

**Comparing transport emissions and impacts for energy recovery from domestic waste (EfW):
centralised and distributed disposal options for two UK Counties.**

Lucy Bastin ^a & David M. Longden ^a

^a School of Engineering and Applied Science,
University of Aston,
Aston Triangle,
Birmingham B4 7ET

Tel. (+44 (0) 121-204-3560)

Email: l.bastin@aston.ac.uk

Fax: +44 (0) 121 204 3676

KEYWORDS:

EfW, GIS, routing, Dijkstra, transport, MCA

Abstract

Many local authorities (LAs) are currently working to reduce both greenhouse gas emissions and the amount of municipal solid waste (MSW) sent to landfill. The recovery of energy from waste (EfW) can assist in meeting both of these objectives. The choice of an EfW policy combines spatial and non-spatial decisions which may be handled using Multi-Criteria Analysis (MCA) and Geographic Information Systems (GIS).

This paper addresses the impact of transporting MSW to EfW facilities, analysed as part of a larger decision support system designed to make an overall policy assessment of centralised (large-scale) and

distributed (local-scale) approaches. Custom-written ArcMap extensions are used to compare centralised versus distributed approaches, using shortest-path routing based on expected road speed. Results are intersected with 1-kilometre grids and census geographies for meaningful maps of cumulative impact.

Case studies are described for two counties in the United Kingdom (UK); Cornwall and Warwickshire. For both case study areas, centralised scenarios generate more traffic, fuel costs and emitted carbon per tonne of MSW processed.

1. Introduction

1.1 Energy Recovery from Waste (EfW): the policy and spatial planning context.

The issue of EfW is currently important for UK local authorities working to comply with the European Union (EU) Landfill Directive by reducing the volume of MSW sent to landfill. The UK Department for Food, Environment and Rural Affairs has introduced a variety of financial incentives/disincentives to ensure that these targets are met, including the Landfill Allowance Trading Scheme, and fines for non-compliance, which will be passed on to LAs. In addition, EfW schemes have the potential to reduce overall greenhouse gas emissions, assisting compliance with UK climate change targets derived from the Kyoto Protocol. Traditional, large-scale EfW facilities have typically encountered problems in negotiating the UK planning permission system, and an approach which disperses several smaller-scale distributed facilities across a municipal area may be less vulnerable to the public opposition reported in Upreti and van der Horst (2004).

Such localised approaches also increase the potential for combined heat and power schemes (Beggs, 2002), which further offset carbon dioxide emissions from the use of fossil fuels. For example, heat generated from an EfW facility can be supplied to local housing, hospitals, greenhouses or, in the case of a hybrid facility, may be used to dry green biomass material in preparation for incineration. In the spatial context, further environmental, social and economic benefits could accrue from the reduced transport required by local-scale scenarios, since locations of waste arising should be generally closer to the final disposal locations. This last hypothesis is specifically addressed in this paper.

The above arguments combine to imply that distributed EfW facilities may make a greater contribution to the objectives of sustainable development (World Commission on Environment and Development, 1987) than a centralised, large-scale facility. Several key UK policy drivers also act to encourage the distributed EfW approach. In 2002, the UK Prime Minister's Strategy Unit expressed great concern that the UK Government's targets of achieving a 60% reduction in carbon emissions by 2050 would not be met (Performance and Innovation Unit, 2002). In response to these concerns, the Energy White Paper of 2003 (Department of Trade and Industry, 2003) states in its scenario for a 2020 energy system that "There will be much more local generation, in part from medium/small community power facilities, fuelled by locally

grown biomass and generated waste”. To encourage such smaller-scale development and the use of new technologies other than conventional combustion, Renewable Obligation Certificates have been made available to provide a premium for the electricity generated.

Another policy driver for transport minimisation is the UK Waste Strategy, which clearly states that waste should be disposed of as near to its place of origin as possible. This is described as the “Proximity Principle”- a key compliance requirement in the development of an effective waste management strategy. (Waste Strategy for England and Wales, 2000).

This work models and compares the transport impact (carbon emissions, fuel costs and localised traffic densities) of centralised and distributed EfW scenarios for each of two UK LAs; Warwickshire and Cornwall. The objectives of this analysis are to answer the following questions;

1. What are the relative transport and mobile emission impacts of centralized and distributed EfW scenarios, respectively?
2. *Where* is the increased traffic, if any?

1.2 GIS for transport modelling.

To answer the above questions, we consider the road networks in the two LAs. Topological networks in a GIS are essentially graphs which would historically have been represented as adjacency or cost matrices (Taaffe & Gauthier, 1987, chapter 5) for analysis. In the past, GIS could be ‘loosely coupled’ in this way with transport-specific routines, particularly for sophisticated and computationally demanding problems such as optimal equilibrium modelling and minimum cost flow (e.g., Nyerges, 1995). However, since the early 1990s, there have been moves towards a closer integration of GIS data models with transportation planning and modelling. In many cases this involved a re-purposing or re-focussing of tools and models which already existed within GIS. Goodchild (1998) documents how edges and nodes, which were traditionally used primarily to delineate polygons in early GIS which focussed on land mapping and cadastral management, became the objects of analysis as the fundamental components of topological networks when GIS was adapted to become GIS-T (GIS for transportation). This adaptation required a new

approach to the assumptions of connectivity which held within a normalised, relational Node/Arc/Polygon database: for example, two crossing polylines could no longer be assumed to be topologically connected, if non-planar networks containing overpasses and underpasses were to be realistically modelled. In addition, subtler restrictions on edge connectivity had to be introduced, for example through the use of turn-tables to represent physical and legal barriers to real-life movement between links, and through the mapping of information on multiple lanes to single road segment geometries (Goodchild, 1998). The integration of GIS with transportation planning also required a recognition that linear links are not necessarily homogeneous in their characteristics, but may vary along their length. The traditional mapping of one edge entity to one attribute value must therefore be replaced by a one-to-many relationship in which changes in quality, and the location of those changes, are recorded for each edge. This is usually achieved through linear referencing or dynamic segmentation, and the use of these tools within GIS-T is very clearly described in Miller & Shaw (2001, chapter 3).

Once these topological networks and their attributes are defined within a GIS, the costs of travelling down each link, and across each node, can be used for network analysis to generate optimal routes, using a variety of functions and heuristics which are excellently summarised in de Smith et al. (2007, chapter 7). A tool which is commonly used for this purpose is Dijkstra's shortest-path algorithm (1959), which yields exact solutions when applied to a network on which a cost can be defined for each element. This cost is usually based on a numerical attribute, which may represent distance, expense, time or some other outlay. Most commercial GIS now incorporate network analysis tools as standard functions, and many incorporate at least some of the data models and linear programming tools necessary for advanced transport modelling.

1.3. Decision support in waste planning.

The design, location and fuelling of bioenergy and EfW facilities involves numerous economic and spatial choices, and GIS-based decision support systems are useful at all stages, from the identification of suitable facility locations and sources of biofuel and/or waste (Noon & Daly, 1996; Dagnall et al., 2000; Voivontas et al, 2001; Ma et al., 2005), to the routing of fuel materials to proposed facilities (Graham et al.

1997; Perlack & Turhollow 2003). Specifically regarding MSW, Tyson et al. (1996) have made extensive use of GIS to estimate quantities of MSW that can be potentially diverted from landfill, for use in either new biomass-ethanol or new MSW-electricity facilities, and to estimate where new facilities may be located.

The work described here was initially carried out in order to provide input data for a larger multi-criteria analysis (MCA) comparing centralised and distributed EfW options (see Figure 1). MCA is a common approach in comparing policy/strategic options; Selected criteria are weighted according to their relative importance, and performance scores for alternative options (in this case, centralised and distributed EfW scenarios) are calculated for each criterion. Scores and weights are multiplied, to produce an overall result where higher values represent more attractive options.

Table 1. MCA criterion weightings for the Cornwall and Warwickshire contexts (based on Longden et al, 2007). Criteria affected by waste transport are marked with asterisks.

	Criterion	Cornwall	Warwickshire
Social	Health of local community	11.0	10.8
	Jobs created	4.0	6.3
	* Lorry traffic impact on local communities	9.1	7.7
	Community ownership	3.7	7.4
Economic	Technical maturity	10.1	8.2
	Flexibility and strategic value	8.4	6.9
	Net cost per tonne processed	7.1	9.7
	* Cost of WTS and road transport	6.5	6.9
Environmental	Individual plant site visual impact	5.6	2.6
	Individual plant site footprint	3.7	3.1
	Plant emissions to land	2.4	3.4
	Plant emissions to air	5.8	4.2
	Plant water discharges to sewer	2.0	3.2
	* Net carbon dioxide savings	14.6	12.2
	* External costs of road transport	5.9	7.4

The full MCA analysis, and its results, are documented in Longden et al., 2007; it can be seen from the

criterion weights in Table 1 that many of the criteria selected by the participants were evaluated without the use of a GIS (e.g., ‘Monetary costs’, ‘Technology maturity’, and some elements of environmental and social impact). Other criterion scores, however, needed to be calculated or estimated using spatial information, namely; ‘Lorry traffic impact on communities’; ‘External costs of transport’; ‘Costs of operating waste transfer stations (WTS) and road transport of waste’. This paper describes the approach to and results of the GIS analysis which calculates these inputs by modelling the routing of MSW from domestic waste sources to EfW facilities. It gives more detail on the important differences between centralised and distributed scenarios (for example, localised effects of increased traffic), which are masked when, as in the MCA, each input is considered as a simple, single value.

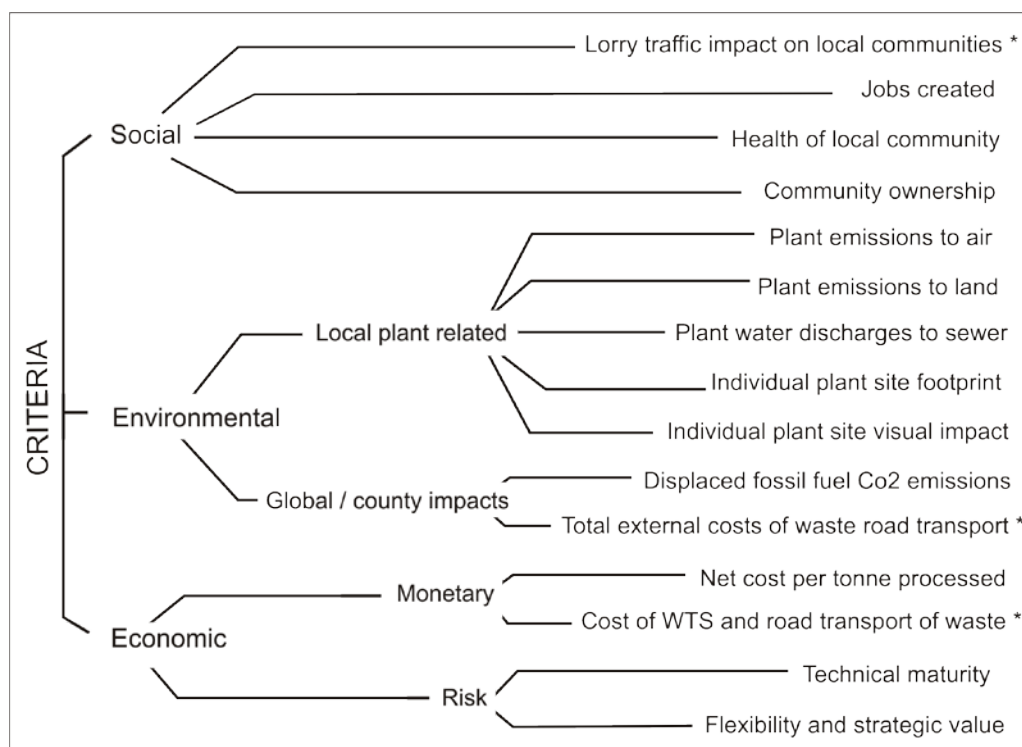


Figure 1. Illustration of the multi-criteria model. Inputs related to transport are marked with an asterisk.

1.4. Research design.

There were three stages to the MCA analysis:

1) *Agreement of criterion weights.*

2. *Calculation of criterion scores:* for the transport criteria considered here, this involved:

2a) Modelling of waste arisings based on demographic information.

2b) Siting of proposed EfW facilities with reference to these resources, and to other constraints.

2c) GIS routing analysis to calculate the vehicle movements necessary to transport typical annual waste arisings to facilities.

2d) Calculation of transport impact from these routes, in terms of traffic, carbon emissions and fuel costs.

3) Final MCA analysis, combining all criterion scores and weights.

Stage 1 is detailed briefly here, and is more fully documented in Longden et al., 2007, while stage 3 is not addressed in this paper (again, a full account can be seen in Longden et al., 2007). We will focus on the detail of the transport impacts calculated in stage 2, since these merit consideration in their spatial context and full detail, rather than as the simple numerical summaries (i.e., criterion scores) generated for the MCA.

2. Data and Methods

Each of the two EfW scenarios involves the processing of ~180,000 metric tonnes of domestic MSW per annum (~180 ktpa), so that scenarios differ only in the number, location and capacities of EfW facility. Surplus waste is sent to landfill, and the transport impact of this diversion was also considered in the analysis. The scenarios, for each LA, are as follows:

Centralised (referred to henceforth as ‘large-scale’): one large EfW facility, capable of processing 180 ktpa of waste.

Distributed (referred to henceforth as ‘local-scale’): a network of medium (60 ktpa) and small (30 ktpa) EfW facilities.

The large-scale scenarios incorporate bulking waste transfer stations (WTS) in response to expert advice from LA staff. WTS were also included to a lesser extent in the local-scale scenario for Cornwall, on the

suggestion of local experts. WTS can lower transport impact by allowing the bulk transfer of accumulated waste, reducing the number of journeys required. To handle surplus waste, the Cornwall scenarios divert 46 ktpa to landfill, while in the Warwickshire scenario, 30 ktpa are diverted to an existing EfW facility outside the area. Waste from a domestic source is carried either to a WTS, or directly to an EfW facility or landfill site. Bulked waste from WTS is carried to EfW facilities or to landfill.

2.1. Stage 1: Agreement of criterion scores.

Officers from both counties, specialising in waste management, spatial planning, sustainable development and energy planning, translated their expert and local knowledge to the MCA model in the form of criterion weights (see Table 1), and also suggested specific criteria for the initial models. The LA officers constituting the user group have a considerable resource of GIS data and in-house expertise, and have provided useful feedback throughout the development of this work. This MCA analysis uses a commercially available software tool, HIVIEW, developed by the London School of Economics, to construct its tree hierarchy model of weighted criteria and calculate scores. HIVIEW (more fully described by Phillips, 2004) uses multi-attribute value analysis (Keeney & Raiffa, 1993) in a weighted linear combination approach to support decision making where several mutually exclusive options are available.

2.2. Stage 2a: Modelling of waste arisings.

Resource points for the modelling exercise consist of domestic waste collection points. For each Output Area (OA) centroid from the 2001 Census, tonnes of waste per annum are estimated from the number of domestic households, combined with LA projections on waste growth and recycling targets to 2011. This gives a set of spatially located collection points generating variable quantities of waste, according to local population density. The non-planar road network used to model the movement of waste to target locations is derived from Ordnance Survey Meridian data and edited to restrict motorway access to valid junction points. It is important to note at this point that Cornwall has no motorways, while several motorways pass through

the Warwickshire study area.

2.3. Stage 2b: Siting of proposed EfW facilities..

Two complementary GIS processes are used to identify the most suitable locations for EfW facilities. The first uses ArcMap's 'Neighbourhood Statistics' tool to apply a flat circular kernel of varying radius to the domestic waste source points to generate 1ha-resolution raster layers showing 'hotspots' of waste arisings. This process (similar to that described in Malczewski, 1999, page 53) is an initial means for roughly identifying potential areas where the required threshold of waste for supplying a facility can be collected within a reasonable radius (i.e., within the radius of that particular kernel). The radii required to accumulate sufficient waste vary between the two case study counties because of 'edge effects'. In other words, because Cornwall is an elongated peninsula bounded by coastline, a 180 ktpa facility in Cornwall requires a 63km circular kernel to generate sufficient waste, while the Warwickshire area yields suitable hotspots for a 180 ktpa facility from kernels of radius 38km. This stage of the analysis allows the immediate discounting of areas whose environs cannot yield, within a reasonable transport distance, at least 70% of the volume of waste required to operate an EfW facility (the lowest volume at which a plant can typically function continuously without operational difficulties). It also allows distinctions to be made between areas suitable for large (180 ktpa), medium (60 ktpa) or small (30 ktpa) facilities. These 'hotspot' zones are then overlaid with a suitability map produced from an overlay of GIS data layers representing industrial sites within 1 km of a primary electricity substation and 500m of an A/B road or motorway junction, and further than 2 km from the boundary of an institutional constraint. The latter include Sites of Special Scientific Interest, Special Areas of Conservation, National Nature Reserves and Ramsar sites. Where more than one suitable site is located within or in proximity to a hotspot zone, a multi-criteria analysis model is applied to identify the final site. The criteria included distance to the centre of the hotspot zones, area of vacant/derelict land and the number of potential heat users (e.g., schools, hospitals, institutions) within 2 km. Sites for large-scale facilities were required to cover at least 4 hectares (ha).

This method of identifying 'hotspots' or high densities of collectable waste, and further refining them

by combinatory overlay with other site criteria was used by Dagnall et al, (2000). The selection of criteria is similar to other studies (Dagnall et al, 2000; Voivontas et al, 2001; Varela et al, 2000) but those used in this study were finalised with respect to Planning and Policy Statement 10 (Office of the Deputy Prime Minister (ODPM), 2005). References for the criteria are given in Table 2. The proposed locations were verified with local experts from the relevant LAs as plausible and realistic sites for potential EfW facilities. The resulting configurations of facilities are shown in Figure 2 (Warwickshire) and Figure 3 (Cornwall). WTS and landfill sites used within these models are pre-existing locations, and so are fixed within the model, as is the existing EfW site outside the Warwickshire boundary.

Criterion	Distance threshold	Reference
Industrial Sites	Within boundary	ODPM, (2005)
BSPs/Substations	Within 3 km	Brown, (2003)
Roads	Within 1 km	Varela et al. (2001) Dagnall et al. (2000) Cole et al. (1996)
Institutional constraints	Over 2 km	Friends of the Earth (1995)

Table 2. **Criteria and decision rules for identifying suitable sites for EfW facilities.**

2.4. Stage 2c: GIS routing.

Each domestic waste source point is allocated to its closest EfW facility, WTS or landfill site, *with the constraint* that all volume thresholds must be achieved for EfW facilities, whether the waste comes directly from its source or is bulked and forwarded via a WTS. Because of this constraint, some sources which are at similar distance from two targets are allocated to the second-closest target. Overall, total travel distance is minimised across each study area, as far as is possible within the constraints of the individual facilities' feedstock requirements. This generates catchments which are primarily defined by distance, but also governed by facility capacity. Table 3 summarises the numbers of source points allocated to each site, the volumes of waste generated, and the minimum, maximum and average road travel distances between sources and the facilities to which they were allocated.

Table 3. Summary of the numbers of sources allocated to each EfW facility, distances between sources and facilities, and the total projected volumes of waste collected.

SCENARIO	Number of sources	Total waste (ktpa)	Min. distance (km.)	Max. distance (km.)	Average distance (km.)
CORNWALL - local-scale					
Domestic waste direct to EfW facilities					
EfW A (30 ktpa)	234	29.92	0.28	21.79	10.44
EfW B (60 ktpa)	461	59.21	0.19	31.68	11.58
EfW C (60 ktpa)	399	51.03	0.64	28.92	8.45
EfW D (30 ktpa)	147	20.03	0.57	36.93	17.07
Domestic sources to WTS	237	29.96	0.09	4.96	2.11
Domestic sources direct to landfill	280	35.83	1.59	20.45	11.94
CORNWALL - large-scale					
Domestic waste direct to EfW facility (180 ktpa)	437	56.56	0.86	23.98	14.83
Domestic sources to WTS	991	127.14	0.09	33.55	8.62
Domestic sources direct to landfill	330	42.29	1.60	34.43	14.04
WARWICKSHIRE - local-scale					
Domestic waste direct to EfW facilities					
EfW A (30 ktpa)	250	29.87	0.72	16.32	7.17
EfW B (30 ktpa)	246	30.05	0.29	9.75	2.47
EfW C (30 ktpa)	247	30.02	2.55	9.87	8.04
EfW D (30 ktpa)	243	30.05	0.38	15.31	3.19
EfW E (30 ktpa)	255	30.29	0.19	25.69	9.01
EfW F (60 ktpa)	494	59.53	0.19	22.43	6.42
WARWICKSHIRE - large-scale					
Domestic waste direct to EfW facility (180 ktpa)	738	87.85	0.21	41.89	14.87
Domestic sources to WTS	754	92.44	0.09	17.79	3.67
Domestic sources direct to external EfW	243	30.06	2.55	9.87	8.05

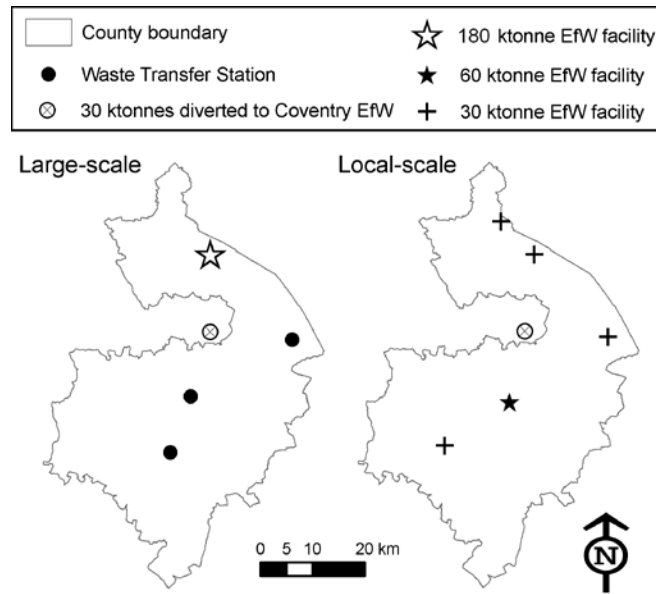


Figure 2. Proposed locations for EfW facilities in large- and local-scale scenarios for Warwickshire.

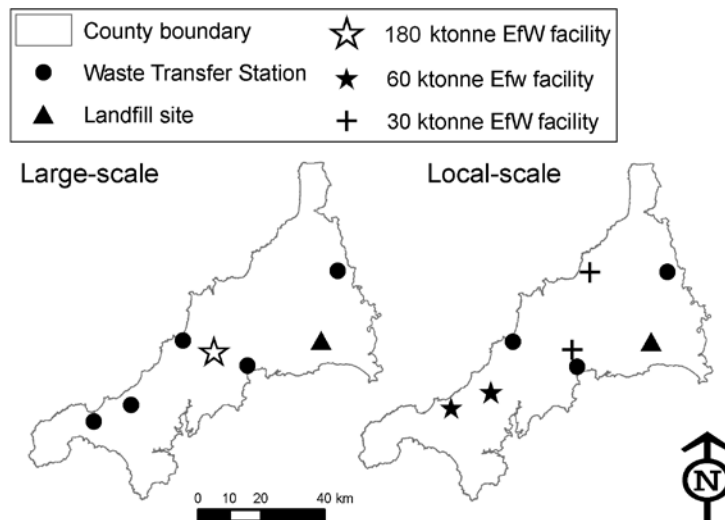


Figure 3. Proposed locations for EfW facilities in large- and local-scale scenarios for Cornwall.

The routing required for this study was simple, and could be performed on the road data described in Section 2.2, using routines embedded in ESRI's ArcMap 9.1, primarily Dijkstra's shortest-path algorithm (1959). However, in order to ease the calculation of cumulative path generation and overlay analysis, bespoke extensions were written for ArcMap 9.1. We worked entirely within the GIS environment (rather than exporting the network to adjacency matrices for faster analysis in packages such as R) largely so that we could exploit a high-quality commercial GUI which allows users to view contextual information, and to

interactively edit the data, alter parameters or introduce barriers, and re-run the analysis. The focus is user-accessibility and a flexibility which allows rapid recalculation of inputs under different hypothetical regimes (e.g., for sensitivity analysis).

Randall & Baetz (2001) took a similar approach in the creation of their ‘PRD Evaluate’ ArcView extension, which allows quick calculation of pedestrian route directness, while exploiting the existing GIS user interface for easy editing of transport links. Working entirely within the GIS environment saves time and effort on data transfer, but means that performance cannot be ‘tuned’ by accessing alternative implementations of the routing algorithms (as suggested by Zhan & Noon, 1998).

Data on existing traffic densities and flows were not available to us for consideration. The aim of the analysis is therefore to quantify the impact of traffic generated by waste transport, *over and above* ambient traffic densities, and this impact is calculated as follows:

‘Shortest-time’ routes are generated from each waste source to the target, using a shortest-path algorithm (Dijkstra, 1959). To generate the fastest routes, each road link in the GIS database is cost-weighted according to its type, using an ‘impedance’ value inversely proportional to observed average speeds for that type of road (Department for Transport (DfT), 2005). This scheme applies equal weights to urban and rural roads, in the expectation that rural speed limits applied in the UK may more closely approach urban limits in the future. These impedance values represent the difficulty of moving a unit distance, and are summarised in Table 4.

Type of road	Average speed: miles (km)/hr	Impedance factor	Carbon emissions (g/km)	
			7-tonne load	21-tonne load
Motorway	54 (87)	1.00	634.5	1481.1
A-road	48 (77)	1.125	646.8	1509.8
B-road	35 (56)	1.543	695.6	1622.9
Minor road	29 (47)	1.862	734.5	1713.7

Table 4. Impedance factors applied to road types for shortest-time routing. These are estimated from UK Department of Transport statistics (DfT, 2005, Table 7.10) and represent ease of travel, based on observed average speeds for rigid and articulated HGVs.

Each linear section of road is labelled with a cost value based on a multiple of its length and the impedance value for that road type. This cost represents the expected time it would take to traverse that section. When cumulative travel times, rather than physical distances, are used as the criterion for the shortest-path algorithm, faster routes are preferentially selected.

Cumulative journey counts are then attached to each link in the road network, based on the projected number of journeys necessary to collect the estimated annual volumes of waste. The centroid connector arcs shown in Figure 4 were automatically generated by our toolkit, and join each waste source (OA centroid) to the closest node on the topological road network, so that Census OAs are effectively treated as aggregated ‘Traffic Analysis Zones’ (Miller & Shaw, 2001, p. 57).

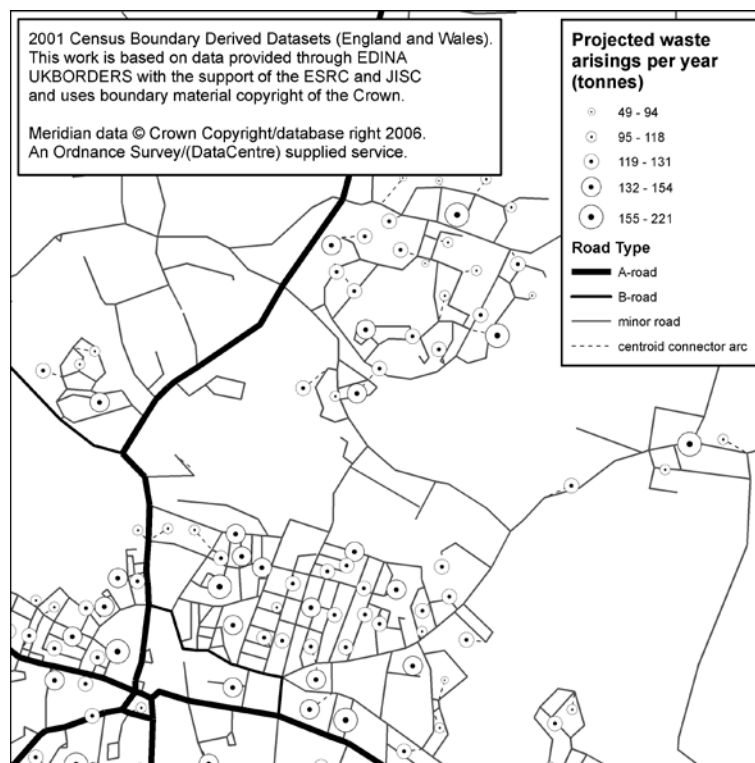


Figure 4. Waste sources based on Census OA population centroids, labelled with projected waste arisings per annum, are hooked into a topological road network.

Connectors of this type are often referred to in transport analysis as ‘fictive links’ (Nielsen et al, 1997)

and can be cost-weighted according to an expected average intrazonal travel cost (Sheffi, 1985, page 15). It is assumed that, given rigid waste collection schedules and the small size of OAs, traffic impact within each zone is constant between EfW scenarios, and in keeping with this assumption, journeys down centroid connector arcs to reach the network are considered to be of zero-length.

In all scenarios, the average estimated payload of collection truck hauling directly to EfW facilities and other final points of disposal, including WTS, is 7 tonnes. The average payload of transfer truck hauling bulked waste from WTS to EfW facilities and other points of disposal is 21 tonnes. These figures are based on a United States Environmental Protection Agency (US-EPA) modelling assessment of WTS economics, (US-EPA, 2002) which is also cited in Biffa (2002).

2.5. Stage 2d: Calculation of fuel and carbon impacts..

The analysis described above identifies the cumulative distances travelled to collect waste over a typical year, but we also went on to calculate the impact of these vehicle journeys in terms of realistic emissions estimates based on the nature of the vehicle and its expected speed. Carbon emissions per km are calculated using NAEI (National Atmospheric Emissions Inventory) speed-emission coefficients and represent 'ultimate CO₂', referring to all the carbon in the fuel emitted at the tailpipe as CO₂ (carbon dioxide), CO (carbon monoxide), unburned hydrocarbons and particulate matter which ultimately have the potential in forming CO₂' (NAEI, 2002). The estimated average speeds used to calculate the coefficients for each road type are shown in Table 4. The coefficients for a 7-tonne load are based on a partly-loaded rigid 20-tonne Heavy Goods Vehicle (HGV), and coefficients for 21-tonne loads are based on a partly-loaded articulated 40-tonne HGV. In both cases, it is assumed that the vehicles complied with Euro II emissions standards (European Union, 1997), since NAEI coefficients for the more recent Euro III and IV standards were not available at the time of analysis. Fuel costs are also specific to vehicle type, and are based on DfT 2005 statistics on fuel consumption as follows: rigid HGVs, 8.3mpg, articulated HGVs, 7.9 mpg; cost of a litre of diesel, 89.6p. This gives a cost per km. of 30p for a waste truck, and 32p for a lorry transferring bulked waste.

The waste sources in this study, based on Census geographies, are of course an approximation of ideal or actual waste-collection routes. It is obviously most efficient, on a waste collection route, to visit a group of neighbouring waste sources before returning to the EfW or transfer station. The typical payload of waste collected on municipal rounds (7 tonnes (US-EPA 2002)) is 2-3 times the average weekly waste produced by the OAs in this study (mean 153.8 tonnes p/a, s.d., 19.7 tonnes p/a). In other words, given a cluster of 3 typical OAs which are collectively producing 7 tonnes of waste per week, and a typical waste collection of 7 tonnes, the waste from those OAs could be collected in two fortnightly journeys (each collecting a fortnight's waste from a subset of the OAs) or two weekly journeys (each circulating around all three OAs). The route to and from the 7-tonne aggregated source is very similar to that which would be taken to visit the OAs singly, but less frequently. Given a consistent payload, the *number* of journeys to collect the yearly waste from each OA remains similar whether each OA's waste production is considered in isolation (as in this routing analysis) or grouped with its neighbours (as happens in reality) to fill a sequence of waste trucks. Given the relatively small size of OAs, the distance travelled *between* 2-3 OAs on a multi-stop route is small, relative to the distance travelled within the OA, and the typical distance from the OA to the waste facility. Therefore, for this analysis, the sum of individual journeys is a reasonable surrogate for the distances involved in aggregated collection routes.

The ideal, of course, is that the payload of waste collected on each municipal route will in fact increase in the future, and there are active and strategic plans in most UK LAs to achieve this aim via carefully designed routes for fortnightly, rather than weekly, kerbside collection. However, many LAs are still obliged to have weekly collections for all separate parts of the wastestreams – especially residual waste destined for incineration/landfill. While no data on planned waste collection routes was available at the time of this analysis, our Traffic Analysis Zones will in future be flexibly adapted to represent real waste collection routes.

3. Results

3.1 Relative transport impacts.

Carbon and fuel impacts for all scenarios are calculated from the routes generated by the analysis, and

are summarised in Table 5. The overall results where journey time is minimised (method b) show a higher cumulative transport impact from large-scale than local-scale scenarios, even with the addition of Waste Transfer Stations. In Warwickshire, least-cost travel distances p/a are 2.36 times higher in the large-scale scenario. The ratio of estimated carbon emissions (estimated as ‘ultimate CO₂’), between large and local scenarios is 5.54 – a substantial difference which stems from the fact that many of the extra travel kilometres in the large-scale setup are undertaken by larger vehicles hauling bulked waste, which emit more carbon per kilometre. The disparity in Cornwall is less striking, with travel distances 1.49 times those of the local-scale scenario and a carbon emission ratio of 1.85. Relative fuel costs in all cases are very similar to relative distances travelled, as the fuel efficiency assumed for the two HGV classes is very similar (see above).

CORNWALL				
Scenario	Total km. p.a.	Carbon (t.p.a.)	Fuel cost	Waste collected (t.p.a.)
Large	1,369,503	1,297.70	£424,198	225,974
Local	919,167	702.3	£281,519	225,972
Ratio, large to local: km. travelled, 1.49, carbon emissions 1.85, fuel costs 1.51				
WARWICKSHIRE				
Scenario	Total km. p.a.	Carbon (t.p.a.)	Fuel cost	Waste collected (t.p.a.)
Large	1,455,095	2,262.50	£452,309	210,346
Local	617,602	408.4	£188,146	209,807
Ratio, large to local: km. travelled, 2.36, carbon emissions 5.54, fuel costs 2.4				

Table 5. Cumulative transport impacts from shortest-time routing for all scenarios. Carbon estimates are based on the emission factors shown in Table 4. Fuel costs are based on DfT 2005 statistics as described in the text.

The smaller difference between Cornwall large- and local-scale scenarios is to be expected, since, in contrast to Warwickshire, journey frequencies for the large-scale scenario are less obviously biased towards large distances when compared to the local-scale scenario. This is in part because the Cornwall large-scale EfW facility lies at the centre of a group of 5 WTS, while the Warwickshire facility is located towards the

edge of the study area.

3.2 Interacting with the analysis..

The decision to create our bespoke tools as extensions to the existing ArcMap software allows easy access to the existing cartographic and interactive features of the software, allowing use of existing network analysis tools such as barriers to alter and effect analysis without permanently updating the topological network. Figure 5 shows results generated by the toolkit, before and after barriers have been placed on important network links.

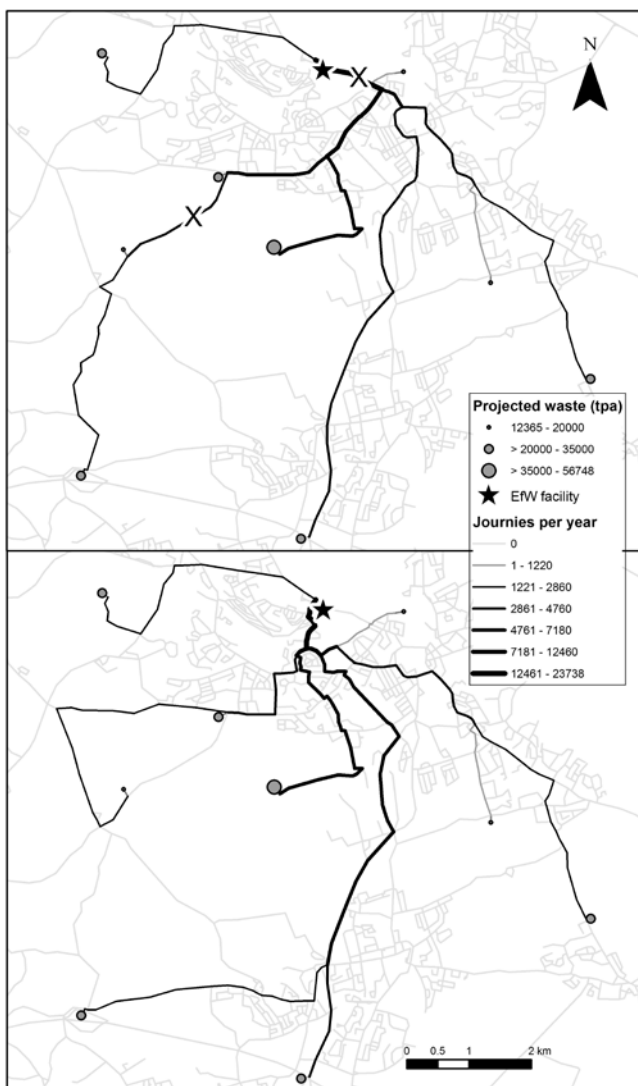


Figure 5. Incorporation of tools into the ArcMap GUI allows use of existing features; for example, interactive placement of barriers on the network. Above, cumulative journey numbers per annum have been calculated from 9 example waste sources, and assigned to road segments. The lower image shows recalculated journeys from the same sources when barriers (shown as crosses) are placed on critical road segments.

3.3 Visualising and exploring the results..

These routing approaches, by their nature, generate spatially-referenced estimates of *local* transport impact, which can then be used to assess the effects on local populations of predicted traffic concentrations. For example, in Figure 6, it can be clearly seen how a consideration of expected traffic speed in the Warwickshire context concentrates traffic onto larger roads for the longer journeys of the large-scale scenario, driving many journeys outside the county via the motorways.

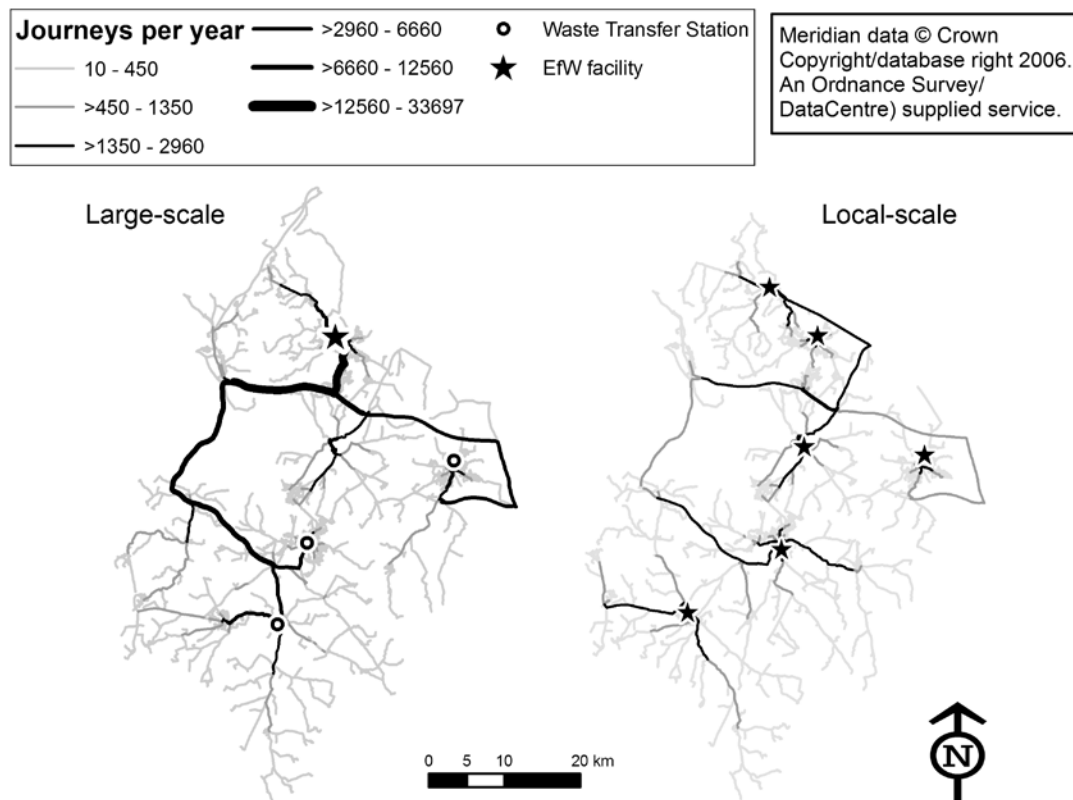


Figure 6. Cumulative transport impacts generated from shortest-time routing in Warwickshire (journeys per annum for each road segment). Large-scale scenario is shown on the left, and local-scale on the right.

The results can also be aggregated to administrative polygons (e.g., wards, OAs) or to a regular grid, for ease of comparison between scenarios. For example, Figure 7 shows how the large-scale Cornish scenario increases and redistributes expected transport impact, with much heavier use of the single major road which runs down the centre of the county. This aggregation to consistent areal units allows the maps to be easily

subtracted to identify local differences between proposed strategies; useful in strategic assessment of varying transport impact across a city, region or Environmentally Sensitive Area.

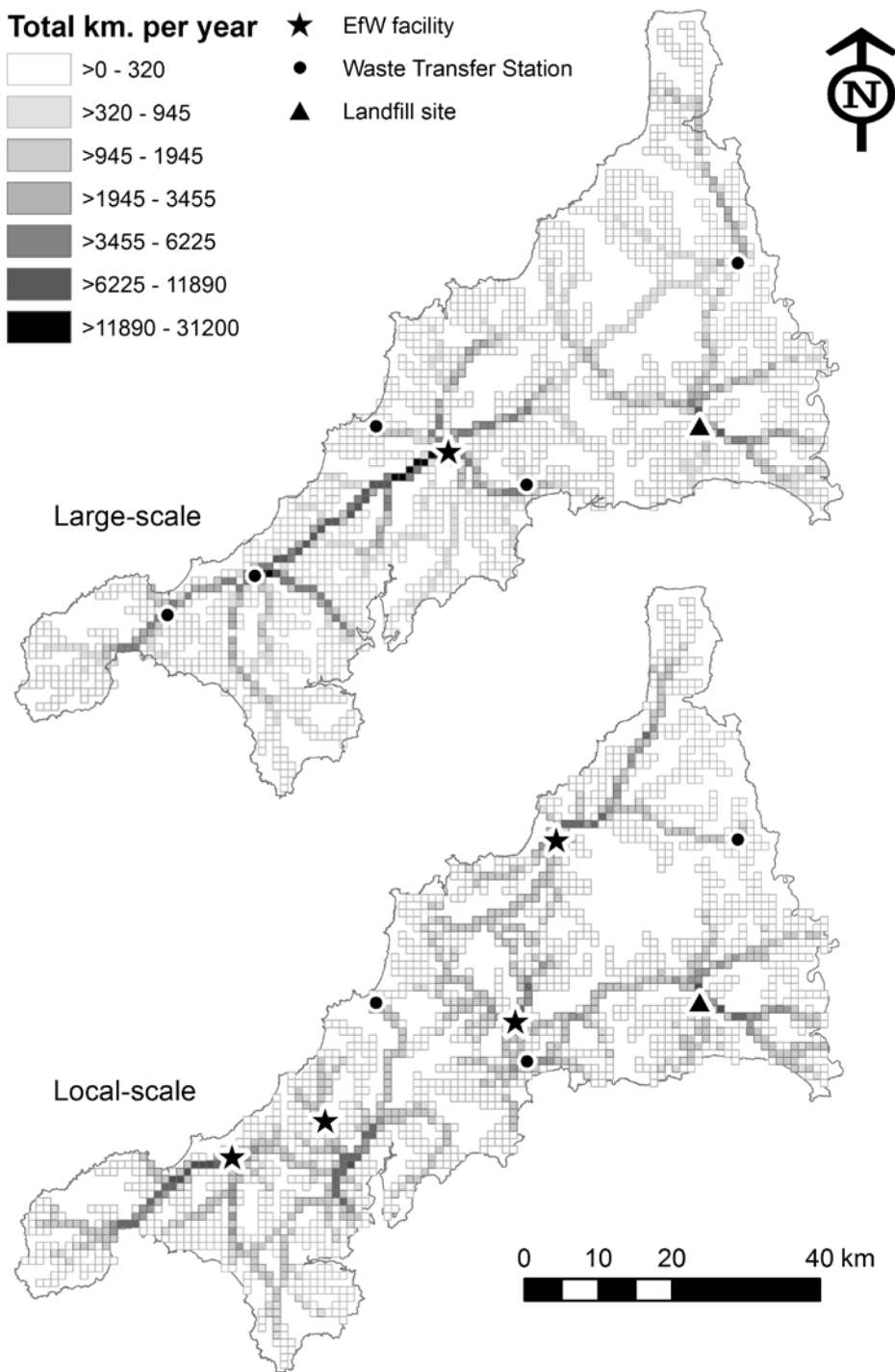


Figure 7. Transport impact for large- and local-scale scenarios in Cornwall, aggregated to 1km grid squares for ease of comparison (transport impact summarised as km travelled per annum per sq. km.).

Figure 8 illustrates this by identifying those areas where the local-scale scenario would *increase* traffic,

in comparison to the large-scale scenario (i.e., extra km. travelled per year within an area if the local-scale solution is selected). An inset shows a more detailed investigation of the travel impact of this scenario in a selected sub-area, in relation to local population density. UK Census data (2001) have been used to calculate total km. travelled in each Census Output Area under the local-scale scenario, relative to the number of people living in that area, as ‘traffic generated per head of local population’. This illustrates how, to quote Kuby et al. (2005), “network analysis within a GIS can incorporate environmental, economic and political data layers, which canlead to a more complete grasp of the effect transportation policy has on social welfare”.

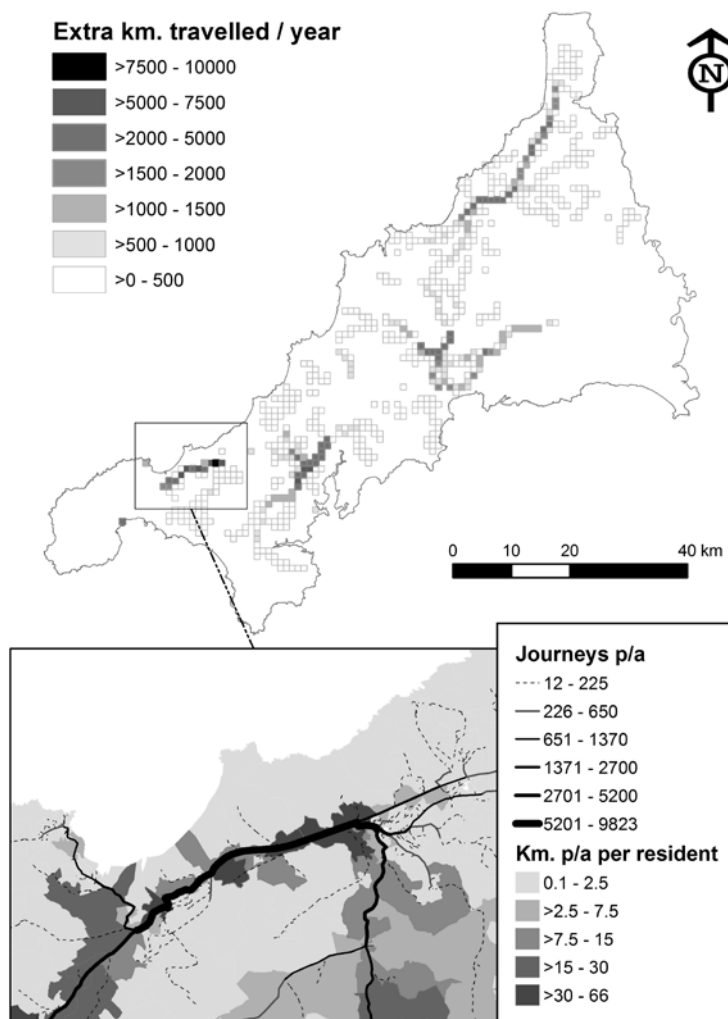


Figure 8. In the overview at the top, the areas where the local-scale scenario would *increase* traffic are identified. The inset shows a more detailed investigation of travel impact in a selected area, in relation to local population density. UK Census data (2001) have been used to show total km. travelled in each Census Output Area under the local-scale scenario, relative to the number of people living in that area.

The assignment of cumulative journey numbers and vehicle sizes to specific road segments allows these figures to be easily combined with other segment attributes such as road type, lane number and expected average speed. This can help in generating realistic estimates of carbon emissions for the different scenarios (for example, by the use of specific speed-emission coefficients as shown in Table 4). This approach has potential for combination with more complex traffic flow and equilibrium models.

4. Conclusions

The significance of this analysis lies in the correct selection and application of well-tested spatial analysis techniques to a real, policy-driven, decision-making context involving GIS at several important stages of development. In the two case study areas assessed here, the greater transport impact of large-versus local-scale scenarios is apparent. We have worked closely with experts on the ground to ensure that the assumptions and parameters in this analysis are realistic, and the results have important implications for future waste planning.

In some practical contexts, the importance attached to transport impacts is relatively low. For example, with biomass energy sources such as wood chips, the bulk of the financial outlay to get fuel to the energy plant has historically been expenditure on land, fertilisers and pesticides (Craig et al (1995). However, it cannot be assumed that fuel and pollution will continue to be so lightly costed in the future. In addition, the national policy and local compliance targets discussed in Section 1.1 will often combine to weight long-term transport impacts (e.g., carbon emissions, increased local traffic) strongly in a MCA. From Table 1, it can be seen that, for our MCA, the three criteria related to transport comprise around 20% of the experts' weightings for both LAs. In addition, the highest-scoring criterion for both LAs is 'Net carbon dioxide savings'. If this criterion is taken to include long-term CO₂ emissions from waste transport, the local-scale scenarios score highly, particularly in Warwickshire.

Domestic waste, unlike bioenergy crops, can be seen as a 'negative cost feedstock' which must, unless composted at source, be collected and disposed of in some way. Collection and transport costs (including

labour) may be minimised, but will always be a significant baseline element in the waste handling budget. (Even the lower estimated costs of local-scale scenarios ranged between ~£180,000 and ~£280,000 per annum, for fuel alone). A Scottish study of 2000 (Scottish Executive Central Research Unit, 2000) estimates waste haulage costs at 26p/tonne/mile: this value, applied to the case study areas here, gives approximate costs of between £1.5 and £3 million per annum.

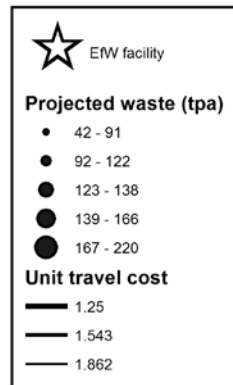
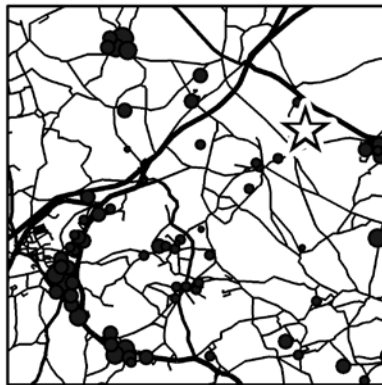
Overall, the Cornwall scenarios are less easily distinguished on the basis of transport impacts alone. The additional costs and perceived risks of the newer, small-scale EfW technologies may ultimately weight decision making against a distributed network of smaller facilities. However, the differences in transport impact between the Warwickshire scenarios were found to be substantial, particularly where carbon emissions were concerned. This is particularly pertinent since, under the 'Proximity Principle' (see Section 1.1), LAs may in future be required to defend their spatial decisions on waste disposal, and to demonstrate that environmental problems such as domestic waste are managed as close to their source as practically possible.

The tools used for this analysis have been designed so that selected parameters (e.g. road weights, estimated lorry size, facility locations and waste arisings) and network topology (including barriers) can be altered between runs, allowing ready comparison of scenarios and a degree of sensitivity analysis, as well as potential combination with more dynamic models of traffic flow and density. An approach which avoids permanent attribute and topology edits is to represent alternative scenarios as database states within a versioned GIS database (e.g. Smallworld, ArcSDE or Oracle Workspace Manager). Figure 9 illustrates how the existing toolkit can be used in combination with ArcSDE versioning to assess two alternative hypothetical EfW scenarios. In one database version, the road network has varying impedance according to expected travel speed, and the user selects an estimated average lorry load of 21 tonnes. In an alternative version, all network links have equal impedance, the EfW facility is moved, and the user-selected lorry load is 40 tonnes.

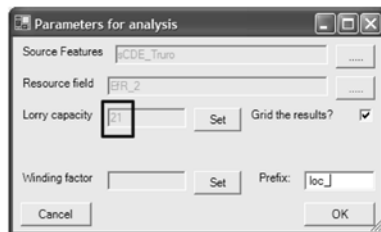
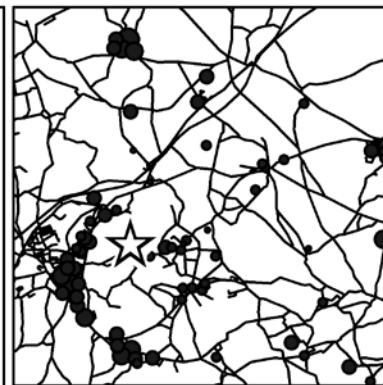
There is also potential to more closely model real waste collection routes by modifying fictive links to

connect to multiple closest nodes, to allow multi-directional routing. The traffic impact of waste trucks travelling (and idling) within OAs might also be modelled by attaching impact attributes to the fictive links. The next step will be to elicit waste collection schedules from the LAs, and generate realistic multi-stop waste collection routes. When electronic data from radio frequency identification (RFID) scanning and weighing of bins becomes available, this will be a useful benchmark against which to assess the accuracy of the estimated waste per household.

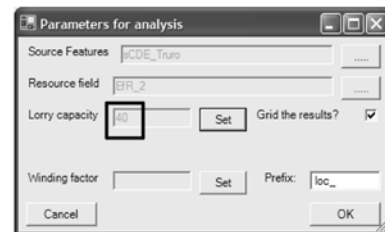
Version 1: roads weighted by ease of travel.



Version 2: roads equally weighted, EfW facility moved



Average lorry load of 21 tonnes assumed for this run.



Average lorry load of 40 tonnes assumed for this run.

Figure 9. Database versions in ArcSDE can be easily combined with user-specified parameters to evaluate alternative scenarios.

5. Acknowledgements

We are grateful to Tony Holmes of Warwickshire County Council for advice and assistance in this work.

6. References

Beggs, C. (2002). *Energy: Management, Supply and Conservation*. Oxford : Butterworth Heinemann.

Biffa (2002). *Future Perfect* (page 66). Available online at <http://www.biffa.co.uk/files/FuturePerfect-Chapter7.pdf> (Last accessed 17/04/2009).

Brown, R. (2003, personal communication). *Grid connection criteria of small and large generators*. Northampton, Central Networks. Telephone contact: 01908 510453.

Craig, .R., Bain, R.L. & Overend, R. (1995). Biomass Power Systems: where are we, where are we going, and how do we get there? The role of gasification. In *The Proceedings of the EPRI Conference on New Power Generation Technology*, October 1995, San Francisco, California. Available online from <http://www.p2pays.org/ref/19/18949.pdf> (Last accessed 14/05/2009).

Dagnall, S., Hill, J. & Pegg, D. (2000). Resource mapping and analysis of farm livestock manures – assessing the opportunities for biomass-to-energy schemes. *Bioresource Technology*, 71, 225-234.

de Smith, M. J., Goodchild, M. F., Longley, P. A. (2007). *Geospatial analysis: A comprehensive guide to principles, techniques and software tools*, (2nd ed.), Troubador, UK.

Department of Trade and Industry (2003). *Our Energy Future – Creating a low carbon economy*. HM Government, London.

DfT (Department for Transport) (2005). *Transport statistics Great Britain: 31st Edition*. TSO, London.

- Dijkstra, E. W., (1959). A note on two problems in connexion with graphs. *Numerische Mathematik*, 1, 269-271.
- European Union (1997). *Directive 96/69/EC*. Available online at:<http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:1996L0069:19961121:EN:PDF>. (Last accessed 17/04/2009).
- Friends of the Earth (2002). *Incinerator Inquiries: A review of recent public inquiries considering planning permission for municipal waste incinerators*. Available online at http://www.foe.co.uk/resource/briefings/incinerator_inquiries.pdf (Last accessed 29/04/2009).
- Goodchild, M.F. (1998). Geographic information systems and disaggregate transportation modeling. *Geographical Systems*, 5, 19–44.
- Graham, R. L., Liu, W., Downing, M., Noon, C. E., Daly, M. & Moore, A. (1997). The effect of location and facility demand on the marginal cost of delivered wood chips from energy crops: a case study of the state of Tennessee. *Biomass & Bioenergy*, 13, 117-123.
- Keeney, R.L. & Raiffa, H., (1993). *Decisions with Multiple Objectives: Preferences and Value Tradeoffs*. New York: Wiley. (Chapter 3).
- Kuby, M., Roberts, T., Tierney, S. & Upchurch, C. (2004). A comparison of Geographic Information Systems, complex networks, and other models for analyzing transportation network topologies. *A report for National Aeronautics and Space Administration*. Langley Research Center. Available online at http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20050082846_2005082801.pdf (Last accessed 20th May 2009).

Longden, D., Brammer, J., Bastin, L. & Cooper, N. (2007). Distributed or large-scale energy-from-waste policy? Implications of technology and scale at municipal level. *Energy Policy*, 35: 2622-2634.

Ma, J., Scott, N., Lembo, A. & DeGloria, S. (2005). Siting analysis of farm-based centralized anaerobic digester systems for distributed generation using GIS. *Biomass & Bioenergy*, 28, 591-600.

Malczewski, J. (1999). *GIS and Multi-criteria decision analysis*. New York: John Wiley & Sons.

Miller, H.J. & Shaw, S. (2001). *Geographic Information Systems for Transportation: Principles and Applications*. Oxford: Oxford University Press.

NAEI (National Atmospheric Emissions Inventory) (2002). Vehicle Speed Emission Factors (Version 02/3). Spreadsheet available online from http://www.naei.org.uk/data_warehouse.php. (Last accessed 17/04/2009).

Nielsen, O. A., Israelsen, T. & Nielsen, E. R. (1997). GIS-based method for establishing the data foundation for traffic models. In *The Proceedings of the Arc/Info User Conference 1997*; Available online at: <http://proceedings.esri.com/library/userconf/proc97/proc97/to600/pap573/p573.htm> (Last accessed 17/04/2009).

Noon, C. E. & Daly, M. J. (1996). GIS-based biomass resource assessment with BRAVO. *Biomass & Bioenergy*, 10, 101-109.

Nyerges, T. L. (1995). Geographical Information System support for urban/regional transportation analysis. In S. Hanson (Ed), *The Geography of Urban Transportation* (Chapter 10). London: Guilford.

- Office of the Deputy Prime Minister (2005). *Planning Policy Statement 10: Planning for sustainable waste management*. London, The Stationery Office.
- Perlack, R. D. & Turhollow, A. F. (2003). Feedstock cost analysis of corn stover residues for further processing. *Energy*, 28, 1395-1403.
- Phillips, L (2004), *The mathematics of HIVIEW and Equity*. Available online at <http://www.catalyse.co.uk>. (Last accessed 28/03/2009).
- Performance and Innovation Unit (2002). *The Energy Review*, DTI, London.
- Randall, T.A. & Baetz, B.W. (2001). Evaluating Pedestrian Connectivity Using GIS. *Journal of Urban Planning and Development*, 127, 1-15.
- Scottish Executive Central Research Unit (2000). *Local Authority Waste Management Costs Study: Implications from diversion targets in Landfill Directive*. A report by Enviros Aspinwall. Free summary available online at <http://www.scotland.gov.uk/Publications/2000/11/costimplications> (Last accessed 17/04/2009).
- Sheffi, Y. (1985). *Urban Transportation Networks: equilibrium analysis with mathematical programming methods*. New Jersey: Prentice-Hall.
- Taaffe, E. J. & Gauthier, H. L. (1987). *Geography of transportation*. New Jersey: Prentice-Hall.
- Tyson, K. S., Rymes, M. & Hammond, E. (1996). Future potential for MSW energy development. *Biomass & Bioenergy*, 10, 111-124.

Upreti, B. R. & van der Horst, D. (2004). National renewable energy policy and local opposition in the UK: the failed development of a biomass electricity plant. *Biomass & Bioenergy*, 26, 61-69.

US-EPA (United States Environmental Protection Agency) (2002). *Waste Transfer Stations – A Manual for Decision Making*. Available online at <http://www.epa.gov/garbage/pubs/r02002.pdf>. (Last accessed 17/04/2009).

Varela, M., Saez, R. and Audus, H. (2001). Large-scale economic integration of electricity from short-rotation woody crops. *Solar Energy*, 70 (2): 95-107.

Voivontas, D., Assimacopoulos, D. & Koukios, E. G. (2001). Assessment of biomass potential for power production: a GIS based method. *Biomass & Bioenergy*, 20, 101-112.

Waste Strategy for England and Wales (2000). Available online at <http://www.defra.gov.uk/environment/waste/strategy/cm4693/index.htm>. (Last accessed 17/04/2009).

World Commission on Environment and Development, (1987). *Our Common Future*. Oxford: Oxford University Press.

Zhan, F. B. & Noon, C. E. (1998). Shortest Path Algorithms: An Evaluation using Real Road Networks. *Transportation Science*, 32, 65-73.