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A Systems Approach to Materials Flow in Sustainable Cities: A Case Study of Paper

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ABSTRACT *This study develops a modelling framework within which the effects of technology choice and policy on the sustainability of cities may be assessed. A life cycle accounting system for environmental impacts is combined with systems analysis, to represent the flows of resources into cities, the wastes and pollution generated and the technological choices available in an urban environment. The approach is demonstrated through a case study of the demand for paper and management of wastepaper. The case study questions the applicability for paper of the accepted 'hierarchy of waste management techniques; incineration imposes lower environmental costs than recycling, and consequently lower total costs under some circumstances.*

Introduction

This paper represents the first case study arising from a larger research project, funded by the UK Engineering and Physical Sciences Research Council (EPSRC), within their programme 'Towards the Sustainable City .

As noted in the final text from the recent United Nations Conference on Human Settlements (Habitat II), by the turn of the century more than 3 billion people—one half of the world s population—will live and work in urban areas (UN, 1996). Extensive urbanization implies that to achieve sustainable development, urban areas must have the capacity to manage production and consumption patterns, transport and waste disposal systems with appropriate consideration for their environmental impacts. The European Commission (1994) points out that many problems arise from the particular features of cities and urban life. Conversely, many solutions are specific to cities and urban management. The overall goal of the EPSRC Sustainable Cities programme is to understand the city as a system, with research that will contribute to improved urban sustainability.

The overall purpose of the research project at Imperial College is to provide a methodology for representing the material and energy flows which govern the sustainability of cities, and thus allow systematic assessment of the contributions of specific technologies and strategies to enhanced sustainability. The novelty of the project and the method adopted lies in the capture of the interactions between several of the principal systems on which sustainability depends—materials, energy, air, water and transport.

In the first phase of the project, a framework has been developed in which the inputs and outputs for a multitude of activities or processes within an urban area may be calculated and summed in a consistent format. In the second phase of the project, a series of modules are being developed within this overall framework, representing various identifiable systems within an urban area.

The first system investigated, as a case study of the approach, represents the demand for paper in the city, the supply structures required to fulfil that demand and the management of resulting wastes.

Modelling Methodology

The intention of the project is to couple comprehensive inventory-style models of the inputs and outputs from individual processes within the city, with a systems analysis approach, which sets each process within the overall city system. The individual inventories may be produced by following a Life Cycle Analysis (LCA) approach for processes or the products of those processes. LCA is a methodology to quantify environmental impacts over the complete life of a product or process. A commonly accepted methodology is defined by the Society for Environmental Toxicology, described by Fava & Denison (1991). The systems analysis allows the representation of resource limits and emission constraints on the processes, and provides a tool for visualization of the system.

An advantage of the systems approach is that the model can be built up gradually as a series of linked modules. A series of modules is being developed, representing individual and identifiable material 'flows , based on the demand for some commodity or service for a certain set of end-uses. For example, the flow of fibre, pulp and paper associated with the demand for different grades of paper, or the abstraction of ground water, its treatment and distribution for various final uses. There are interactions between many modules as, for example, the manufacture of paper uses large quantities of water and energy. The LCA-style input–output accounting is used to capture these interactions. Figure 1 shows the structure of the model, with just a limited number of linkages shown for clarity.

Structure of Individual Modules

The individual modules are described by network flow models, which simulate the flow of materials and energy through different processes. The models are based on a novel extension of the Reference Energy System (RES), a technique for the conceptualization and modelling of an energy system. The technique was originally developed at the Brookhaven National Laboratory in 1971 for assessment of energy research and development. Since then it has been extended by other groups for many different uses. In pictorial format, an RES is a type of network flow diagram, which indicates the energy flows through different stages or 'activity groups of the energy system. These groups will conventionally include the 'supply of primary energy, 'conversions into different fuel products, 'transmission and 'distribution and eventual 'end-use .

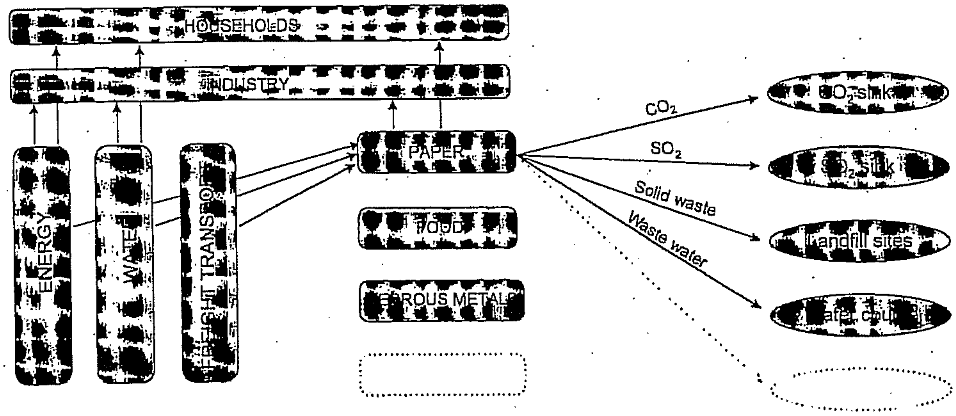

Figure 1. Structure of the modelling framework.

For a given network structure, with suitable conversion efficiencies specified at each node, a set of exogenously defined energy demands can be used to 'drive calculation of the energy flows required through each node and link. In the present application, the RES methodology is extended to include resource or material flows into cities and wastes or emissions of pollutants from cities; the methodology will be called the Reference Sustainability System (RSS). This methodology would be applicable at scales and to units other than the city, although the level of detail in activity representation and the data requirement would be different.

The activity groups appropriate for each material flow are different, and thus it is not practicable to use a single network model to describe all the flows within the city. The modular approach adopted has separate but connected network models for each of the main commodities and services under study. Each network model is assumed independent of the others, but they are connected through their requirements for common services such as energy and water supplies, and the generation of common pollutants.

The structure of the model can thus be envisaged as a multi-page spreadsheet. Each material flow is described in a network model on one page, the derived demands for water, energy and pollution sinks can be summed up across all of the individual pages to modules describing the supply of these services. In a similar fashion, costs and other data can be summed across the individual pages to summary pages. The RSS model thus becomes a multi-dimensional system, which has many advantages of comprehension. It also means that new subsystems can be easily added and the representation of existing systems incrementally improved.

Each model may be optimized as a network Linear Programming (LP) problem. Material and service transfers between modules are influenced through a set of prices, allowing each model to be optimized individually—a form of partial-equilibrium modelling. Many alternative objective functions could be specified for the LP, or a multi-objective approach can be used. For the present paper, the optimization minimizes the total social cost, where environmental impacts are included as monetary costs to society. Some of the issues surrounding such internalization of environmental costs are discussed later, within the case study.

The Case of Paper

Paper and paper-based products are a key commodity in the urban system, with a multitude of end-uses from newspapers to packaging. However, the interest in paper does not finish at the point of use: the majority of paper products have a very short life, and thus wastepaper and packaging form 35% of the total Municipal Solid Waste (MSW) stream, imposing substantial costs on the city (Ogilvie, 1995).

There is increasing pressure to recover and recycle more wastepaper, both from the UK Government and from the European Commission. The UK Producer Responsibility initiative was prominently directed at the packaging industry and has led to plans for increased packaging recovery. The EC packaging and waste directive will further affect the industry in time.

The UK Government approach to waste management, as set out in the recent white paper '*Making Waste Work* (Department of the Environment (DoE), 1995), is based on a hierarchy of options, illustrated in Figure 2, which is intended to represent the relative sustainability of each. The White Paper notes that this ranking will not be appropriate for every type of waste. However, the hierarchy is fast becoming accepted wisdom, whilst little analysis has been done to justify the validity of the approach (Pearce, 1995).

Paper in particular may be one category of waste for which the hierarchy is inappropriate. Wastepaper must be de-inked producing air and water pollution, and re-pulping uses energy which must usually come from fossil fuel sources. In contrast, virgin paper pulp is made from a renewable resource (trees), usually with renewable forms of energy (tree thinnings and offcuts). An alternative is to use wastepaper as a biofuel, burning it as an energy source in a modern incinerator. The carbon dioxide released will re-cycle to future generations of trees, and the electricity generated will displace use of fossil fuels.

Comparison of the alternatives is complex, since the range of pollutants and wastes generated from paper and wastepaper processing is large, and raw materials may come from sources of quite different character. Moreover, wastepaper is not simply recycled into the same product again—there is a

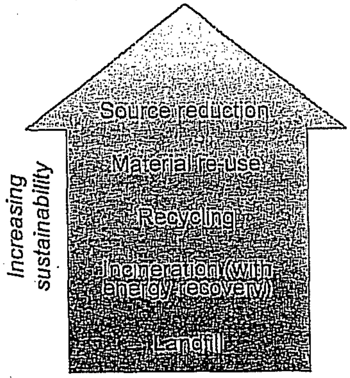

Figure 2. The waste hierarchy.

recycling 'cascade with used paper of one grade recycled into papers of the same quality or into lower quality grades. These issues are addressed in the case study described below.

Previous Studies

Many different approaches have been taken to study the environmental impact of technical choices or process activity for waste management. Huang *et al.* (1994) provide a useful review of applications of the Input–Output (I–O) approach in the environmental field, and describe a development of I–O analysis for regional solid-waste planning. I–O analysis offers a comprehensive accounting framework for the complex flows associated with urban systems, and in this sense has much in common with Life-Cycle Analysis (LCA). However, Heaps (1990) points out that, within I–O analysis, no attempt is made to explain the technical processes represented within the model, and as such the I–O approach is relatively cumbersome when used to analyse technological changes.

Linear Programming (LP) techniques have also been applied to analyse waste management issues. Glassey & Gupta (1974) construct a simple LP to investigate different rates of paper recycling. The LP approach proves quite capable of describing the production of 13 different paper grades, and the 'cascading flow of used paper. The study was, however, focused on physical recycling limits and not the environmental or resource implications. As such, the range of inputs and outputs to the model was quite limited, and few technology parameters were included.

A number of studies have been made of the paper–wastepaper cycle utilizing LCA directly, with a consequent improvement in the range of environmental effects considered. The Faculty of Technology at the Open University conducted a restricted LCA of the newsprint fraction of the municipal solid waste stream (Energy Technology Support Unit (ETSU), 1993). They concluded that LCA shows clear potential for application in the field, but found no absolute justification for recommending any particular management option for old newsprint; subjective trade-offs between energy sources and environmental criteria would be required. Johnson (1993) also investigated newsprint wastes, concluding that incineration offered environmental benefits over recycling, with her chosen system of impact weighting.

In a joint study, commissioned by the British Newsprint Manufacturers Association (BNMA), the Centre of Socio-economic Research in the Global Environment (CSERGE), Economics for the Environment Consultancy (ETEC) and Jaakko Pöyry used LCA to consider the same issues as Johnson (BNMA 1995). However, they integrated a social cost–benefit analysis in place of the more subjective impact weighting. Their study found that, with current technology, incineration might impose a lower net environmental cost than recycling, but that with Best Available Technology (BAT), the position would be reversed. When other financial aspects of the alternatives were considered, the case for recycling was said to strengthen.

The integration of economic valuation with LCA broadens the analysis beyond the scope of conventional life cycle studies. However, conventional LCA is not able to represent the volumes of material and waste to be treated by each process, and cannot assess the effects of resource or capacity constraints. Moreover, differences in the origin and destination of energy or material flows

7071

are often not identified, although these can be crucial. In the joint CSERGE–ETEC–Jaakko Pöyry study described above, Pearce (1995) notes that increased energy prices would raise the credit to recycling if recycling displaces energy-intensive virgin fibre production. However, most virgin pulp-based paper in the UK is produced in integrated mills in Scandinavia, where energy requirements are met primarily from wood harvest residues and bark; often these plants are net exporters of energy.

While their study was hampered by the same limitations of conventional LCA, Virtanen & Nilsson (1993) recognized the importance of energy sources in their study of the environmental impacts of waste paper recycling. They found that the demand for non-renewable energy would almost double if recycling rates were increased to a maximum. This finding contributed to the study s conclusion that old newsprint should be seen as a biofuel, to be burnt as an energy source.

Pistikopoulos *et al.* (1995) embedded the principles of LCA within a systems analysis/optimization framework, and could thereby investigate sourcing and constraint issues directly. Whilst the principles developed are of relevance for the present study, Pistikopoulos *et al.* are concerned with tightly defined chemical engineering systems. As such, their models are relatively limited in the range of activities described, and in the interactions between different systems. Bauen (1995) presents the first attempt to model the paper system through the resource and waste flows that arise. Linking a Linear Programming formulation of a network analysis with life cycle concepts, the approach he developed formed the starting point for the present study.

Scenarios for the Paper Analysis

The complexity of the paper system and the number of uncertainties in costs and environmental impacts suggests that a scenario approach is appropriate for the analysis. For the present paper, only a restricted number of scenarios are described, but these capture two of the key elements in the waste paper management decision—the importance attached to pollution emissions and the role of the carbon cycle. The matrix of scenarios connecting the two elements is illustrated in Figure 3.

Environmental Externalities

The US Department of Energy (USDoE) (1995) describes an externality as a benefit or cost which is an unintended by-product of an economic activity, and

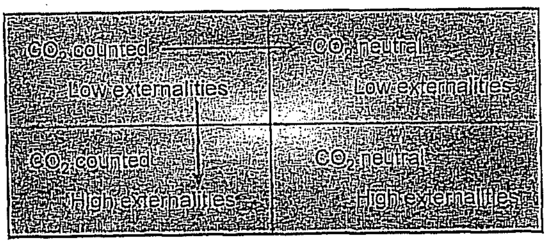

Figure 3. Scenarios for analysis.

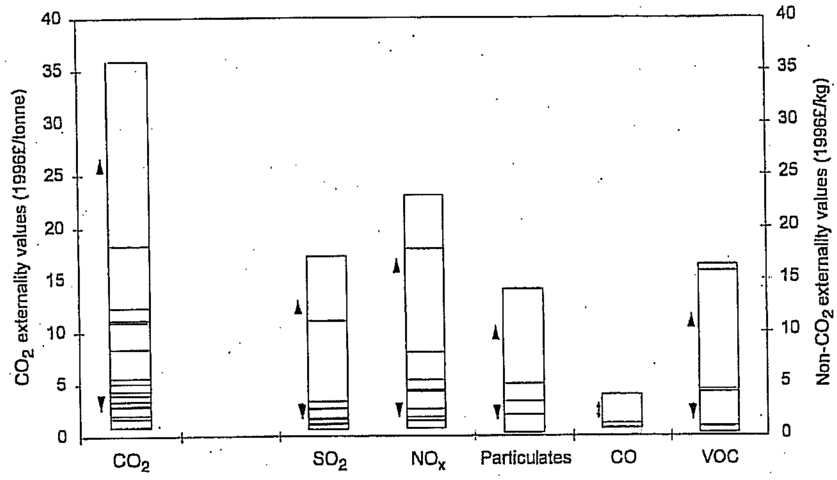

Figure 4. Environmental externalities in the literature, and those used for scenarios. *Source:* adapted from survey by Hörmandinger (1995).

which accrues to someone other than the parties involved in the activity. As a result, externalities do not enter into the market-pricing of the activity. Environmental external costs are important because they affect the value of real benefits to society, such as health and environmental cleanliness, which are otherwise neglected in the appraisal of investments.

Unfortunately, there is no simple method of defining or calculating environmental costs, and identifying each and every effect of emissions to the environment is extremely difficult. Furthermore, values calculated for one polluting process or one geographic area may not be transferable and, as highlighted by the European Commission in a recent study of externality costing (EC, 1995) each case should strictly be investigated separately.

Figure 4 shows the wide range of estimates of the appropriate externality cost for common air pollutants, identified in a literature review by Hörmandinger (1995). For the purposes of this study, a set of low and a set of high values were chosen, indicated in the figure by arrowheads. These values are intended to reflect the range of estimates in the literature, but to exclude the most extreme.

Carbon Cycle

Modern integrated paper pulp mills obtain the bulk of their energy requirements by burning 'thinnings from forest management and from discarded parts of the tree, such as the bark. This fuel is a renewable resource. Assuming that forests are managed on a sustainable basis, an amount of carbon equivalent to that emitted in the form of carbon dioxide during combustion of forest products will be sequestered by the next generation of trees before they too are cut. Heat and electricity generated from forest products may therefore be regarded as CO_2 neutral. Clift (1995) notes that some object to this analysis, since it assumes that trees are farmed sustainably, which is not always the case. For this reason, an alternative scenario is included in which CO_2 emissions from forest product combustion are counted in the externality evaluation.

Options Considered

Figure 5 shows a part of the network model developed for the paper system analysis. Four options are considered to manage post-consumer waste paper: recycling to the same grade of paper, or lower grades; incineration with energy recovery; anaerobic digestion and landfill with energy recovery.

The characteristics of each technology or strategy were drawn from a number of studies; of particular note are studies undertaken for the Department of Environment as part of the process to design the new landfill tax. To enable others to replicate our results, the key data used and assumptions made in the present study are attached as an appendix; further details can be obtained from the authors.

A contentious topic in this field is the potential danger to human health posed by emissions of dioxins from waste incinerators. However, it is assumed in this analysis that all plants operate to BATNEEC standards. Risk assessment from HM Inspectorate of Pollution (now part of the Environment Agency) indicates that such plants pose no significant health risk (HMIP, 1996).

Not all paper delivered to the end-user becomes available for re-use: some is 'stored in the form of books and packaging, amounting to some 10–20% of the total quantity. A set of constraints is applied to the system which represents degradation through shortening of pulp fibres as they are recycled. Adopting industry estimates that fibres may on average be recycled four times, and assuming a recovery factor for waste paper of 85%, in steady state the minimum input of virgin pulp required is approximately 27%.

Results

Figure 6 shows the configuration of technical options for waste management selected by the optimization process for the four scenarios. In all cases, a proportion of waste is sent directly to landfill, representing material deemed unrecoverable from the municipal waste stream. With low values assigned to environmental externalities, recycling of all paper grades is the optimal choice. However, with higher values attached to environmental impacts, other waste options offer lower total costs and are selected.

With low environmental externalities, the assumption made about carbon neutrality has no effect on the choice of options. Showing the composition of total paper supply costs, Figure 7 illustrates that, with low externality values, environmental costs comprise just 7% of the total production and supply costs for paper. Furthermore, CO_2 contributes only 10% of the total environmental costs, and only CO_2 emitted from paper or wood product combustion is affected by carbon neutrality assumptions.

The effect on the selected mix of options of increasing externality values from low to high is substantial. As Figure 7 shows, with high externality values, environmental costs rise to represent 45% of the total costs of the paper system. With these higher externality values, carbon neutrality suggests that zero recycling is optimal, whilst with carbon emissions from renewable sources counted, the highest grade of paper is still recycled. The lowest grade of paper considered, predominantly packaging materials, is selected for digestion because of its high degradability and associated gas yield.

7074

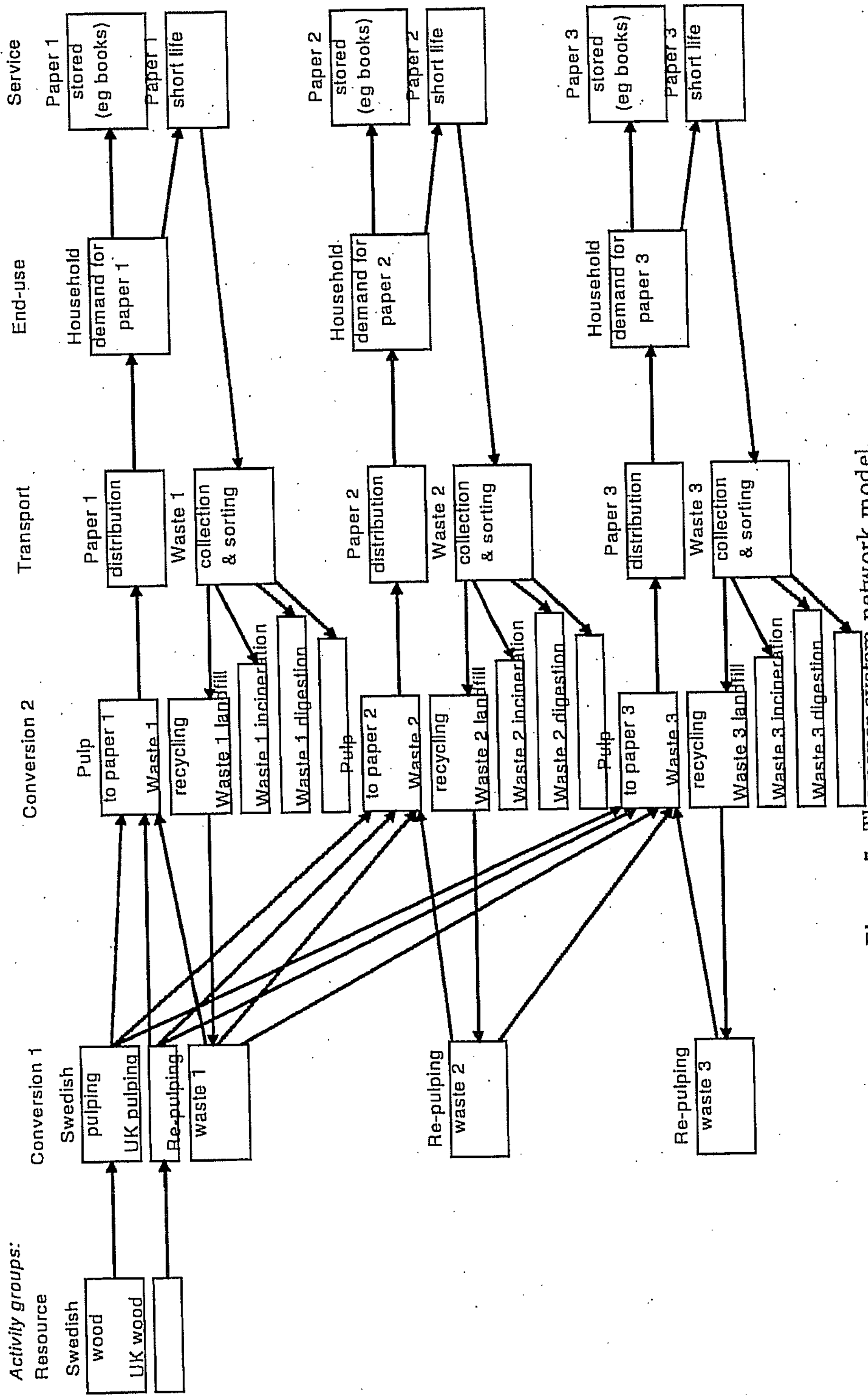

Figure 5. The paper system network model.

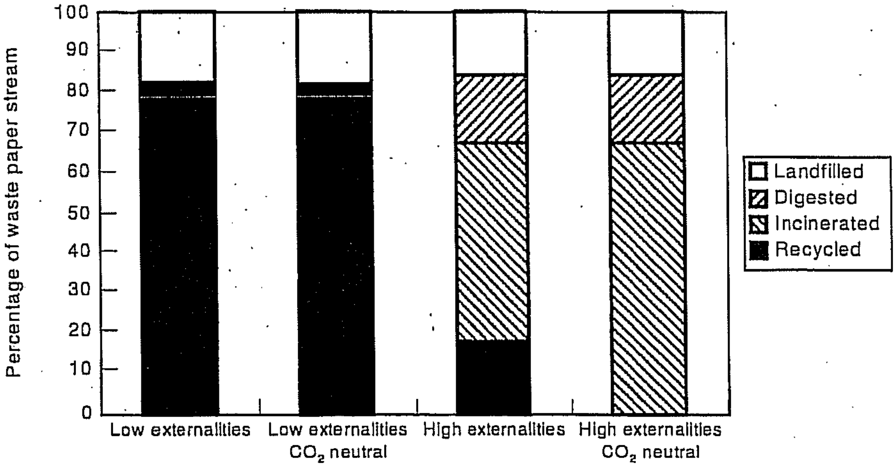

Figure 6. Optimal technical configurations by scenario.

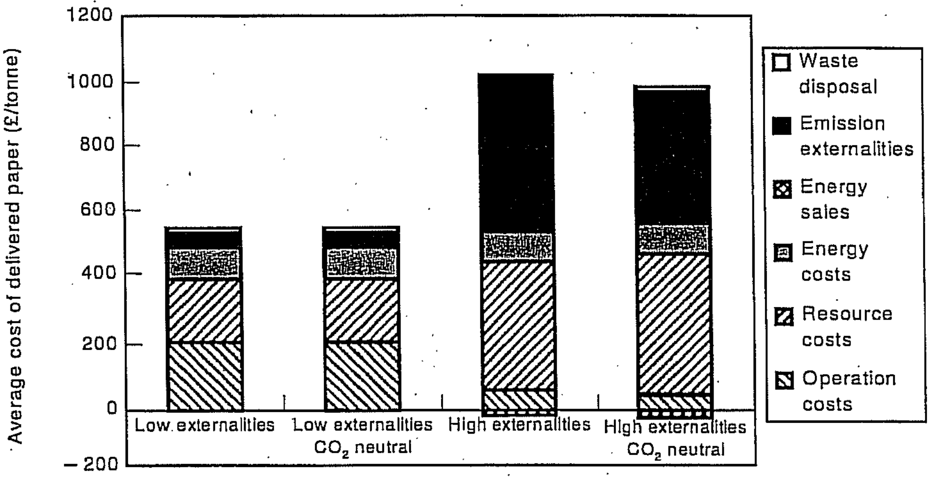

Figure 7. Composition of paper costs.

Figure 8 shows the contribution of each air pollutant to the aggregate environmental cost. Whilst costs associated with CO_2 and methane are significant at higher externality levels, emissions of pollutants that act at the regional or local level represent a greater cost of the paper system.

Table 1 shows key resource implications of the different scenarios. The consumption of primary energy is much lower for the two scenarios with high externality values. This mainly reflects the greater proportion of energy which is recovered from waste paper through incineration, resulting in the displacement of energy which would otherwise have been produced from non-renewable resources. This energy displacement results in an environmental 'credit for the pollution emissions avoided. The input of virgin wood pulp also rises for higher externality values, simply reflecting reduced recycling rates.

Somewhat counter-intuitive is the rise in freight transport activity seen with increased incineration at higher externality levels. This activity follows the increase in virgin pulp input, since the majority of virgin pulp used in the UK

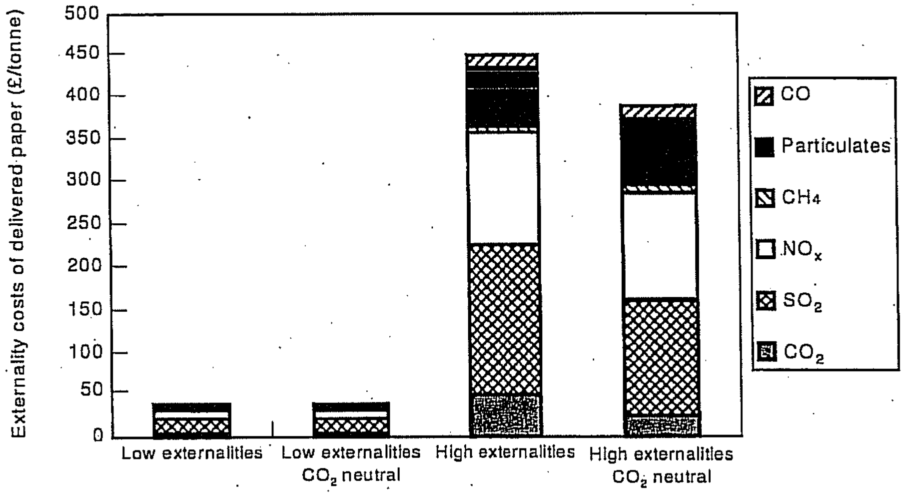

Figure 8. Externality costs of individual air pollutants.

is imported by long-distance sea freight. Whilst total freight tonne-kilometres increases, road haulage diminishes, since incinerators are usually located closer to cities than paper re-pulping facilities.

One of the arguments levied against incineration is that significant solid waste arisings still occur, in the form of bottom and fly ash. Whilst this is true, the model indicates that solid wastes deposited in landfill would reduce by 15% under a high externality scenario, as incineration increased. A lower proportion of the total waste stream is suitable for recycling than for incineration, and at present the unsuitable component is usually landfilled.

Table 2 shows the air pollution generated under each scenario, broadly divided by the scale of impacts. As externality values rise and emission costs take a greater share of the total scenario cost—becoming more significant in the optimization process—emissions of most pollutants decline by between 10% and 35%. There are two notable exceptions, carbon monoxide emissions increase by 60% due to a relatively high emission factor for combustion of wood residues; total CO_2 emissions are also greater at higher externality levels. However, CO_2 emissions from non-renewable sources—stationary and transport fossil fuel combustion—fall by 35%. Thus net CO_2 emissions to the atmosphere decline, whilst the size of the carbon cycle between atmosphere–wood–paper–atmosphere increases.

An additional reason for the rise in incineration with externality values results from the greater global warming potential, and thus higher externality value, of methane than CO_2. On average 40% of landfill gas, predominantly methane, cannot be recovered due to the slow manner of its release. However, incineration converts the majority of carbon in the waste into CO_2.

Figure 9 summarizes the cost per tonne of waste treated for each of the technical options, under low and high externality value assumptions. With current technologies and market conditions, the composition of the financial cost of alternative disposal routes varies between options, but the totals are similar. With higher externality values, the cost of incineration becomes negative, reflecting the environmental 'credit for the electricity displaced from the

Table 1. Resource use by scenario

Scenario	CO_2 from wood	Externalities	Virgin input (t wood/t paper)	Primary energy (TJ/t paper)	Freight transport (t-km/t paper)	Solids to landfill (t waste/t paper)
1		Low	0.43	31	634	0.220
2	Neutral	Low	0.43	31	634	0.220
3		High	0.95	20	1120	0.192
4	Neutral	High	1.11	17	1271	0.187

Note: Measured per tonne of paper demand.

Table 2. Wastes and air pollution by scenario

			Golbal impacts			Regional and local impacts			
Scenario	CO_2 from wood	Externalities	CO_2 (total) (kg CO_2/t)	CO_2 (non-renewable) (kg CO_2/t)	CH_4 (kg/t)	CO (kg/t)	SO_2 (kg/t)	NO_x (kg/t)	Particulates (kg/t)
1	Counted	Low	2425	1910	17.1	2.7	17.9	8.7	5.6
2	Neutral	Low	2425	1910	17.1	2.7	17.9	8.7	5.6
3	Counted	High	2686	1287	15.4	4.5	11.8	7.7	6.7
4	Neutral	High	2830	1115	14.9	5.2	10.2	7.5	7.2

Note: Measured as average per tonne of paper demand.

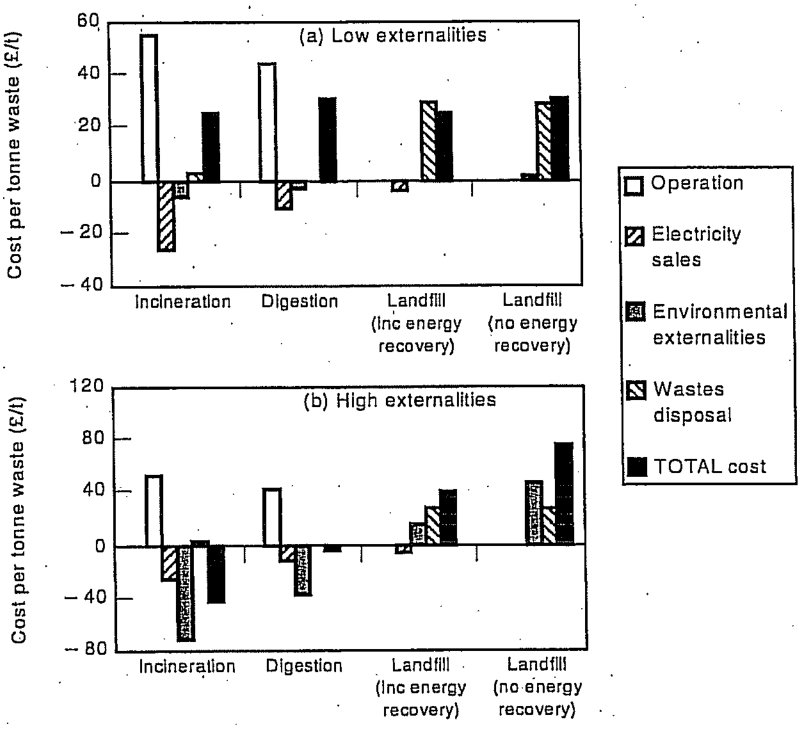

Figure 9. Comparison of waste management costs.

conventional power generation system. The high environmental costs of landfill result mainly from emissions of methane.

Conclusions

Conclusions may be drawn at two levels: concerning the findings in the case study of the paper system; and conclusions on the wider applicability of the modelling approach.

The case study has shown that recycling wastepaper may not be the best use of this resource. Many environmental impacts of alternative management options, such as incineration and anaerobic digestion, are lower. Moreover, these options lead to lower total social costs when environmental externalities are assigned relatively high, but reasonable values. Whilst sustainable forest management reinforces these findings, it is not the principal determinant, as the environmental benefits are not limited to CO_2 emission reductions alone. This finding may have important implications for the UK paper industry, which currently uses a substantial proportion of recycled fibre and advocates greater recycling due to the relatively high cost of UK virgin pulp.

It is not possible to make detailed comparisons between our results and those of the study commissioned by the BNMA, as the assumptions and details of application in the latter are unfortunately not in the public domain. The study concludes that as Best Available Technology is used increasingly in the future, recycling will impose lower environmental costs than incineration. The present study includes a more realistic representation of the sources of pulp and environmental effects, and suggests the reverse. Increasingly stringent environmental regulation is being applied to waste management sites and operations, particularly with respect to local environmental impacts. Such regulation is a form of internalization of external costs, and will therefore make incineration and digestion increasingly attractive.

Whilst incineration may be perceived as a threat by the paper industry in its present structure, in terms of overall UK industry the implications for other elements of the waste management business and environmental technology suppliers are very positive.

The case study of the paper system has demonstrated the advantages of linking a detailed LCA-style accounting framework with systems analysis techniques. The network model structure allows a detailed representation of the alternative sources of paper and pulp incorporating, for the first time, environmental benefits of virgin pulp produced with energy derived from wood residues. The network model also allows representation of the recycling 'cascade , revealing benefits from selective recycling of certain paper grades to allow energy recovery from others. Previous studies have been unable to identify such mixed strategies, due to the constraints of conventional LCA techniques.

Within the wider sustainable cities project, the intention is to replicate the type of analysis shown here for other commodities, and for broader services, such as water and energy. As additional models are developed and linked, it will be possible to incorporate a wider range of environmental and economic impacts in the analysis for individual commodities. As the project progresses, the impacts associated with individual modules will be combined into various indicators of the types presented in this case study. Through such sustainability indicators of the city, alternative strategies and sets of technological choices may be explored, to help steer a path towards sustainable development.

Acknowledgement

We are grateful to the EPSRC for supporting this research.

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Appendix

Note: For the key to numbers in the sources column of each table, see below for the Data Sources section of the Appendix.

Table A1. Electricity generation data

Item	Source	Unit	Natural gas	Fueloil	Coal	Nuclear	Hydro	Imports
Plant mix	(2)	%	10	8	51	28	1	2
Emission CO_2	(3)	kg/GWh	448	987	1079	40	—	—
factors: SO_2	(3)	kg/GWh	0.48	16.4	14	0	—	—
NO_x	(3)	kg/GWh	0.90	2.5	5.3	0.20	—	—
CH_4	(3)	kg/GWh	2.0	0.50	4.10	0.20	—	—
CO	(3)	kg/GWh	0.70	0.40	0.30	0	—	—

Table A2. Emission factors for stationary fuel combustion

Item	Source	Unit	CO_2	SO_2	NO_x	CH_4	Particulates	CO
Electricity (UK)	Table A1	kg/GJ	190.3	2.4	0.85	0.66	—	0.071
Natural gas	(1)	kg GJ	48.6	0.00025	0.13	—	0.0020	0.015
Fueloil	(1)	kg/GJ	65.9	0.016	0.19	0.00081	0.024	0.014
Coal	(1)	kg/GJ	109.6	0.63	0.33	0.0010	1.33	0.066
Wood residues	(1)	kg/GJ	105.4	0.0035	0.096	n/a	0.35	0.38
Incineration	(4)	kg/t waste	710	0.68	1.1	n/a	0.10	n/a

Table A3. Emission factors for transport

Item	Source	Unit	CO_2	SO_2	NO_x	CH_4	Particulates	CO
HGV	(4)	kg/000 t-km	61.8	0.16	1.6	—	0.22	0.54
Ship	(5)	kg/000 t-km	7.8	0.62	1.2	—	0.079	0.05
Refuse (local)	(4)	kg/000 t-km	46	—	0.62	—	0.09	—
Refuse (long)	(4)	kg/000 t-km	97	—	1.9	—	0.04	—

Table A4. Anaerobic digestion data

Item	Source	Unit	Average	Grade 1	Grade 2	Grade 3
Digester biogas yield	(6)	m^3/t	—	150	120	310
Fraction of methane in biogas	(6)	%	55			
Calorific value of methane	(7)	GJ/m^3	0.037			
Carbon content of waste	(4)	%	40			
Moisture content of waste	(4)	%	25			
Carbonaceous matter degraded	(4)	%	30			
Electricity generation efficiency	(8)	%	30			

Table A5. Incineration data

Item	Source	Unit	Value
Electricity generation	(10)	%	20
Carbonaceous matter	(4)	%	60
Solid waste remaining	(4), (6)	%wt	10
Calorific value of waste	(6)	GJ/t	12

Table A6. Landfill data

Item	Source	Unit	Value
Gas recovery	(10)	%	40
Methane in biogas	(6)	%	55
Landfill gas yield			As anaerobic digestion (Table A4)

Table A7. Energy for paper manufacture

Item	Source	Unit	Grade 1	Grade 2	Grade 3
Virgin pulp, TMP	(6)	TJ/t	24	20	26
Recycled pulp, TMP	(11)	TJ/t	18	16	20
Virgin pulp, chemical pulping	(12), (13)	TJ/t	12	10	13
Recycled pulp, chemical pulping	(12), (13)	TJ/t	9	8	10

Table A8. Energy forms used in paper industry

Item	Source	Unit	Electricity	Natural gas	Fueloil	Coal
Share of total energy input (UK)	(14)	%	44.0	28.0	9.0	19.0

Table A9. Share of energy by activity

Item	Source	Unit	Procurement sorting/cleansing	Pulping/effluent treatment	Paper manufacture
Virgin paper production	(6), (11)	%	10.8	39.4	49.8
Recycled paper production	(6), (11)	%	26.0	19.0	55.0

Table A10. Transport requirements (total distance of return journeys)

Item	Source	Unit	HGV	Refuse (local)	Refuse (long)	Ship
Forest to pulping plant, UK	(15)	t-km/t	20	—	—	—
Forest to pulping plant	(15)	t-km/t	10	—	—	—
Pulp to paper plant	(15)	t-km/t	100	—	—	1000
Paper distribution	(15)	t-km/t	100	—	—	—
Waste collection to re-pulping	(15)	t-km/t	140	—	—	—
Waste collection to incinerator	(9)	t-km/t	—	40	16	—
Incinerator ash to landfill	(9)	t-km/t	160	—	—	—
Waste collection to digester	(8)	t-km/t	—	40	—	—
Waste collection to landfill	(4)	t-km/t	—	10	160	—

Table A11. Operation costs

Item	Source	Unit	Average	Grade 1	Grade 2	Grade 3
Kerbside collection and sorting	(9)	£/t	60	—	—	—
Waste paper price	(16)	£ /t	—	160	50	40
De-inking and re-pulping	(17)	£ /t	—	90	40	30
Incineration	(10)	£ /t	55	—	—	—
Anaerobic digestion	(6)	£ /t	45	—	—	—
Landfill charge	(4)	£ /t	30	—	—	—

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