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A Decision Support Framework
for Sustainable Waste Management

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Keywords

integrated waste management (IWM)

sustainability

life cycle assessment (LCA)

life cycle assessment interpretation

National Pollutant Inventory (NPI)

Multi-attribute utility theory (MAUT)

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Summary <heading level 1>

This article describes a decision support framework which can assist the evaluation of scenarios for the integrated management of municipal solid waste (MSW) within a local government area (LGA).

The work is initially focused on local government (i.e. municipal councils) in the state of Queensland, Australia. However, it is broadly applicable to LGAs anywhere. The goal is to achieve sustainable waste management practices by balancing global and regional environmental impacts; social impacts at the local community level; and economic impacts. The framework integrates life cycle assessment (LCA) with other environmental, social and economic tools. For this study, social and economic impacts are assumed to be similar across developed countries of the world. LCA was streamlined at both the life cycle inventory (LCI) and life cycle impact assessment (LCIA) stages.

For this process, spatial resolution is introduced into the LCA process to account for impacts occurring at the local and regional levels—considerations usually neglected by conventional LCA. This has been done by considering social impacts on the local community and by use of a regional scaling procedure for LCA data for emissions to the environment which may have impacts at the regional level.

The integration follows the structured approach of the Pressure-State-Response (PSR) model suggested by Organisation for Economic Cooperation and Development (OECD). This PSR model has been extended to encompass non-environmental issues and to guide the process of applying multiple tools. For this process, a clear relationship between pressure, state and response at the community, regional and global levels was required.

The framework primarily focuses on decision analysis and interpretation processes. Multi-attribute utility theory (MAUT) is used to assist with the integration of

qualitative and quantitative information. MAUT provides a well-structured approach to information assessment and facilitates objective, transparent decisions. A commercially available decision analysis software package based on MAUT has been used as the platform for the framework developed in this study.

Introduction <heading level 1>

The development of a decision support framework as described in this article stemmed from a critical review of the previously published approaches to the assessment of management systems for municipal solid waste (MSW) or its components. These earlier frameworks were found to be deficient when a waste management system was required to be assessed against the principles of sustainability which now provides the basis for planning and environmental legislation in Queensland, other states of Australia and most developed nations.

Past Approaches to the Assessment of Waste Management Systems <heading level 2>

Waste hierarchy <heading level 3>

The waste hierarchy has been widely endorsed to direct the choice of waste management practices from the 1980s. It involves ranking of waste management options—usually in the order: waste minimization, recycling, treatment and disposal (the least preferred). To be effective, the waste hierarchy should encompass not only the

waste management system, but also to the background (production) system where the waste minimization and recycling practices have the greatest benefit (Schall 1992).

However, waste planners and managers have very little control over waste minimization practices (i.e. the production system). Therefore, the background system in the current study does not encompass the production system for products which will ultimately become wastes, but only background processes which can assist managing the wastes (e.g. resource extraction for and production of equipment). This study's approach further negates validity of the waste hierarchy.

In addition, because the hierarchy is primarily focused on the environmental performance, the application of the waste hierarchy has not always resulted in the most sustainable outcome. Consequently, the waste hierarchy has often been criticized by regulators, academics and industry (e.g., UK EA 1997 and Thorneloe et al. 1998).

Integrated waste management systems <heading level 3>

Although the concept of integrated waste management system (IWMS) predated the waste hierarchy in some respects, it has primarily been offered to address the weaknesses of the waste hierarchy and associated policies. Initially, the IWMS concept was only based on supplementary rather than competing combinations of waste management options as it is with waste hierarchy (e.g., Tchobanoglous et al. 1993). Later, some workers also suggested that IWMS must be “environmentally sustainable, economically affordable and socially acceptable” (White 1998).

Linear programming techniques were specifically applied by many workers as economic IWMS analysis tools. The *MARKAL* model developed by the International Energy Agency is a linear dynamic model and provides a representation of the economy

of a region (e.g., Gielen 1998 and Cosmi et al. 1998). There are also non-linear static models such as Swedish *MIMES/Waste* (e.g., Sundberg 1998) or Italian *DSS* (Fiorucci et al. 2003).

More recently, other workers included some environmental or social impacts as part of their linear programming-based IWMS models (e.g., Najm et al. 2002, Shekdar and Mistry 2001 and Wang et al. 1998). *MARKAL* and *MIMES/Waste* models discussed above have also been extended to include environmental / LCA data (e.g., Gielen 1998 and Sundberg 1998, respectively). *DSS* also is also planned to include some environmental impact data (Fiorucci et al. 2003).

Full cost accounting <heading level 3>

Since the early 1990s, the regulatory agencies have promoted the concept of full cost accounting (FCA) to account for intangible costs in the waste industry decision making processes. This environmental accounting method considers: environmental expenditures; future liability costs; and external costs which encompass social and environmental impacts. However, not all social and environmental costs can yet be assessed in monetary terms. FCA is therefore unable to adequately consider all external costs of waste management operations. Therefore, inclusion of any external costs in FCA models is still not yet a common practice. For example, a widely used FCA-based IWMS planning model *WastePlan* developed by Tellus Institute in the United States does not include any external costs (Tellus Institute 2003).

Life cycle assessment <heading level 3>

More recently, there has been a growing interest in the application of life cycle assessment (LCA) to waste management issues including the IWMS assessment. Although the LCA was pioneered in the 1960s, its methodology was developed and standardized 30 years later by the International Organization for Standardization (ISO) with a considerable input by the Society of Ecological Toxicology and Chemistry – SETAC (Guinée 2002). Several European research projects in the mid-1990's – specifically in Sweden (Sundqvist et al. 1997) and the United Kingdom (Clift et al. 2000 and UK EA 1997)—contributed significantly to the development of the methodology of the life cycle inventory (LCI) stage of *LCA for waste management*.

LCA-based decision support tools <heading level 3>

The progress and standardization of LCA methodology has been conducted concurrently with work to develop LCA-based decision support tools for the IWMS evaluation. In particular, LCI-based model *IWM* developed by Procter & Gamble (McDougall et. al. 2001 or White et. al. 1995) has found numerous application by all tiers of government in Europe and North America (e.g., McDougall and Hruska 2000 and McDougall and White 1998). Another widely cited model is Swedish *ORWARE* (ORGanic Waste REsearch) which involves a combination of substance flow analysis (SFA) and LCIA methodologies (e.g., Eriksson et al. 2002 and Björklund et al. 2000).

The United States Environmental Protection Agency (US EPA) and United Kingdom Environment Agency (UK EA) also embarked on projects involving decision support tools on the basis of the LCA methodology in the mid-1990's (e.g., Solano et al. 2002 and Coleman 1998 respectively). The UK EA project resulted in the development of software *WIZARD* (Ecobilan 2003).

Project Aim <heading level 2>

The project reported in this article is aimed at the development of a decision support framework to achieve sustainable waste management practices by balancing environmental, social and economic dimensions at the global, regional and community levels as appropriate. For this process, LCA is being used as the base.

However, the framework attempts to rectify the identified deficiencies of the conventional LCA in the assessment of the sustainability of IWMS and operationalizes the following three critical aspects of sustainability (in accordance with the requirements of Queensland legislation):

- ensuring consideration is given to current and future issues (*intergenerational equity*);
- balancing environmental, social and economic dimensions of sustainability (*triple bottom line*); and
- ensuring consideration is given to burdens and impacts at the community, regional and global level (*geographical equity*).

Although conventional LCA has no *temporal resolution*, it clearly has some *temporal dimension* and assists the implementation of the intergenerational equity principle. The assessed impacts extend beyond instantaneous emissions or a single generation. Discounting based on ethical and ideological factors is also possible which might introduce some resolution.

However, LCA is unable to take into account the other two requirements. LCA does not readily accommodate the social and economic dimensions of sustainability.¹ A further deficiency of LCA is that it does not have sufficient spatial resolution to adequately consider environmental impacts at the regional or community levels (e.g., Udo de Haes et al. 2002). Recent attempts based on extensive modeling for various countries

or macroregions continually increase LCIA complexity, but are only able to introduce a *site-dependent* rather than a *site-specific* assessment (e.g., Bare et al. 2003 in the United States, Nagata et al. 2002 in Japan and Potting et al. 1998 in Europe).

Therefore, it has recently been more widely realized that LCA cannot exist in isolation from other tools (e.g., Wrisberg et al. 2002) such as a site-specific environmental impact assessment (EIA) process using risk assessment (RA) analytical procedures. In the waste management context, there have been reported recent attempts in literature to utilize LCA data along with social and economic information to facilitate triple bottom line assessment (e.g., Klang et al. 2003).

In addressing the above LCA deficiencies, the framework described in this article integrates LCA data with social and economic information. It also introduces spatial resolution into LCA to account for impacts at the regional level. To achieve these extensions, LCA is being applied in parallel with other environmental, social and economic tools.

Tools for Integration of LCA Data with Social and Economic Information <heading level 1>

Pressure-State-Response model <heading level 2>

The integration of LCA data with social and economic information is assisted by the structured approach of the Pressure-State-Response (PSR) model suggested by the Organisation for Economic Cooperation and Development (OECD 1993). In this article, the PSR model has been modified / extended to clearly encompass non-environmental issues (see figure 1) and guide the process of applying multiple tools where a clear

relationship between *pressure*, *state* and *response* needs to be established. The adopted terminology is consistent with that used in the guidelines for LCIs for waste management systems (e.g., Clift et al. 2000 and UK EA 1997).

Figure 1 clearly shows the relationships between environmental burdens (e.g., emissions or materials and energy used)—pressures box of the PSR model—and environmental, social and economic impacts. Environmental impacts in the PSR model are dependent on the sensitivity of locality (the *state* box) where burdens occur. With a few exceptions discussed below in section ‘Social Impacts’, the social and economic impacts have been assumed to be independent of the locality (i.e. *state* box) in which they occur.

This is because social impacts are defined in this framework as the impacts associated with the community perception of the waste management operations—not the actual impacts caused by these operations. The actual social impacts of some yet-to-be-constructed waste management facility cannot be accurately determined so the decision makers must rely on the community perception of similar, existing facilities.

Economic impacts (financial costs) are assumed to be of similar relative magnitude across developed countries. Therefore, both social and economic factors are generally referred to in this study, and the resulting framework, as *impacts* rather than as *burdens* (or more accurately non-flux/fixed burdens), although the terminology non-flux or fixed burdens could be used interchangeably. However, it is prudent to critically test the above assumptions of independence of social and economic impacts of the locality through the data analysis and interpretation processes.

As depicted in figure 1, the only decisions that can be made, are waste and environmental management decisions (e.g., about pollution control technologies). This is because the public perception of proposed operational plant and equipment and the financial costs cannot be easily changed by the decision makers.

<Insert figure 1 here>

Multi-attribute utility theory <heading level 2>

Another tool used to facilitate data integration within the framework is multi-attribute utility theory (MAUT).² It helps:

- integrate qualitative and quantitative information;
- provide a well structured approach to the information assessment; and
- achieve objective, transparent decisions.

A commercially available decision analysis software package—Criterium DecisionPlus 3.0 (CDP 3.0)—developed by InfoHarvest Inc. is used as the platform for the framework.

The Proposed Framework <heading level 1>

The framework, within which the various tools are used, involves the five sequential steps as illustrated in figure.

<Insert figure 2 here>

The five steps depicted in figure 2 are described in detail in the following sections:

Streamlined LCA (Step 1) <heading level 1>

***Streamlined Life-Cycle Inventory* <heading level 2>**

The streamlined LCI process broadly follows the requirements of Australian Standard/New Zealand Standard (AS/NZS) ISO 14041 (1999) and guidelines on life-cycle inventory (LCI) for waste management systems (e.g., Clift et al. 2000 and UK EA 1997). The inventory of emissions with global consequences and distribution accounts for all relevant foreground (waste management system) processes along with background processes (e.g., equipment-related resource extraction and production). This is because global impacts are generally independent of the locations where the respective emissions occur.

As already discussed in the section ‘Waste hierarchy’ above, the current study only focuses on the waste life cycle and ignores background processes related to the life cycle of products which have become wastes. The waste life cycle commences at the waste generation point and ends at the time the waste has been released to the receiving environment – as emissions or discharges - from waste management facilities.

In contrast to the above procedure for global impacts, impacts from regional emissions are generally related to locations where they occur. Consequently, regional impacts from many background emissions can not be easily predicted and data collection processes are focused, in this instance, on data which can be assessed through the proposed impact assessment processes. These approaches to impact assessment are more closely discussed in the subsequent sections of this article.

In addition, the streamlining used in this study is limited to the use of published data and models. That is, screening LCA is used herein as a stand alone study rather than as a precursor to full LCA. Testing of the proposed framework on a case study involving residential organic waste management options (Kijak and Moy 2003 or Kijak and Moy 2002) showed that the use of such published data in this process was unlikely to affect the results when equal weights were adopted for the three dimensions of sustainability (environmental, social and economic dimensions). However, if a greater weight is adopted by the decision maker for environmental criteria, the quality of the LCA data becomes of importance. Sensitivity analysis is used in this framework to assess the data quality requirements as discussed in the section ‘Interpretation (Step 5)’.

Impact Assessment for Environmental Burdens with Global Impacts <heading level 2>

For emissions with potential global distribution and consequences (e.g., carbon dioxide (CO₂) pollutant in air), life cycle impact assessment (LCIA) closely follows conventional classification, characterization and normalization according to AS/NZS ISO 14042 (2001). A simple theme oriented approach as described, for example, by Guinée (2002) is applied in this process. The only impact categories which were initially considered here, were 20, 100 and 500 year global warming potentials, GWP, (e.g., Kijak and Moy 2003). Normalization is carried out by dividing the total emission by the total global annual emission per capita. Normalized data—expressed as *person-equivalents*—become inputs to the valuation phase.

Impact Assessment for Environmental Burdens with Regional Impacts <heading level 2>

Emissions to the environment with regional consequences from the waste management system are assessed using a proposed impact assessment process. To encompass relevant background processes occurring in the LGA under study, the waste management system is expanded here to encompass any ancillary activities such as wastewater and water treatment processes included as part of the organic waste management system (Kijak and Moy 2003). In contrast, impacts of emissions from the other background processes can not be easily predicted and are disregarded. This assumption is, however, subsequently tested through data analysis and interpretation processes (e.g., sensitivity analysis).

The impacts attributable to natural resources (materials and energy consumption), as identified in the environmental LCI (both from the waste management and background systems), are included only as financial costs and assessed through the application of the relevant economic tools.

The impact assessment process used in this framework consists of a regional scaling procedure / step followed by normalization and valuation (Kijak and Moy 2003). It accommodates considerations of the sensitivity of the locality (LGA) where the emissions occur and the human and environmental hazards associated with these emissions in accordance with the general steps of the screening risk assessment (RA) procedure.

For this process, the concept of an environmentally sensitive area is introduced. An environmentally sensitive area is defined:

- for air and water contaminants, as an area in which the assimilative capacity of the receiving environment has been exceeded or is likely to be exceeded as a result of some additional load of these contaminants; or

- for contaminants emitted or discharged to land, as an area of high population density.

Steps of the conventional screening risk assessment (RA) (e.g., LaGrega et al. 1995) and corresponding steps of the impact assessment process introduced in this study are depicted in figure 3. The conventional RA steps are showed as headings for each step (box) in figure 3.

<Insert figure 3 here>

The conceptual impact assessment process depicted in figure 3 has been operationalized by the use of regional scaling and normalization discussed below in this section and weighting processes discussed in the section ‘Valuation (Step 4)’. For this process, information from the Australian pollutant release and transfer registry (PRTR), the National Pollutant Inventory (NPI) database is utilized. The NPI is currently maintained by the Australian Department of Environment and Heritage (DEH 2004) and:

1. contains all the required spatial information regarding air, water and soil emissions for 90 substances (reporting year 2002-2003);
 2. collates emission data for 33 airsheds, 31 watersheds and all LGAs throughout Australia;
 3. considers, for included substances, human health and environmental hazards (i.e., their toxic and carcinogenic nature and persistence and bioaccumulation in the environment), as well as their exposure pathways;
- and

4. provides human health and environmental hazard scores (scale of 0-3) associated with the NPI-listed substances.³

The NPI substances were selected from around 400 substances (other than banned, ozone depleting and greenhouse substances)—based on the considerations (3) and (4) above —by the NPI Technical Advisory Panel in the late 1990s (DEH 1999).

Regional scaling is not a new concept in LCA and has been used by other workers (e.g., Hogan et al. 1997 and Tolle 1997). It introduces spatial resolution into the LCIA process—an aspect that is typically neglected in LCA.

The regional scaling procedure used in this study disregards emissions that have insignificant environmental impacts. This is done by consideration of potential impacts on human and environmental health and on the assimilative capacity of the receiving environment. The impacts of substances not included in the 90 NPI-listed substances are assumed insignificant. This approach is justified because substances included in the NPI were selected on the basis of their potential effects on the human health and environment including their exposure pathways (Environment Australia 2002).

Further, only impacts from relevant emissions within a LGA situated within an NPI-designated airshed or watershed (classified here as an environmentally sensitive area), are considered as significant. This does not distinguish between the risk posed by various emissions and may overestimate the number of emissions being actually of importance for these areas. However, at a later stage, the weighting process will utilize the normalized emissions and the respective NPI's human health and environmental hazard scores to rank all these emissions (see the section 'Valuation (Step 4)').

In contrast if a LGA is located outside the environmentally sensitive areas, emissions in this LGA may be disregarded. This is because (1) the model assumes that there is no import of contaminants to this LGA from the environmentally sensitive areas;

and (2) the assimilative capacity of the receiving environment in this LGA is unlikely to be exceeded.

The second assumption is generally justified because emissions of substances related to the functional unit definition are unlikely to substantially increase ambient concentrations for these substances. Further, the potential impacts from air emissions at the community level (e.g., dust or odor nuisance) are primarily considered here as social impacts (see the section ‘Supplementing Environmental Information with Social and Economic Impacts (Step 2’).

In some situations, the above assumptions may, however, introduce oversimplification (e.g., when an air contaminant is transported to an adjacent LGA situated within an NPI-designated airshed). Therefore, these assumptions need to be subsequently tested and carefully assessed through decision analysis and interpretation processes.

The NPI contains total emissions or discharges to land for all Australian LGAs. This data is useful for normalization of emissions to land. The framework’s assumption is that emissions to land are only of importance for urban LGAs (i.e., environmentally sensitive areas) because a greater population density increases the likelihood of human exposure to contaminated land or other land-based hazards. For typical rural LGAs in Queensland with a very low population density, emissions or discharges to land can therefore be ignored.

Following this simple elimination process, the remaining emissions were normalized as a function of the total emissions within an environmentally sensitive area (by dividing them by the total NPI emissions per capita within this area) and then ranked and assessed on the basis of the NPI human and environmental hazard factors associated with the specific emissions in the valuation phase.

One of the benefits of the proposed impact assessment process is that this process does not require use of the conventional LCIA characterization (AS/NZS ISO 14042 2001) where emissions are aggregated into several impact categories (e.g., eutrophication or smog formation). The conventional characterization processes are primarily carried out to reduce the number of decision attributes, but they also introduce a greater data uncertainty.

The regional scaling procedure used for this study reduces emissions to a manageable number and the further data aggregation can thus be avoided. Following normalization processes, emissions can be directly used as decision attributes. This is because the NPI identifies the most relevant emissions (i.e. reduces their number) and ranks these emissions according to their impacts on the environment and human health (e.g. eutrophication and smog formation). Moreover, the subsequent utilization of MAUT-based software makes valuation / interpretation of a relatively large number of emissions easier.

Supplementing Environmental Information with Social and Economic Impacts (Step 2) <heading level 1>

***Social Impacts* <heading level 2>**

Social impact factors were identified through a desktop social impact assessment (SLA) assisted by the brainstorming functionality of the CDP 3.0 software. Although social impacts are generally considered to be independent of the locality or sensitivity of the receiving environment, their significance is associated with two broad types of LGA

character—namely rural and urban as suggested in the regional planning documents in Queensland (SEQRCC 2001).

The initially identified list of social impact factors was revised following an initial pilot survey⁴ (based on questionnaires) conducted for the purpose of this project between December 2000 and February 2001. The pilot questionnaire was developed and tested on a representative group of stakeholders to identify potential problems and to refine the scope and complexity of the survey. For this process, the respondents were also encouraged to provide comments regarding relevance of these factors and suggest any changes. The final list included eight social impact factors, namely:

1. impact on visual amenity;
2. odor;
3. noise;
4. traffic increase;
5. dust;
6. impact on public health (e.g., disease transmission via disease vectors);
7. impact on property value; and
8. stigma perceived by affected community.

These social impacts were prioritized using the data from a final questionnaire sent to 169 stakeholders representing waste managers and planners from local and state government, industry, consultancy and academia in Australia in April 2001. The response rate exceeded 30 percent. This survey was used to rate relevant waste management operations and to determine the relative sensitivity of the rural and urban LGAs to the identified social impact factors. The survey data are used in the valuation phase.

The survey questionnaire was designed to be as simple as possible to increase the participation rate and data reproducibility. The data provides default values for use in

subsequent applications of the framework. Therefore, each fixed waste management operation was classified as one of four broad activities: home composting, waste recycling, waste treatment and waste disposal. All itinerant operations (i.e. waste collection and haulage on public roads rather than incoming and outgoing traffic at waste facilities) were assumed to have insignificant social impacts. The survey results are illustrated in figures 4 and 5 where the vertical axes depict the relative significance of the impact from a low of 1 to a high value of 5. The horizontal axes show the respective social impact factors as listed above.

<Insert figures 4 and 5 here>

This assessment process is limited in the present study wherein the weights of the eight social impact factors for waste management operations are extrapolated from the corresponding weights of four broad waste management activities assessed through the survey. The extrapolation is carried out as follows:

- A single waste management operation at a site is assigned the corresponding activity weight (e.g., aerobic composting is assigned social impact factor weights for waste recycling as per figure 4).
- If multiple operations are carried out at a site (e.g., garden waste shredding—waste recycling occurring at the site used for waste disposal), only the primary operation at that site is taken into account. The primary waste management operation (i.e. waste disposal in the above example) is solely assigned the corresponding weight. The secondary activity, waste recycling is disregarded.

Economic Impacts <heading level 2>

Economic impacts are identified using a modified full cost assessment (FCA). The system boundaries in this modified FCA are identical to those used for the LCA. In a case study for residential organic wastes used to test the framework (e.g., Kijak and Moy 2003), the system boundaries were initially delineated to only encompass the waste management system. However, this system was expanded to include background processes such as wastewater and water treatment processes.

All costs are also standardized to the functional unit for consistency with the LCA process. This standardization takes into account the waste quantity and the period during which that waste has been generated.

The full cost of a waste management operation is estimated as the difference between the net costs (up-front costs, operating costs and back-end costs) and net benefits (revenues from the sale of materials and energy along with any avoided costs).

Although environmental burdens such as energy and materials identified by LCA are quantified in FCA as financial costs, the remaining environmental burdens (emissions to the environment) or external costs often considered in FCA, are not included as part of the FCA this study. Instead, they are assessed using socio-environmental tools. This is to avoid double counting of economic impacts and environmental emissions and subsequent bias in the outputs of the assessment of waste management options.

The cost depreciation is carried out according to the capital recovery equation - equation (1) (e.g., University of Berkeley 2002). This provides long term capitalized costs. All costs are also updated to their present values according to the compound amount equation - equation (2) (e.g., University of Berkeley 2002).

$$A/P = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (1)$$

$$F / P = (1 + i)^n \quad (2)$$

where:

i is the interest or discount rate per accounting period

n is the number of accounting periods

A is a uniform capital cost per period (for n periods).

P is a present value at time 0

F is a future value at time n .

Data Integration (Step 3) <heading level 1>

The process of environmental, social and economic data integration was previously discussed in section ‘Tools for Integration of LCA with Social and Economic Information’.

Valuation (Step 4) <heading level 1>

The CDP 3.0 software’s default *simple multi-attribute rating technique* (SMART) is applied in the valuation process. The previous work by Hertwich and Hammit (2001) and Miettinen and Hämäläinen (1997) provided theoretical foundations for the use of *multi-attribute utility theory* such as SMART technique in the context of the valuation phase of LCIA. In the proposed framework of this present study, SMART has found a practical application primarily because it is well suited to deal with quantitative data. It also adds

useful functionality by allowing for the inclusion of additional alternatives in the decision process.

The decision process starts with construction of a decision hierarchy to identify all levels of criteria connected, on one side of the decision hierarchy, to the decision goal (*sustainability*) and, on the opposite side, to the waste management options (decision alternatives). The highest level criteria connected to the decision goal are the three dimensions of sustainability (i.e. environmental, social and economic criteria). The lowest level criteria (or more correctly, lowest level sub-criteria) connected to the decision alternatives are defined as decision attributes. For example, all social impact factors weighted in the social survey (see the section ‘Social Impacts’) become decision attributes. *Social criteria* is the parent criterion for these decision attributes.

Following construction of the decision hierarchy, all criteria are weighted. A direct comparison method is used in the weighting process. Equal weights are typically adopted for all criteria with the exception of weights for social impact factors connected to their parent criterion and weights for emissions with regional consequences. Survey data about the sensitivity of social impact factors in relation to the area character (see figure 5) are used to weight social impact factors. NPI human health and environmental hazard scores (see section ‘Impact Assessment for Environmental Burdens with Regional Impacts’) are applied in the weighting process for emissions with regional impacts. Finally, financial costs, social impact factor weights (see figure 4) along with normalized global impacts and emissions with regional impacts are directly used as *ratings*, i.e. weights of decision alternatives connected to the lowest level criteria – the decision attributes.

Weights which are initially adopted here as equal (e.g., for three dimensions of sustainability) are dependent upon the decision makers’ preferences. The decision makers can decide, for example, that *social criteria* should be given a greater weight than environmental or economic dimensions of sustainability. In either case, the adopted

weights are further tested in data analysis and interpretation processes. The interactive CDP 3.0 software package allows for real-time evaluation of results to *see* how the weights and choices made affect the decision scores of waste management alternatives (see section ‘Interpretation (Step 5)’).

SMART normalizes these user’s weights to *priorities* (i.e. SMART internal weights in the range 0 – 1) according to equation (3) (InfoHarvest Inc 1999). Although *priorities* of *ratings* could be calculated in a similar way, the CDP 3.0 software uses *value functions* in transforming ratings to priorities. The software provides linear, exponential, and custom *value functions* with a positive or negative (i.e. increasing or decreasing) slope. Value functions are useful here because they typically deal well with broad / wide environmental data distribution (i.e. emissions which differ by several orders of magnitude). The mathematical processes ensure that the determined *priorities* for all alternatives are mutually independent.

Single value decision scores can finally be computed by the CDP 3.0 software for all waste management alternatives to show how these alternatives meet the decision goal (*sustainability*). SMART calculates decision scores for a hierarchy of M levels of criteria (including the decision goal) according to equation (4) (InfoHarvest Inc 1999).

$$W_S^C = \frac{(r_S^C - r_0^C)}{\sum_{S'=1}^{N^C} (r_{S'}^C - r_0^C)} \quad (3)$$

$$D_A = \sum_{C_1=1}^{N^G} W_{C_1}^G \sum_{C_2=1}^{N^{C_1}} W_{C_2}^{C_1} \dots \sum_{C_M=1}^{N^{C_{M-1}}} W_{C_M}^{C_{M-1}} P_A^{C_M} = \sum_{C_M=1}^{N^{C_M}} A_{C_M}^G P_A^{C_M} \quad (4)$$

where:

Equation (3)

r_s^C – the user’s weight of a sub-criterion S connected to the parent criterion C (e.g., a sensitivity weight for rural and urban areas against social impacts as depicted in figure 5)

$r_{s'}^C$ – the user’s weight of a sub-criterion S' where $S' = 1, \dots, N^C$ – the number of all sub-criteria connected to the parent criterion C

r_0^C – the user’s defined scale minimum (i.e. ‘1’ in the above example)

W_s^C – priority of a sub-criterion S connected to the parent criterion C

Equation (4)

D_A – decision score for a waste management alternative A

N^G – the number of criteria connected of the decision goal (i.e., environmental, social and economic criteria connected to sustainability)

$W_{C_i}^G$ – priority of criterion C_i connected to the decision goal where $C_i = 1, \dots, N^G = 3$ as explained above)

C_i – a criterion at the i level of criteria in the decision hierarchy where $i = 1, \dots, M = 4$ because of the four levels of criteria adopted in the decision hierarchy (i.e. sustainability dimensions, locality, impact and burden levels)

N^{C_i} – the number of sub-criteria connected to the parent criterion C_i at the i level of criteria where $i = 1, \dots, M = 4$ as explained above)

$P_A^{C_M}$ – priority of the lowest level criteria (attribute) connected to alternative A

$W_{C_i}^{C_M}$ – priority of criterion C_i connected to the parent criterion C_M .

Interpretation (Step 5) <heading level 1>

The CDP3.0 software is also a useful tool in the process of life cycle interpretation (AS/NZS ISO 14043.2001) due to the software’s data analysis

functionalities. Specifically, contributions-by-criteria analysis, sensitivity analysis and trade-off analysis were found useful in the interpretation process.

In the contributions-by-criteria analysis, it can be determined which criteria made the greatest contribution to the total decision score of each alternative. An example of this analysis for the highest level criteria (three dimensions of sustainability) from a case study for five residential organic waste management options (e.g., Kijak and Moy 2003), is illustrated in figure 6. The contributions in the stacked bar graph are shown as greyscale coded strips. The longer the strips for environmental, social and economic criteria, the greater the contribution of these criteria to sustainability. Contribution-by-criteria analysis clearly showed that whilst Option 3 had the greatest contributions from the social and environmental criteria, Option 1 was assessed as the second most preferred option due to its significant contribution of economic criteria (i.e. the option's low cost) to sustainability. In contrast, Option 5 was assessed as the least preferred due to its high cost.

<Insert figure 6 here>

Sensitivity analysis for the criteria weights in the CDP 3.0 software can be performed graphically using so called sensitivity plots. An example of sensitivity analysis from the same case study is illustrated in figure 7.

<Insert figure 7 here>

In the sensitivity plot shown in figure 7, the horizontal axis shows *priorities*—SMART internal weights in the range between 0 and 1—used in the calculation of decision scores. The vertical axis shows the decision score for each waste management

option. The plot shows how changing the priority value of the current weight would affect the decision scores if it is varied over all possible values when all other weights are fixed.

Decision scores change linearly so that each alternative is represented by a numbered straight line on the sensitivity plot (see figure 7). Cross-over points on the plot are critical points of the decision, especially if they are situated adjacent to the current priority shown as a vertical priority line. By dragging the slider at the bottom of the priority line within the software environment, it can be seen how other changes in the priority affect the decision scores of each alternative. For example, figure 7 shows that when the priority value of a weight given to social criteria decreases from 0.33 (*current value* in this figure) to 0.28 (*temp value*), Option 2 becomes the third most preferred option rather than Option 4 at the priority 0.33 (i.e., when equal weights are given to all three dimensions of sustainability).

Along with the sensitivity plots, criticalities (i.e., numerical results of the sensitivity analysis for all priorities of the user's weights) are also calculated by the software. Criticalities indicate how much the current priority needs to be changed before the model's preferred alternative is superseded by a different alternative. They are expressed as a percentage estimated by taking into account the minimal change required in relation to the total priority scale. A model is typically considered as stable if criticalities are greater than five percent. In the above example, criticality of social criteria was estimated by the software as 45.1 percent.

Finally, another standard functionality of CDP 3.0—trade-off analysis—is arguably the most useful tool in any multi-criteria decision process (e.g., MAUT). It determines trade-offs of ratings—weights of decision alternatives connected to attributes—by showing how ratings must change in order to alter the decision score of the best scoring decision alternative (i.e., Option 3 in the considered example) by the

same amount as arises from a change of one unit in the scale of a selected reference attribute. For instance, Option 3 *net cost* rating requires 375 percent smaller change (or a change by 9¢ only) in relation to the adopted net cost scale (\$0-\$5) than do ratings for any reference social impact factor. This implies that the net cost rating of Option 3 is as much as 375 percent more sensitive than ratings for any reference social impact factor in their relevant scales.

Discussion and Conclusions <heading level 1>

Framework Applicability <heading level 2>

The proposed framework can assist municipal councils in the assessment of the sustainability of scenarios/options for the integrated waste management system.

Generic social data collected in an Australia-wide survey of waste managers and planners can be used as default data along with more readily available environmental and economic data in the application of the tool to the siting and operation of waste management technologies.

As part of this study, environmental and economic life cycle data for various residential organic waste management operations have been collected and used in a case study to test and refine the proposed framework (e.g., Kijak and Moy 2003). These data can be used in the future studies of other organic waste management scenarios.

Framework Benefits <heading level 2>

The proposed decision support framework addresses the identified deficiencies of the previous tools such as LCA in the evaluation of waste management systems.

Despite some deficiencies, the LCA methodology as described provides life-cycle perspective and allows for a more objective assessment of waste management alternatives.

The framework integrates multiple environmental, social and economic tools in accordance with the triple bottom line philosophy of sustainability. In this process, the PSR model is applied to introduce a clear relationship between the model boxes pressure, state and response and identify all flows of materials and burdens between these model boxes. The model assists the identification of burdens—which are dependent on the locality (or the state box of the model) and require site-specific assessment (e.g., environmental emissions with regional consequences).

Spatial resolution is consequently introduced into the LCIA process to account for these emissions to address the geographical equity principle of the sustainability definition. This has been done by considering social impacts on the local community and applying a regional scaling procedure to LCA data. These modifications help accommodate the social dimension of sustainability and emissions to the environment that may have impacts at the regional level. These socio-environmental impacts are also supplemented by consideration of financial costs.

Another benefit of the regional scaling procedure is that the problem of aggregation of emissions to the environment into an impact category in the conventional LCIA is avoided. This makes the impact assessment process more transparent.

Finally, the alternative LCIA approach of this framework streamlines the conventional LCIA framework making it more user-friendly to non-LCA experts such as waste planners and managers. The application of the CDP 3.0 software as the framework's platform helps the integration of qualitative and quantitative information; provides a well structured approach to the information assessment; facilitates objective,

transparent decisions; and facilitates the LCIA valuation and life cycle interpretation processes.

Further Work Required <heading level 2>

So far, all initial modelling and calculations have been carried out outside the CDP 3.0 software. A future work is required to develop a Microsoft Excel spreadsheet which will automate all these calculations and modelling. Hyperlinks included in the spreadsheet could connect a user to the NPI Internet site to access the relevant information used in the regional scaling procedure.

CDP 3.0 could be connected to this spreadsheet by a hot Direct Data Exchange (DDE) link. The DDE link will allow for the changes to be automatically forwarded to the CDP 3.0 software and all weights and scores updated if data in the spreadsheet change.

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¹ Editor's note: For discussion of issues involved in incorporating sustainability concerns into LCA, see the column by Cooper (2003).

² Editor's note: For discussions of the foundations of the application of MAUT to LCA, see the work of Seppälä, Lauren and Norris (2001) and Rahimi and Weidner (2004a, b) in this issue of the *Journal of Industrial Ecology*.

Figure 1 Modified Pressure-State-Response model (after OECD 1993)

Figure 2 Sequential steps of the framework

Figure 3 Relationship between steps of the conventional screening risk assessment (e.g., LaGrega et al. 1995) and the corresponding steps of the impact assessment process for emissions with regional impacts used in this study

Figure 4 Assessment of social impact factors of waste management activities (vertical axis: social impact factor weights on the scale 1-5 or *insignificant impact – significant impact*)

Figure 5 Assessment of sensitivity of rural and urban areas against social impacts

(vertical axis: sensitivity weights on the scale 1-5 or *low sensitivity – high sensitivity*)

Figure 6 An example of a contribution-by-criteria graph showing contribution of social, economic and environmental criteria to the decision goal sustainability (horizontal axis: contributions of these criteria to sustainability depicted as greyscale coded strips – the longer the strips the greater the contributions)

Figure 7 An example of a sensitivity analysis for social criteria against the decision goal, sustainability

$$A/P = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (1)$$

$$F/P = (1+i)^n \quad (2)$$

$$W_S^C = \frac{(r_S^C - r_0^C)}{\sum_{S'=1}^{N^C} (r_{S'}^C - r_0^C)} \quad (3)$$

$$D_A = \sum_{C_1=1}^{N^G} W_{c_1}^G \sum_{C_2=1}^{N^{C_1}} W_{C_2}^{C_1} \dots \sum_{C_M=1}^{N^{C_{M-1}}} W_{C_M}^{C_{M-1}} P_A^{C_M} = \sum_{C_M=1}^{N^{C_M}} A_{C_M}^G P_A^{C_M} \quad (4)$$

³ Editor's note: For a discussion and evaluation of ways to weight PRTR data, see the work of Toffel and Marshal (2004).

⁴ A copy of the survey form can be found on the Journal's website <http://mitpress.mit.edu/JIE> as an e-supplement.