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Coupling Hidden Flows and Waste Generation for Enhanced Materials Flow Accounting

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ABSTRACT

We present an adaptation of an existing materials flow model to account for waste flows in the domestic environment. The revised approach offers added functionality for economic parameters that influence waste production and disposal. Hypothetical waste and resource management futures illustrate the utility of model. A sensitivity analysis confirms that imports, domestic extraction and their associated hidden flows impact mostly on wastes generation. The model offers enhanced utility for policy and decision makers with regard to economic mass balance and strategic waste flows.

KEYWORDS

Resource management, material flow, modelling, accounting, waste

1. INTRODUCTION

An essential contribution to informed policy decisions on waste and resource management is the analysis of the materials flow within an economy. Several authors (Matthews et al, 2000; Hendricks et al, 2000; Bringezu and Schütz, 2001a, b; EUROSTAT 2001; 2002; Bringezu et al, 2003; 2004; Longhurst et al, 2005; Mutha at al, 2006; Dahlström and Ekins 2006a, b) have developed mass balance models based on the principles of industrial ecology, and present important insights into resource efficiency and productivity in industrialised economies.

One objective of these studies has been to evaluate the decoupling of economic growth from waste production (Defra, 2002). Though reasonably resource efficient, the UK economy makes a considerable demand on materials use (Bringezu and Schütz, 2002). Officer (2007) reports the real gross domestic product (GDP) of the UK in 2005 as £1.17 x 106m and, with a growth rate of c3% per annum (Asif and Muneer, 2007), this is one of the fastest in Europe. Sheerin (2002) reports a UK materials input (total materials requirement for the economy) of 35.1 tonne (t) per capita. The Royal Society for Wildlife Trusts (2006) estimate a UK ecological footprint of 5.4gha (global hectares - an area of productive land or sea required to produce the resources consumed and absorb the wastes generated in an economy) per capita, compared to a global average of 2.2gha per capita, exceeding the available global biocapacity of 1.8gha per capita.

Several studies have quantified resource flows and their associated impacts in the context of waste management (Matthews et al, 2000; Hicks et al, 2004; Zhao et al, 2005; Jose et al, 2005; Longhurst et al, 2005). In an influential study, Matthews et al, (2000) present a comprehensive account of materials flow modelling and detail a number of critical materials flows to which the reader is referred. Adapting their approach, we present a materials flow model for the UK that couples hidden and waste flows. We introduce and test a strategic waste flow element to the model (Raffield, 2006; Figure 1), that can be used to explore hypothetical scenarios on waste and resource futures.

2. METHODOLOGY

Key model variables are presented in Table 1. The direct material input (DMI; Figure 1) is the principal variable representing material tonnage into the economy. The relationships between DMI and other variables enables the model to express the onward fate of the

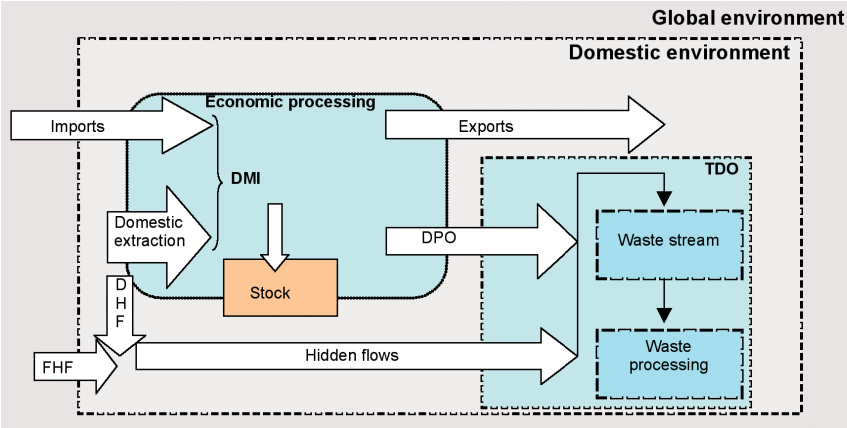

Figure 1: The advanced materials flow model (after Matthews et al., 2000; Raffield, 2006)

Input or output flow	Flow name	Symbol	Flow description
I	Imports	Q_i	Imported materials from abroad
I	Domestic extraction	Q_{de}	Domestically extracted materials
I and O	Foreign hidden flows (FHF)	Q_{fhf}	Foreign hidden flows entering the domestic environment with the imports, e.g. loose soil and foliage attached to timber
I and O	Domestic hidden flows (DHF)	Q_{dhf}	Domestic hidden flows, e.g. mining overburden or the dust like material from aggregate crushing that has no utility.
I and O	Hidden flows	Q_{hf}	Total of both foreign and domestic hidden flows
I	Net addition to stock	Q_{nas}	Additions to stock that occur within the economy and domestic environment.
O	Domestic processed output (DPO)	Q_{dpo}	Materials used in the economy and then flow to the domestic environment. Include wastes and emissions. Materials recycled would be deducted from this output.
O	Exports	Q_e	Exports out to other countries. This waste is assumed not to have an impact on the domestic environment
I	Direct material input (DMI)	DMI	Total material input into the economy from both domestic and foreign sources
I	Total material requirement (TMR)	TMR	The total amount of material entering the domestic environment including hidden flows (TMR = DMI + Q_{hf})
-	Initial stock	Initial S	The initial level of stock in the economy and domestic environment
-	Total stock	Total S	The total level of stock in the economy and environment after any net additions(= Initial S + Q_{nas})
O	Total domestic output	TDO	The total output to the domestic environment including waste, emissions and hidden flows (= Q_{dpo} + Q_{hf})
O	Total material output	TMO	The total output of materials from all sources including exports (= TDO + Q_e)

Table 1: Key model variables (adapted from Matthews et al, 2000)

DMI in million tonnes (Mt) per unit time as material is used for economic processing, in manufacturing, for example.

Flows in the model were constructed in consecutive Excel™ spreadsheet layers where variables can be altered. To model the constituent components of the DMI and the onward fate of materials as output flows, a number of additional variables were incorporated, adapting Bringezu and Schütz, (2002) and Enviros Consulting Ltd, (2006) (Table 2). For quality control, sheets with underpinning assumptions were "locked" and preconditions set (Table 2) to ensure input data was consistent. For example, the precondition of securing a mass balance throughout.

A fundamental assumption of this approach is described by Matthews et al, (2000). Hidden flows enter the domestic environment from foreign imports and domestically extracted materials (Figure 1). They include domestic material such as mining overburden, eroded soil and ancillary substances extracted coincidently with the desired resource (coal, sand and gravel, clay etc) and accumulating residues that can become waste. Once hidden flows enter the domestic environment they remain largely unaltered and are represented by a simultaneous input and output (Figure 1). Here, we utilise an adapted model (Matthews et al, 2000) to explore innovative scenarios and secure detailed DPO and TDO outputs including those for specific waste streams. Data were selected from Environment Agency (2006a; Table 3). Sewage sludge was estimated as contributing <1% w/w of the UK waste production and, for the illustrative purposes of simplifying the modelling calculations, assumed to be zero. To expand the utility of the model, it was necessary also to represent wastes disposal routes (Environment Agency, 2006b; Table 4). Input data were used to evaluate a proof of concept and examine a number of hypothetical scenarios. The consistency of model outputs were verified by reference to an independent parallel analysis (Enviros Consulting Ltd., 2006) and found to be consistent.

3. RESULTS AND DISCUSSION

3.1 Scenario analysis

The utility of the model was illustrated using three scenarios: (i) a UK reference base case; (ii) a UK depleted of domestic resources; (iii) a dramatically reduced UK reliance on landfill. We also discuss a sensitivity analysis, commenting on critical model features. The base scenario input variables are presented in Table 5 and model outputs in Table 6.

The resulting mass output derived from the base calculation is presented in Table 6, acting as a reference for the subsequent scenarios. When a scenario did not require variables to be changed they remained as presented in the base case.

The UK is increasingly reliant on imported resources. We sought to understand the impact of future changes on materials and waste flows over successive time intervals, T1, T2 and T3. Table 7 identifies variables modified from the base case (Table 5).

Model results (Table 8) illustrate the principal change is associated with the FHF as a result of growing imports. Imports increased by

Symbol	Value	Description
Q_i	33%w/w	The amount of the DMI imported for abroad
Q_{de}	67%w/w	The amount of the DMI extracted domestically
Q_{fhf}	2.0 per tonne	The amount of hidden flows that accompany imported materials. For every imported tonne of material there is 2 tonnes of hidden flow
Q_{dhf}	0.6 per tonne	The amount of hidden flows that accompany domestically extracted materials. For every tonne of material there is 0.6 tonnes of hidden flow
Q_{nas}	65%w/w	The amount of the DMI that becomes a net addition to stock (adapted Enviros Consulting Ltd, 2006)
Q_e	8%w/w	The amount of DMI exported to abroad as an output
Q_{dpo}	27%w/w	The amount of DMI that passes out of economic processing as wastes and emissions (adapted Enviros Consulting Ltd, 2006)

Table 2. Values for the base model variables (adapted from Bringezu and Schütz, 2002; and Enviros Consulting Ltd., 2006)

Waste stream	%w/w contribution
Agriculture	20
Mineral	21
Sewage sludge	0 (assumed)
Dredgings	8
Municipal	8
Industrial	13
Commercial	6
Construction and demolition	24
Total	434 Mt per annum

Table 3. Waste streams incorporated into the base models (after Environment Agency, 2006a)

Waste / route %w/w	Landfill	Energy recovery	Recycled	Other recovery	Other disposal	Reference
Agriculture	2.0	0.0	0.0	0.0	98.0	Environment Agency, 2006b
Mineral	30.0	0.0	50.0	0.0	20.0	Environment Agency. 2006b
Sewage sludge	2.9	21.6	0.0	71.0	4.5	Defra, 2006a
Dredgings	0.0	0.0	0.0	0.0	100	Morris, 2006
Municipal	75.0	9.0	16.0	0.0	0.0	Environment Agency, 2006b
Industrial	35.1	3.5	35.0	15.1	11.3	Defra, 2006b
Commercial	47.9	3.9	30.9	6.7	10.6	Defra, 2006b
Construction and demolition	30.0	0.0	50.0	0.0	20.0	Environment Agency, 2006b

Table 4. Waste streams and disposal routes for the base model (Environment Agency, 2006b, Defra 2006a, b and Morris, 2006)

Variable	Value	Reference
Qi / I	33%	Bringezu and Schütz (2002)
Qde / DE	67%	
Qnas / Split_NAS	65.0%	Adapted from Enviros Consulting Ltd. (2006)
Qe / Split_Exp	8.0%	
Qdpo / Split_DPO	27.0%	
DMI / DMI_Time	1508 Mt	
Qdhf / DHF_ton	0.6 tonnes / tonne	Bringezu and Schütz (2002)
Qfhf / FHF_ton	2.0 tonnes / tonne	

Table 5. Variables for the base case (after Enviros Consulting Ltd., 2006; Bringezu and Schütz, 2002

Variable	Total (Mt) over three time periods
Imports	14923
Dom. extraction	3031
FHF	2986
DHF	1817
Exports	362
DPO	1222
TDO	6026
NAS	2941
Landfill	1647
Energy recovery	85
Recycled	1819
Other recovery	143
Other disposal	2333

Table 6: Model output for the base UK scenario

461Mt over the time period with a consequent impact on FHF of +940 Mt. FHF make up 62.3% of the original DMI and could surpass this figure if the trends continued. Domestic extraction fell by 467Mt, equating to a drop of 281mt for the DHF, reflecting current UK trends (Sheerin, 2002). As a result of these combined effects, TDO increased by 659 Mt with a total over time of 8346Mt, > 39% greater than that produced for the base case.

tA growth in imports increases foreign hidden flows (FHF) that must be treated and disposed of within the UK (Table 8). The UK environment, already strained due to the extraction of the remaining resources, has added pressure from the escalating TDO as a result of FHF attributed to imports. Unless trading partners increase their extraction efficiency or ensure their resources are of a higher quality prior to export, then the UK continues to see an increase in FHF and the associated environmental pressures. The impacts of this scenario will not only be felt in the UK because by becoming increasingly dependant on imports, we place increased environmental burdens on our trading partners.

The statutory instruments introduced in response to the requirements of the EU Landfill Directive and, specifically, the diversion targets for biodegradable municipal waste (BMW) introduced under the Landfill Allowance Trading Scheme allow construction of scenario representing a reduced reliance on landfill (Table 9). The economic variables remained as for the base case. According to Europa (2004), BMW accounts for between 60%w/w and 70% w/w of municipal solid waste and, as such, the change in the landfill variable was based on assumption over three successive time intervals and the targets identified above.

Table 10 highlights the changes in model output. With the exaggerated targets in place, the amount of municipal waste going to landfill decreased by 68.2 Mt while other disposals increased commensurately. The overall tonnage of waste in other disposal and therefore diverted from landfill was 234 Mt, without discussion (here) of other treatment or disposal options.

tStrictly hypothetical, the output provides rudimentary insight however into the challenges the UK faces with respect to waste and resource management infrastructure. Simplistically, if energy-from-waste was adopted for 234 Mt of diverted waste (Table 10), assuming incineration facilities were large with an average capacity of 0.7 Mt/annum, then 334 such facilities would be required, with a significant density of plant likely to be required in central city areas (Longhurst et al., 2005). More usefully however, with the option to incorporate and modify a range of waste and resource management options in response to landfill diversion targets, the revised approach now has improved utility as a strategic planning tool.

3.2 Sensitivity analysis

A comprehensive sensitivity analysis is presented in Raffield (2006). This analysis processed the base case parameters with the waste streams and disposal pathways excluded as they are not main drivers of the model and fluctuate in response to the DPO. For ease, parameters on the economic side of the model were altered, in turn, applying a 10% increase on the base case parameter value (Table 11) and the knock-on influences on other parameters examined.

tThe direct material input (DMI)

Variable	Time			Reference
	T1	T2	T3	adapted FROM DTI (2003)
Dom. extraction	45.0%	31.2%	14.0%	
Imports	55.0%	68.8%	86.0%	

Table 7. Variable for the UK running out of domestic resources scenario

has most influence on the other parameters (Table 11). A 10% increase in DMI (a total material variance of 642 Mt) resulted in increases to domestic extraction (+100 Mt) and TDO (+200 Mt). Similar increases to imports and domestic extraction (Table 11) have a direct impact on hidden flows (DHF and FHF). The domestic economy parameters (NAS, DPO and exports) are influenced by the DMI, irrespective of the percentage share of DMI they account for. The only other parameter these variables impact upon was the TDO.

The sensitivity analysis supports the trends that emerge from the scenario modelling. Hidden flows (DHF and FHF) are sensitive to changes in key materials flow (Matthews et al., 2000; Sheerin, 2002). TDO rises are important and increase if DMI grows in parallel. DMI is the most influencing parameter, but when accompanied by changes in other parameters the results are often dramatic. Overall, the model parameters are interdependent and while one parameter change will not see a significant shift in results, a change in a combination of sensitive parameters can lead to the most significant variances.

Variable	Time PERIOD TOTALS (MT)			Total (MT)	Change (MT)
	T1	T2	T3		
Imports	829	1030	1290	3149	+ 461
Domestic extraction	678	500	211	1389	- 467
FHF	1650	2070	2590	6310	+ 940
DHF	407	282	126	815	- 281
TDO	2464	2759	3123	8346	+ 659

Table 8. Results for UK running out of domestic resources scenario

Variable	Time			Reference
	T1	T2	T3	
Municipal – landfill	48.7%	24.4%	6.1%	**adapted** from Europa (2004) the BMW in the MSW was reduced by 50% w/w and then **75%** w/w to exaggerate the reduction required
Municipal – other disposal	26.3%	50.6%	68.9%	**The** reduction in landfill waste was placed into this category so the change in tonnage could be represented

Table 9: Variables for a reduced reliance on landfill

Variable	Time Period Totals (mt)			Total (MT)	Change (MT)
	T1	T2	T3		
Municipal – landfill	78.2	38.8	10.0	127.0	- 68.2
Municipal – other disposal	42.2	80.8	111.4	234.0	+ 68.2

Table 10: Model output for the change in legislation for the UK

3,3 Model limitations and developments

Although the model was constructed as closely as possible to the materials flow process, there were features excluded due to their complexity. Matthews et al. (2002) included air and water as part of the material flows that were excluded here. Furthermore NAS should take into account a certain degree of outflow due to end-of-life products and buildings lost from the chain of utility as wastes. Both these factors were considered too complex to model at the proof of concept stage and their representation therefore needs to be accounted for in future developments. Additional improvements could include accounting for dynamic decay in stock, so that an inward and outward flow could be attributed, providing a more representative account. With additional sophistication, waste treatment capacity, emissions and carbon and energy flows (Uihlein et al, 2006; Biffaward, 2002) could all be incorporated.

4. CONCLUSIONS

The ability to link economic trends, hidden flows and waste generation provides additional utility to the work of Matthews et al (2000). We offer a proof of concept for these modest amendments and an initial demonstration of utility by references to three hypothetical scenarios. The amendments have utility across a range of scales. Future advancements could include implementing a decay function to the materials stock and the incorporation of flows for air and water. Specific waste streams could be further evaluated and reuse/disposal routes modelled, allowing the model to explore a range of scenarios for the new waste technologies.

5. ACKNOWLEDGEMENT

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Parameter	Model Parameters	Base case (Mt)	With 10% change (Mt)	Variance (Mt)
Imports from 33.0 to 36.5%	Imports	497	547	+ 50
	Dom. extraction	1010	960	- 50
	FHF	995	1090	+ 95
	DHF	606	549	- 30
	NAS	980	980	0
	Exp	120	120	0
	DPO	407	407	0
	TDO	2000	2070	+ 70
Total Variance (Mt) (positive and negative)				295
Dom. Extraction from 67.0 to 73.7%	Imports	497	396	- 101
	Dom. extraction	1010	1110	+ 100
	FHF	995	793	- 202
	DHF	606	666	+ 60
	NAS	980	980	0
	Exp	120	120	0
	DPO	407	407	0
	TDO	2000	1867	- 133
Total Variance (Mt) (positive and negative)				596
DHF from – 0.6 to 0.66 tonne/ tonne	Imports	497	497	0
	Dom. extraction	1010	1010	0
	FHF	995	995	0
	DHF	606	666	+ 60
	NAS	980	980	0
	Exp	120	120	0
	DPO	407	407	0
	TDO	2000	2060	+ 60
Total Variance (Mt) (positive and negative)				120
FHF from 2.0 to 2.2 tonne/ tonne	Imports	497	547	0
	Dom. extraction	1010	960	0
	FHF	995	1090	+ 95
	DHF	606	606	0
	NAS	980	980	0
	Exp	120	120	0
	DPO	407	407	0
	TDO	2000	2100	+ 100
Total Variance (mt) (positive and negative)				195
Exports from 8.0 to 8.8%	Imports	497	497	0
	Dom. extraction	1010	1010	0
	FHF	995	995	0
	DHF	606	606	0
	NAS	980	980	0
	Exp	120	132	+ 12
	DPO	407	395	- 12
	TDO	2000	1990	- 10
Total Variance (Mt) (positive and negative)				34
NAS from 65.0 to 71.5%	Imports	497	497	0
	Dom. extraction	1010	1010	0
	FHF	995	995	0
	DHF	606	606	0
	NAS	980	1070	+ 90
	Exp	120	120	0
	DPO	407	309	- 98
	TDO	2000	1010	- 90
Total Variance (Mt) (positive and negative)				278
DPO from 27.0 to 29.7%	Imports	497	497	0
	Dom. extraction	1010	1010	0
	FHF	995	995	0
	DHF	606	606	0
	NAS	980	939	- 41
	Exp	120	120	0
	DPO	407	447	+ 40
	TDO	2000	2040	+ 40
Total Variance (Mt) (positive and negative)				121
DMI from 1508 to 1658.8 mt	Imports	497	547	+ 50
	Dom. extraction	1010	1110	+ 100
	FHF	995	1090	+ 95
	DHF	606	666	+ 60
	NAS	980	1070	+ 90
	Exp	120	132	+ 12
	DPO	407	447	+ 40
	TDO	2000	2200	+ 200
Total Variance (Mt) (positive and negative)				642

Table 11: Summary of sensitivity analysis

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