implementing an alternative in the field and then bserving its effects on the surrounding ecological, economic and social environment. lowever, this approach has a number of economic, financial, political, social and ngineering drawbacks and, apart from a limited number of trial schemes, this method is ldom used. Hence some form of system model, or simplified abstraction of the real orld, must be relied upon to generate predictions of consequences. A framework for onsideration of the different types of system model is shown in Figure 2. There are iree different types of model; supply models, which describe how physical systems ork; demand models; which describe how users of the system make their decisions; and npact models, which describe the impacts of usage of the system in terms of the conomic, environmental and social consequences. This modelling approach applies qually well to solid waste management as it does to transport management. In the ontext of solid waste systems, "usage" refers to the extent to which users generate solid astes which then flow through the solid waste management process.

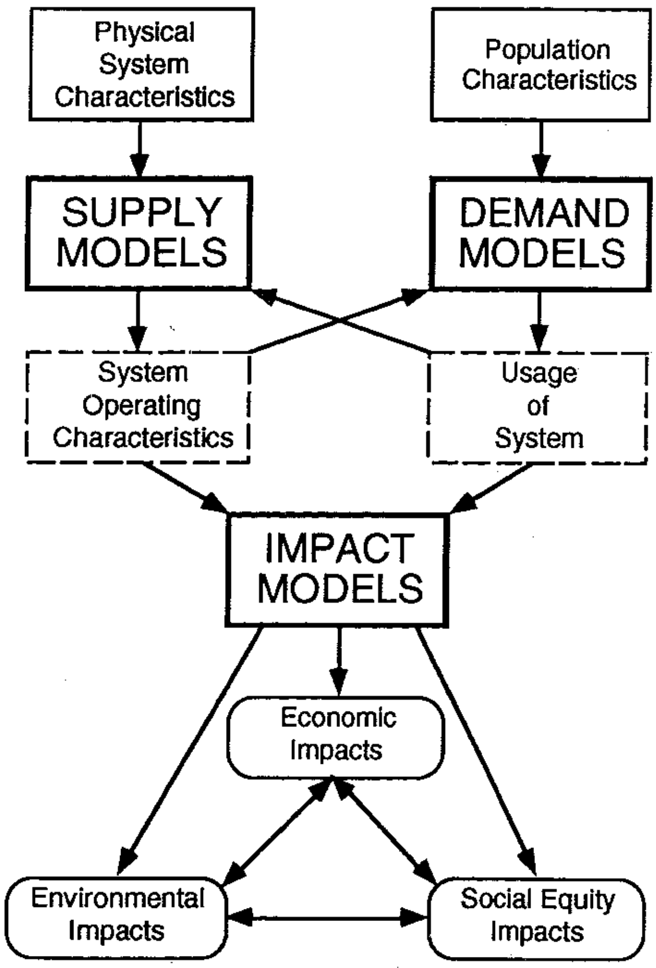

Figure 2 The Systems Modelling Process

The solid waste management supply model takes as input the physical description of the system (e.g. the waste collection fleet operations, the sorting process, and the methods of disposal) and the usage of the system (in terms of solid waste generation rates and recycling scheme participation rates) and then generates an estimate of how well the system is working in terms of system operating characteristics (such as costs of collection and disposal, overload conditions, and reliability of operation). The demand model takes these system operating characteristics as input and then considers how the population in question (described in terms of a range of socio-demographic characteristics) would react to the waste management system. For example, how would they react to various collection frequencies and charging policies. If they decide to make more use of the system (i.e. generate more rubbish), then this will have a feedback effect on how the system works (e.g. longer collection times, higher costs, and hence higher charges). This, in turn, will have a second-order flow-on effect which will further affect the usage of the system.

Given an equilibrium level of usage and operating characteristics, the impact models can now predict the overall economic, environmental and social consequences. These three effects will then need to be traded off against each other to arrive at an overall decision about the management of the solid waste system.

3. THE SWIM MODEL

The above framework has formed the basis for the development of a systems model of the solid waste management process. The SWIM (Solid Waste Integrated Management) model has resulted from the joint research of the Faculty of Engineering at the Royal Melbourne Institute of Technology and the Transport Research Centre at the University of Melbourne. It provides an interactive computer package which demonstrates the economic and environmental impacts of a recycling and solid waste management system and so assists decision-makers in the evaluation and design of such systems (Wang et al., 1993, 1994; Richardson et al., 1993). The SWIM package currently focuses on the supply and impact modelling aspects of Figure 2, and essentially consists of three sub-models:

- physical process models associated with the generation, collection, sorting and marketing processes;
- economic models which cover the economic impacts of the physical processes; and
- environmental models associated with the environmental impacts of the waste management system (energy consumption and greenhouse gas generation).

If one considers the process of solid waste generation and collection, as depicted in Figure 3, then a number of interesting research and practical issues arise. Starting with a household's expenditure of money on a bundle of goods, this gives rise to a waste stream and a stream of potentially recyclable material. How much of each is generated by each household is currently the subject of extensive research and empirical quantification worldwide, and is not unlike the process of trip generation in conventional transport modelling. The recyclable material can go to three destinations. Assuming that some form of kerbside collection is employed, a certain amount will be set-out for collection. This amount will vary depending on the frequency and methods of collection. Some of the recyclables will be taken directly to a transfer station by the household, while some of the recyclables will also "leak" back into the general waste stream, especially when it is not convenient for the household to participate in recycling.

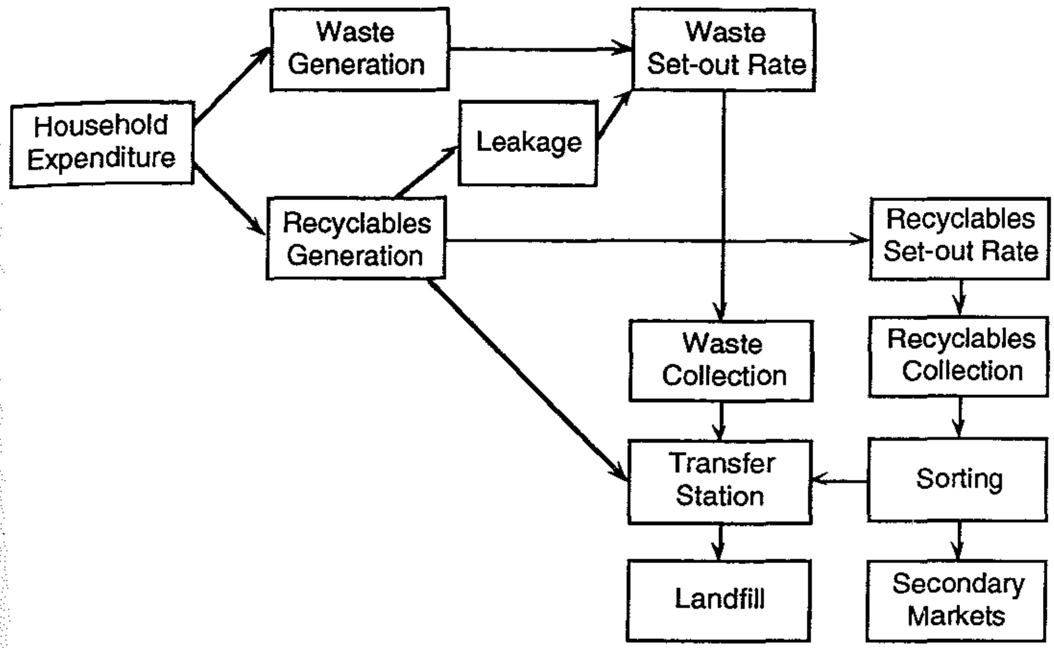

Figure 3 The Solid Waste Generation and Collection Process

The waste and the recyclables will be collected by truck, and here considerable scope exists for optimising the routes used by the collection trucks to minimise the costs of collection. The waste will then (optionally) go to a transfer station, where it may be compacted and then is generally taken to a landfill for disposal (although other means of disposal are also possible). The collected recyclables will need to be sorted, with contamination in the recyclable stream being earmarked for disposal. The "clean" recyclables will then sold on secondary markets for these materials. The health of these markets will obviously have a major impact on the extent to which recycling is profitable and thereby encouraged.

The objective of the SWIM model is to be able to explore the interactions between the various components of the solid waste management process. It consists of models describing the physical processes in waste management, models describing the demands imposed by households in using the physical systems, and impact models for evaluating the economical and environmental implications of the waste management system. For example, the physical models describe the process of waste generation and collection. The demand models relate the system's operating characteristics to householders' involvement in various waste and recycling services available to them. For instance, if the households are provided with a wheeled bins instead of bags for their recycling, it will result in more people participating in the recycling service because of increased convenience. This will enable more materials to be separated from the normal garbage collection, creating a lower demand for the normal garbage collection, and at the same time a higher demand for the recycling service. The implications of this may be manifold; it may enable the collection catchments to be revised for garbage collection so that one garbage collection truck can service more households each day, thereby making it possible to cut down the garbage collection fleet so the cost of total waste collection may decrease. The impact models evaluate the economic impact in terms of cost of providing the system, and the environmental impacts in terms of the CO_2 emissions in the waste collection, disposal and recycling processes.

The SWIM model is currently developed using the Microsoft Excel® package. One of the features of SWIM is that it uses the Census Collector's District (CCD) as the spatial unit of analysis. CCDs are used by the Australian Bureau of Statistics (ABS) for a variety of surveys and data reporting exercises. A typical CCD contains 200-300 households in urban areas. The use of the CCD unit in the SWIM model enables substantial information about the socio-demographics of CCDs to be utilised in waste management and planning.

Major Components of the SWIM Model

The major components of the SWIM model are:

- The specification of waste generation, composition and waste streaming options
- The specification of container types and collection frequencies
- The specification of household participation and set-out rates
- The design of catchment areas for waste and recyclable collections
- The allocation of catchment areas to trucks and days of the week
- The daily simulation of waste collection activities
- The evaluation of the economical and environmental impacts of the physical system

Waste generation, composition and waste streaming options

The solid waste management modelling process begins with the estimation of total waste generation and the composition of the waste. The waste generation rate (kg/household/week) will determine the required capacity of the system to deal with the waste flow, in terms of the collection fleet and the waste transfer station. The literature has shown that the waste generation rate varies from place to place (Alikhan and Burney, 1989). It is generally accepted that the waste generation rate and composition are influenced by various factors such as the climate, the lifestyle, the ethnic background and, on a micro scale, the dwelling type, household income and household size. Because there are correlations between many of these factors, such as between climate and lifestyle and between the household income and the dwelling type, it is difficult to relate the waste generation behaviour to a single demographic factor. Nonetheless, there is a need to use variable rates for waste generation to reflect differences in waste generation between different areas.

In Australia, surveys have been conducted to obtain the aggregated data for domestic waste generation rate and its composition (EPAV, 1983; 1985; 1990). Most of these surveys have been limited in their scope (often measuring just the domestic waste put out at the kerbside) and in their survey timespan (usually about two weeks). As a result, the data may not be representative of a particular locality. It is also recognised that conducting such a survey is a costly practice and may not be possible for a local government authority. In the SWIM model, a category analysis approach has been used, whereby the user can choose from using an average waste generation rate across all groups in the population (based on average values derived from the literature), or to use different rates for various sectors of the population (based on survey information available for that locality). The sectors of the population are defined according to the dwelling type and the number of people in that dwelling. The dwelling types chosen are separate house, townhouses and units, and flats and other dwellings. It conforms with the classification used in the Basic Community Profile information provided by the Australian Bureau of Statistics (ABS). However, the model uses only three dwelling types, instead of the six dwelling categories in the full ABS data, and four household size groupings, instead of the six household size categories in ABS. The three types of dwelling used in the model are separate houses, townhouses, and flats and all others. The dwelling types such as caravan, other and non-stated used in the ABS data consist of a very small percentage of the whole dwellings, so it is practical to group them together with flats. The model uses household size with one, two, three and four or more people. If the users have better information about the waste generation rates, they then can utilise the structure provided by the SWIM model to give a more precise picture of waste generated at the domestic source.

The composition of the waste generated at the source will affect the availability of potential streaming options. For example, if a municipality is situated in an area such that not much of its total garbage is garden waste, then the streaming of garden waste for a special collection will not be an appropriate option for reducing waste going to the landfill.

Given the total waste generation rates for households, SWIM then calculates the total waste generated from each of the CCDs in a municipality. The total quantity generated will normally be much greater than the total quantity collected from the kerbside by the garbage collection service because of many other activities such as recycling services. The diversion rate is defined as the proportion of a quantity of materials going to a waste stream versus the total waste generated. Usually this figure is obtained from previous experience with the various solid waste programs. For instance, if the quantity collected in paper recycling was 10% of the total waste generated from domestic sources, then the diversion rate of paper recycling would be 10%. Depending on the diversion rates given, the model will work out the quantities of wastes or recyclables to be collected by different services.

The specification of container types and collection frequencies

The SWIM model allows for a range of container types to be specified for each type of collection. For garbage collections, the container can range from the older 55 litre garbage bins, through to mobile garbage bins (MGBs) of various capacities (typically 120 litre and 240 litre). For recycling of co-mingled materials, the container can be a bag or a rigid crate or a wheeled bin. The specification of various types of container has an effect on the extent to which participation by households in recycling is encouraged, the amount of waste going into the various waste streams from households, and the cost of the recycling or garbage collection service.

The SWIM model also allows for solid waste or recyclables to be collected at varying frequencies. For garbage services, the normal frequency will be weekly. For recyclables, the frequency can range from weekly to quarterly, depending on the type of recyclable involved. The frequency of collection will depend, to some extent, on the type of container selected for use with each type of collection.

The specification of household participation and set-out rates

The extent to which households take advantage of garbage collection and recycling services can be expressed in terms of participation rates and set-out rates. The set-out rate is defined as the proportion of households in a given population who set out garbage or recyclables at the kerb-side in any given week. This will have an effect on the number of stops required by the pick-up truck, and hence the efficiency of collection. It may also have an effect on the amount of material set out for collection, either in total over a long period or on any one day. The major effect on total quantity for collection, however, will be expressed in terms of the participation rate. The participation rate is defined as the proportion of households who set out materials at any time during an extended period. This period has often been defined, for data collection purposes, as six weeks. The SWIM model assumes that the total quantity for collection (in either the garbage or recycling services) is a function of the participation rate. It is assumed that if a household is a recycler but does not set out its materials in any given week, then they will simply store these materials (e.g. newspapers) and set them out at the next available opportunity.

The design of catchment areas for waste and recyclable collections

Based on the quantity of wastes or recyclables expected to be collected from each CCD, the SWIM model then requires that users design appropriate catchment areas for the collection operations. This process is aided by displaying on-screen a map of the local government area on which there would be buttons symbolising each CCD and buttons symbolising facilities such as the transfer station, garbage truck depot and landfill site. In the design of the recycling catchment areas, there are buttons for recycling facilities such as a material reprocessing facility (MRF). Clicking on each CCD button brings forth information on the total dwellings and the quantity of wastes or recyclables to be collected from the CCD, which assists the user to design realistic catchment areas.

The allocation of catchment areas to trucks and days of the week

Having grouped CCDs into catchment areas, these areas are then allocated to the days of the week, and these catchment areas are allocated to specific trucks.

The daily simulation of waste collection activities

Having specified the characteristics of the collection area and designed the collection systems, the SWIM model then simulates the operation of these systems over a specified period. The period is often specified as a year, which allows the full effect of seasonal variations to be observed. The simulation is performed on a daily basis, with stochastic variations introduced to allow for the random differences in set-out rate and operational efficiencies.

The evaluation of the economical and environmental impacts of the physical system

The evaluation of the economic and environmental aspects of the systems are then performed on the basis of the operational performance of the physical collection systems. The costs of the systems can be evaluated from a number of different perspective's (e.g. the collection contractor or the Local Government agency). The environmental effects are evaluated primarily in terms of energy consumption and CO_2 emissions. These outputs will be used to answer the questions brought out at the beginning of this paper about the economic and environmental effectiveness of waste paper collection.

4. A CASE STUDY OF WASTEPAPER COLLECTION

The following case study presents the results of applying the SWIM model to an investigation of the economical and environmental benefits of a paper recycling program. It does this primarily by estimating the cost and CO_2 emissions associated with the transport systems required to operate a range of paper collection operations. The study assumes that wastepaper can be collected by three different methods:

- using a dedicated kerbside recycling service, where wastepaper is set out separately and is collected by a small truck which then takes the paper to a local transfer station. The paper is stored at this transfer station until it is later taken by a large truck to a regional paper recycling facility for use in the manufacture of recycled paper

- having the wastepaper simply put in with the normal garbage, whereby it is collected by the normal garbage trucks and disposed of to landfill. Since this wastepaper is lost to the paper manufacturing process, the differential monetary and energy costs of using virgin pulp, versus recycled paper, in the subsequent manufacture of paper must be accounted for in this process.

- having households store the wastepaper on their premises until they have a load which could be taken (by them in their own cars) to the local transfer station. It is thereafter transferred to the regional paper recycling facility.

Scenarios are generated with different combinations of wastepaper capture rates which is defined as the percentage of the total wastepaper gathered in a particular collection option. In this study, the Local Government Authority is assumed to be responsible for providing the recycling and garbage collection services, and for the management of the transfer station The evaluations are performed from three perspectives: the total cost of the whole system (to reflect the economic perspective), the net cost to the council (to reflect the equity or distributional perspective),and the total emission of CO_2 (as an indicator of the environmental impact). The questions sought to be answered by this case study are

- to what extent is paper recycling economically viable?
- to what extent is paper recycling environmentally beneficial in terms of energy consumption?
- what is the best system from the council's financial point of view?

Input Parameters

While the case study described in this paper is hypothetical and meant for illustrative purposes only, the demographic and spatial information used in this case study is based on the city of Nunawading, Victoria. Table 1 gives the assumptions used for waste generation in the households, while Table 2 lists assumptions about the vehicles used in the analysis. Other assumptions used in the analysis include:

- For the garbage collection, the trucks go to the transfer station to unload the loads. For the kerbside paper recycling service, the collector takes the load to the depot of Australian Paper Manufacturers (APM) at Fairfield, Melbourne. For paper delivered to the transfer station by private cars, the distance for each trip is calculated using the x-y co-ordinates of the CCD's centroid and that of the transfer station. This paper is then transferred to the APM Fairfield depot by an APM semi-trailer.

- The criteria for finishing a shift is to see whether the volume or weight capacity of the truck has been reached, or whether the total time for a collection day (nominally 8 hours) has been exceeded. Using various paper capture rates for the garbage collection and the kerbside paper collection, the services are simulated so that the services will be operating at about eighty percent of their maximum capacity.

- The fuel consumption rates for different trucks at 40 km/hr are obtained from the work of Ghojel and Watson (1992), and the rates at 10 km/hr are then estimated proportionally using the speed and fuel rate curves for cars given by Bowyer et al. (1985). Although there are more sophisticated model techniques relating vehicle fuel rate with the mass and the speed, it is considered that the current method is sufficiently accurate for this case study.

- The conversion factor used to calculate the CO_2 emission is 2.69 kg/litre of diesel oil for trucks and 2.26 kg/litre for cars using petrol (Cosgrove et al. 1994).

- The landfill cost is assumed to be \$40/tonne. The market price for mixed paper and cardboard is set at \$25/tonne. This is regarded as a lower bound for recycled paper, given that the price has reached \$35/tonne in recent years.

Table 1 Waste generation for different dwellings

	Houses & Units	Flats & others
Total number of households	27599	1149
Domestic garbage rate (kg/dwelling/week)	8.4	6.7
Paper generation rate (kg/dwelling/week)	2.6	2.0

Table 2 Vehicle parameters used in the case study

	Garbage truck	Paper collection truck	APM semi-trailer	Private car
Volume (m^3)	15	15	30	medium
Gross weight (tonne)	15	8	43	1.1
Tare weight (tonne)	6	4	16	0.9
Distance from depot to collection areas (km)	8	10	20	n/a
Distance from collection to unloading site (km)	5	16	20	n/a
Average access speed (km/hr)	40	40	40	40
Average collection speed (km/hr)	10	10	n/a	n/a
Access fuel consumption rat (litre/100km)	25	20	n/a	11.5
Collection fuel consumption rate (litre/100km)	40	32	n/a	n/a
Fuel consumption rate at the full load	n/a	n/a	50	n/a
Fuel consumption rate when empty	n/a	n/a	28	n/a

- The CO_2 emissions in the process of manufacturing paper from virgin pulp and from recycled pulp are 71 and 8 kg per tonne of paper produced (Industry Commission, 1991). If the paper is not recycled, it is assumed that the same quantity of paper will be produced from the virgin pulp so that the total demand for paper will be maintained.

Results of the Simulation

The simulation was run separately for a range of capture rates for each of the three collection systems. These capture rates were varied systematically from 0% to 100% in increments of 10%.

For paper collected in the garbage stream, the marginal cost (and emissions) of adding the paper to the garbage stream has been calculated by subtracting the cost (and emissions) of the 0% capture rate from all the other capture rates to obtain the marginal costs (and emissions). The results of the simulation of the garbage system are shown in Table 3 and Figure 3.

Table 3 Paper captured in the garbage stream

Capture rate	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Marginal cost due to paper collection($)	0	15102	45307	60409	60409	75512	110144	125247	140349	155451	170554
Marginal cost per tonne of paper ($/tonne)	0	40.00	60.00	53.33	40.00	40.00	48.62	47.39	46.47	45.75	45.17
Marginal CO_2 due to paper (kg/year)	0	0	0	0	0	0	8884	8884	8884	8884	8884
Marginal CO_2 per tonne of paper (kg/tonne)	0	0.00	0.00	0.00	0.00	0.00	3.92	3.36	2.94	2.61	2.35

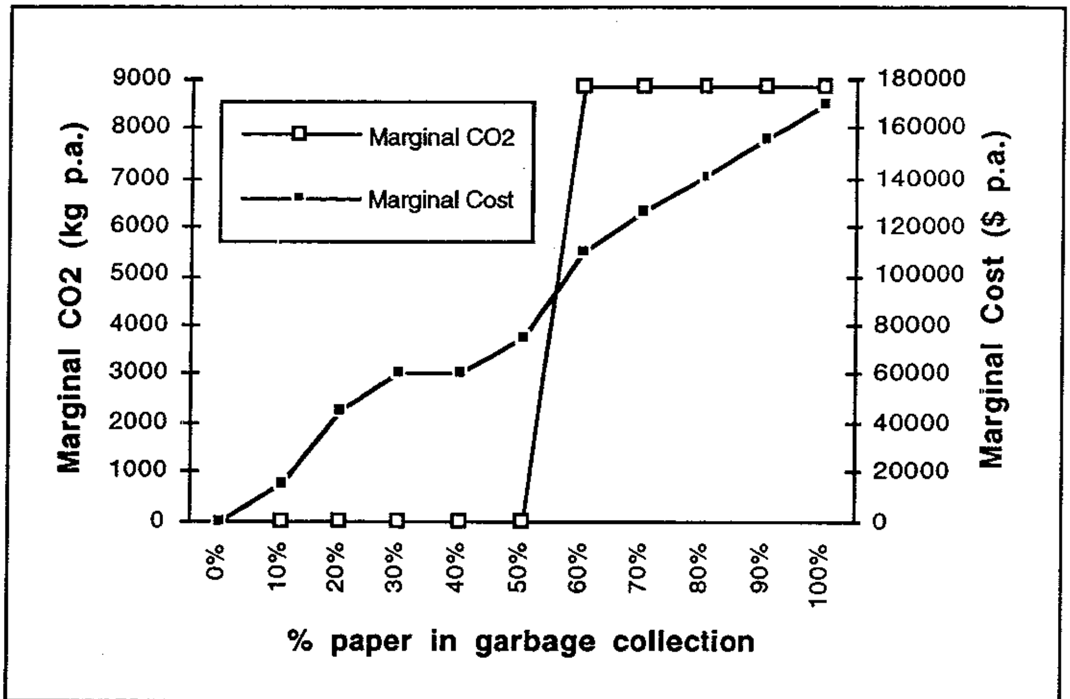

Figure 3 Marginal cost and emissions for garbage collection

It can be seen that while the marginal cost increases fairly regularly with increases in the amount of paper being disposed of through the garbage collection system, the CO_2 emissions remain unchanged until about 60% of paper is disposed of through the garbage collection system. The reason for this is that while it requires more time and labour to collect the extra material when the paper capture rate increases, and the landfill disposal cost (at $40/tonne) must be paid for the wastepaper, there is no extra distance covered (and hence no extra fuel consumption or CO_2 emissions) until an extra truck is required when the paper capture rate reaches 60%. Even then, the collection distance remains the same but the access distance increases to move the extra truck from the depot to the collection area and onto the transfer station.

The cost and emissions of the kerbside paper recycling system are shown in Table 4 and Figure 4.

Table 4 Paper collected through kerbside recycling collection

Capture rate	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Total system cost ($ p.a.)	0	29005	39459	64525	71196	96262	102933	109604	134670	141341	148013
Net cost to council ($ p.a.)	0	10194	20388	30582	40776	50970	61164	71358	81553	91747	101941
System cost per tonne ($/tonne)	0	76.82	52.26	56.97	47.14	50.99	45.44	41.47	44.59	41.60	39.20
Total CO_2 emitted (kg/year)	0	8426	10911	17020	17281	23390	23652	23913	30022	30283	30544
CO_2 per tonne (kg/ton)	0	22.32	14.45	15.03	11.44	12.39	10.44	9.05	9.94	8.91	8.09

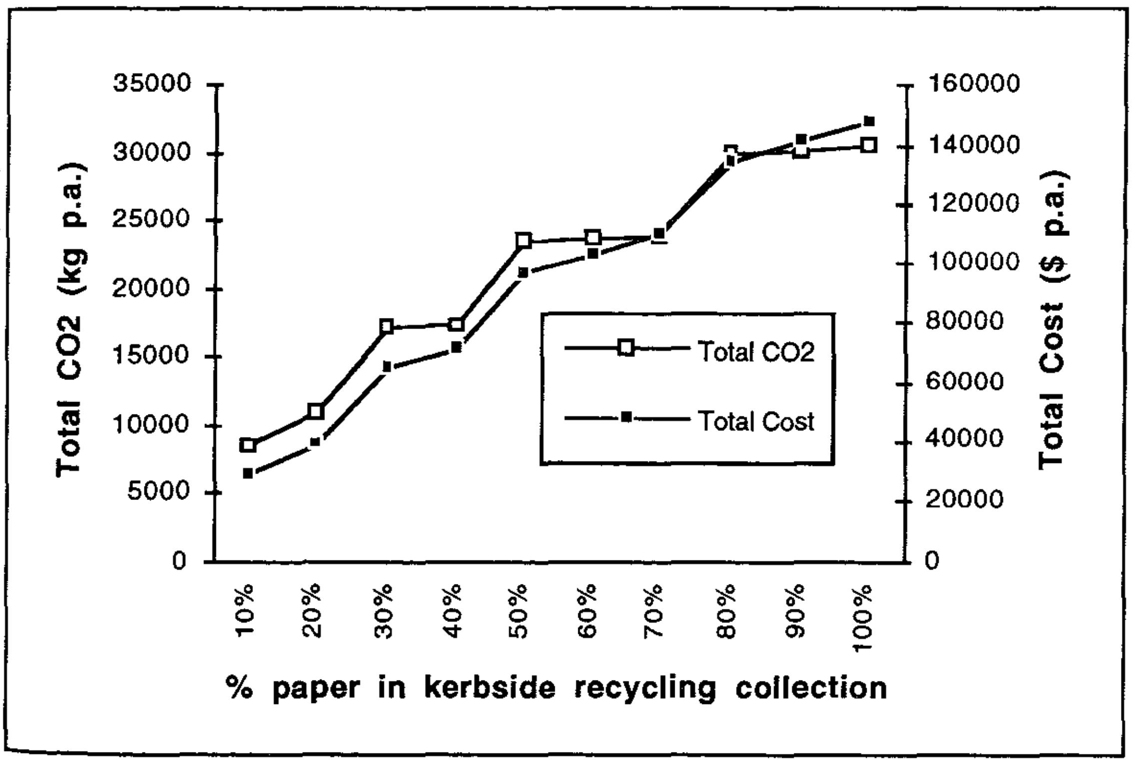

Figure 4 Total cost and emissions for kerbside recycling collection

Both the cost and the emissions rise fairly regularly with the increase in the amount of paper which is captured by the kerbside recycling service. The total cost of the recycling service is borne by the collection contractor. There is a transfer payment from the council to the collector (at $27/tonne) to cover part of these costs, plus a payment by APM to the collector (at $25/tonne) for the delivery of the wastepaper to APM's recycling depot. Note that with these payments, it is not economically feasible for the collector until the recycling capture rate is approximately 50%.

The total cost of the recycling service is of the same order of magnitude as the marginal cost of adding the paper collection to the existing garbage service. Interestingly, however, the CO_2 emissions for the recycling collection are substantially higher than the marginal CO_2 emissions for the garbage system. This is because the recycling service requires separate trucks, whereas the addition of paper to the existing garbage service mostly utilises vehicles which are already in use.

Such a comparison, however, misses out on a major component of CO_2 emissions; indeed, one of the major reasons for paper recycling. If paper is put into the garbage collection, and disposed of in landfill, then an equivalent amount of virgin paper pulp will be needed to replace this lost amount of recycled paper. It is known (Industry Commission, 1991) that the CO_2 emissions from paper manufacturing varies depending on the source of the paper pulp. The use of virgin paper pulp results in CO_2 emissions of 71 kg/tonne, whereas the use of recycled paper pulp results in CO_2 emissions of only 8 kg/tonne of manufactured paper. Therefore, the more that is collected by recycling, the less emissions there will be from the paper manufacturing process, as shown in Table 5.

Table 5 CO_2 emissions from paper manufacture

Capture rate by Recycling Service	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Amount captured by recycling service (tonne)	0	378	755	1133	1510	1888	2265	2643	3020	3398	3776
Amount captured by garbage service (tonne)	3776	3398	3020	2643	2265	1888	1510	1133	755	378	0
CO_2 emissions from paper manufacture (kg)	268096	244307	220518	196730	172941	149152	125363	101574	77786	53997	30208

When the CO_2 production from the manufacture of the paper is added to the CO_2 production from the collection of the wastepaper, then the environmental effectiveness of the two methods of collection of wastepaper is substantially modified, as shown in Table 6, with the minimum CO_2 production being obtained when 100% of the wastepaper is recycled.

Table 6 CO_2 emissions from collection and paper manufacture

Capture rate by Recycling Service	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
CO_2 emissions from paper manufacture (kg)	268096	244307	220518	196730	172941	149152	125363	101574	77786	53997	30208
CO_2 emissions from recycling (kg)	0	8426	10911	17020	17281	23390	23652	23913	30022	30283	30544
Marginal CO_2 emissions from garbage collection (kg)	8884	8884	8884	8884	8884	0	0	0	0	0	0
Total CO_2 emissions	276980	261617	240313	222634	199106	172542	149015	125487	107808	84280	60752

The above conclusion, of course, assumes that the wastepaper collected by the recycling service is indeed re-used in the manufacture of paper, thereby realising the savings in CO_2 emissions from the use of this recycled paper in the manufacture of new paper. If, however, the recycled wastepaper is simply stockpiled, with virgin paper pulp continuing to be used in the manufacture of the new paper, then these environmental benefits will not be realised. The main reason why this might occur is if the cost of using recycled paper pulp in the paper manufacturing process is higher than the cost of using virgin paper pulp in the paper manufacturing process. In addition, it is assumed that the paper disposed of in landfill is entirely lost as a resource. However, paper has a very short "life cycle" (Industry Commission, 1991) decomposing fairly quickly in landfill, in association with other nutrients, and producing "landfill gas" which can be captured and reused as a valuable source of energy.

Table 7 Paper delivered by residents to transfer station

Capture rate	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Total system cost ($ p.a.)	0	10455	20911	31366	41821	52277	62732	73188	83643	94098	104554
System cost per tonne ($/tonne)	0	28.00	28.00	28.00	28.00	28.00	28.00	28.00	28.00	28.00	28.00
Net cost to council ($ p.a.)	0	-3776	-7551	-11327	-15102	-18878	-22653	-26429	-30205	-33980	-37756
Total CO_2 emitted (kg/year)	0	14420	28840	43261	57681	72101	86521	100942	115362	129782	144202
CO_2 per tonne (kg/ton)	0	38.00	38.00	38.00	38.00	38.00	38.00	38 00	38.00	38.00	38.00

An alternative method of disposal of wastepaper is for the residents to deliver their wastepaper to a transfer station as required, rather than have their wastepaper collected by trucks at regular intervals. The costs incurred in this process are the vehicle operating costs to the residents in driving their cars to the transfer station, the time expended by residents in delivering the paper to the transfer station (valued at 25% of the average wage rate), and the cost to APM in picking up the paper from the transfer station and transferring it to their paper recycling depot. In addition, there is a transfer to the council (which operates the transfer station) from APM (at $10/tonne). The costs and emissions for this scheme are shown in Table 7.

It can be seen that the total social cost of this system for the 100% capture rate ($104,554 p.a.) is less than that for the kerbside recycling system ($148,013 p.a.). Perhaps more importantly, the cost to the council is very different. With the kerbside recycling system, the council needs to outlay $101,941 p.a. (as a payment to the collection contractor), whereas the council receives a payment of $37,756 p.a. (from APM) when the residents deliver their paper to the transfer station. There is therefore a substantial economic and financial incentive for the council to adopt the latter scheme.

From an environmental perspective, however, the kerbside recycling scheme has a lower CO_2 emission (30,544 kg p.a.) than when the residents deliver to the transfer station (144,202 kg p.a.). There is thus a trade-off to be made between the economic savings when the residents deliver their own paper to the transfer station and the CO_2 savings when the paper is collected from the kerbside by recycling collection trucks. Note that the calculation of the saving in CO_2 is based on the assumption that residents would make a special trip to the transfer station to deliver their wastepaper, rather than including this trip in their normal pattern of trips and activities.

Assuming, however, that a trade-off exists, what would help in making this trade-off is some estimate of the economic value of savings in CO_2 emissions. For example, Cosgrove et al. (1994) give a value of 2 cents/kg of CO_2 emissions. When applied to the difference in CO_2 emissions of the two schemes described above (113,658 kg p.a.), this yields an economic value of $2273 p.a., which is far less than the social cost difference of $43,459 p.a.

Comparison of the Schemes

The results contained in the previous section can be combined in many ways to generate collection scenarios based on variable levels of use of each of the three methods of collection. Table 8 shows just a few of these scenarios, at the extremes and with intermediate levels of the collection strategies, to demonstrate the nature of the trade-offs involved. For each of the scenarios, the results of a number of evaluations are given:

- **net cost to the council**: to show the distribution of costs between the various parties (this represents the equity dimension of the trade-off problem)
- **marginal system cost**: to show the total marginal cost to all parties, excluding the cost of the environmental externalities (viz. CO_2 emissions) (this represents the economic dimension of the trade-off problem)
- **marginal collection CO_2**: to show the marginal CO_2 emissions resulting solely from the collection system used to collect the wastepaper (this represents a limited evaluation of the environmental dimension of the trade-off problem)

- **marginal system CO_2:** to show the marginal CO_2 emissions resulting from the collection system and the paper manufacturing process (this represents a more complete evaluation of the environmental dimension of the trade-off problem)

- **system social cost:** this represents the marginal system cost plus the economic valuation of the CO_2 emission externality (valued at 2¢/kg) (this represents an attempt to internalise the economic and environmental trade-off)

Table 8 Cost and CO_2 for combinations of the collection systems

Capture rates in three streams (%)			Results of Evaluations				
Recycling	Transfer station	Garbage	Net cost to council	Marginal system cost	Marginal collection CO_2	Marginal system CO_2	System social cost
0	0	100	$170,554	$170,554	**8884**	276,980	$176,094
0	50	50	$56,634	$127,788	72,101	221,253	$132,213
0	100	0	**-$37,756**	**$104,554**	144,202	144,202	**$107,438**
50	0	50	$126,482	$171,774	23,390	172,542	$175,225
100	0	0	$101,941	$148,013	30,544	**60,752**	$149,228

From the results above, it can be seen that from the council's point of view, the most attractive option (financially) is for the residents to take their wastepaper to the transfer station in the boot of their own cars. Not only does the council not have to pay for the collection of the wastepaper, but they also get paid by APM for the wastepaper. This scheme is also the most attractive in terms of total marginal system cost, mainly because it makes use of low-paid labour (assuming that residents value their free-time at only 25% of the average wage rate). It also avoids the landfill tipping fee associated with disposal of wastepaper through the normal garbage system.

In terms of CO_2 emissions, the determination of the best scheme depends on the definition of the system boundary adopted for the evaluation. If one considers only the CO_2 emissions during the collection process, then the normal garbage service is the most attractive because it mainly makes use of an existing service. The worst scheme is the use of the residents own cars, because while they make relatively few trips (one or two per year) there are many households who would make this trip (this assumes that all these trips are extra trips which would not already have been made by the residents to a site near the transfer station).

If, however, the extra CO_2 emissions involved in the use of virgin paper pulp in the paper manufacturing process are accounted for, then the kerbside recycling system has the lowest total CO_2 emissions, and the disposal of wastepaper through the normal garbage system has the highest CO_2 emissions.

It therefore appears that there is a trade-off between the economically efficient system of having residents deliver their wastepaper to the transfer station and the environmentally efficient system of kerbside wastepaper collection. If one attempts to resolve this trade-off by using a value of CO_2 of 2ç/kg (Cosgrove et al., 1994), then the minimum system social cost is obtained for the system where residents deliver their wastepaper to the transfer station, with a total system social cost of $107,438 p.a. compared to the kerbside collection cost of $149,228.

5. CONCLUSION

This paper has demonstrated the economic, environmental and equity trade-offs which need to be addressed when making decisions about the transport options available for collection systems for wastepaper. It has outlined a model of solid waste management systems (SWIM) and has used that model to generate results about the economic and environmental costs of various forms of collection system. In particular, the paper has considered the collection of wastepaper by kerbside recycling systems, by disposal in the normal garbage collection, and by having residents take their wastepaper to a transfer station whenever they have a sizeable quantity collected (a car bootful).

It has been shown that, depending on the criterion used for evaluation and the system boundaries employed, each of these three schemes can appear to be the most attractive. On purely economic and financial grounds, the residents delivering to the transfer station is the most attractive; to minimise the CO_2 emissions in the collection process, the garbage disposal system is to be preferred; to minimise the CO_2 emissions in both the collection process and the paper manufacturing process, the kerbside collection system is to be preferred. Overall, after costing the CO_2 emissions as an externality, the most attractive scheme is to have residents deliver their wastepaper to the transfer station.

Clearly, the results of this case study analysis depend on the input parameters describing the case study situation, and on the assumptions which were required to be made during the analysis. These assumptions have been stated clearly, where appropriate, but there are likely to be many others which could be made as alternative assumptions. What is important, however, is to recognise that the results of the analysis are subject to these assumptions, and will always involve trade-offs between the economic, environmental and equity dimensions.

Nonetheless, the paper has demonstrated that the use of models such as SWIM can unearth seemingly counter-intuitive results, such as the relative attractiveness of having residents deliver their wastepaper to transfer stations (or more generally to local community centre collection sites - an option which has not been explored in this paper). These results are only obtained when one considers a range of economic and environmental costs, and attempts to make some trade-off between these factors. By generating these results, a starting point is provided from which debate about the factors omitted from the modelling can be undertaken, with a view to refining the results from such an analysis.

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