CHAPTER 4

DEVELOPMENT OF SUSTAINABILITY INDICATORS

4.1 Development of Sustainability Indicators for Evaluating Municipal Solid Waste (MSW) Management Systems

A set of appropriate indicators is essential to evaluate the three dimensional sustainability of MSW management systems. This part of research attempts to provide a clear methodology to assess sustainability of MSW management systems via life cycle thinking. Most relevant midpoint indicators were identified, which will be useful for scientific decision making process. To assess the sustainability in a more tangible way, endpoint composite indicators have also been developed considering the most critical ultimate damages/effects of MSW management on environmental, economic and social aspects. The methodology and the developed indicators would be useful in strategic planning, including decision and policy-making with respect to development of appropriate sustainable MSW management systems.

4.1.1 Overview of sustainability indicators development methodology

There is an increasing interest in application of the LCA concept to sustainable development and the years 2010-2020 would be the decade of life cycle sustainability analysis (Guinée et al., 2011). Thus, life cycle framework is used as the systematic basis for developing indicators and sustainability assessment (Finnveden et al., 2009; Ortiz et al., 2009; CALCAS, 2011). It is necessary to consider all the phases of life cycle in a methodical approach such as primary storage at the household level, collection, transportation, processing and final disposal. Moreover, input resources and energy production processes and its emissions also have to be taken into account. In addition to the direct activities, other processes interacting with MSW management system should be evaluated through the system expansion approach (Liamsanguan and Gheewala, 2008b; Cleary, 2009). For instance, energy recovery from incineration and anaerobic digestion, replacement of chemical fertilizer with compost, material recovery from recycling, etc. show the possible displacement of virgin production processes which can be credited.

Considering all those aspects, inventory analysis was done for the entire life cycle of MSW management systems by compiling all the inputs and outputs within the system boundaries (detailed explanations given in Section 3.3). Based on the inventory results, different types of indicators may be distinguished as described below.

• *Basic indicators:* This includes results from the inventory analysis and interpretation of primary data e.g. total CO_2 emissions from one tonne of MSW through entire life cycle, total crude oil requirement for functional unit of waste treatment.

• *Aggregated indicators:* This combines, usually by an additive aggregation method, a number of components (data or basic indicators) defined in the same units, e.g. global warming potential per tonne of waste. To calculate this, all the greenhouse gases (GHGs) have to be converted to CO_2 equivalents (see Table 4.1). These aggregated indicators can be re-named as midpoint indicators in life cycle perspective and are useful for scientific decision making (Pennington et al., 2004; Rebitzer et al., 2004). Most relevant midpoint indicators for assessing the various impacts was explained in Section 3.4

• *Composite indicators:* Composite indicators are measured the aggregated effects of various aspects of a given phenomenon, based on a sometimes complex concept, into a single number with a common unit (Kondyli, 2010) (see Figures 4.1 and 4.2). Composite indicators better reflect the picture of the entire system by concentrating on key relationships of different primary indicators. Damage-oriented methods (endpoints impacts) was followed to develop endpoint composite indicators to quntify the ultimate damages/effects of MSW management on environment/society and which will be useful in strategic planning, including decision- and policy-making (Pennington et al., 2004; Ortiz et al., 2009). The basic advantage of endpoint composite indicators is that they are much easier to comprehend at the decision making stage than the rather abstract midpoint indicators (Goedkoop et al., 2008) thus, robust composite indicators would be an appealing tool for policy makers (Kondyli, 2010).

Sustainability indicators may be easier to understand and interpret when assembled in a conceptual framework, perhaps with a hierarchical arrangement of sub-domains (Hák et al., 2007; Finnveden et al., 2009; Kondyli, 2010). Such a conceptual framework of sustainability indicators development and sustainability assessment is presented in Figure

4.1, where linkages of aggregated/midpoint and endpoint sustainability indicators are shown.

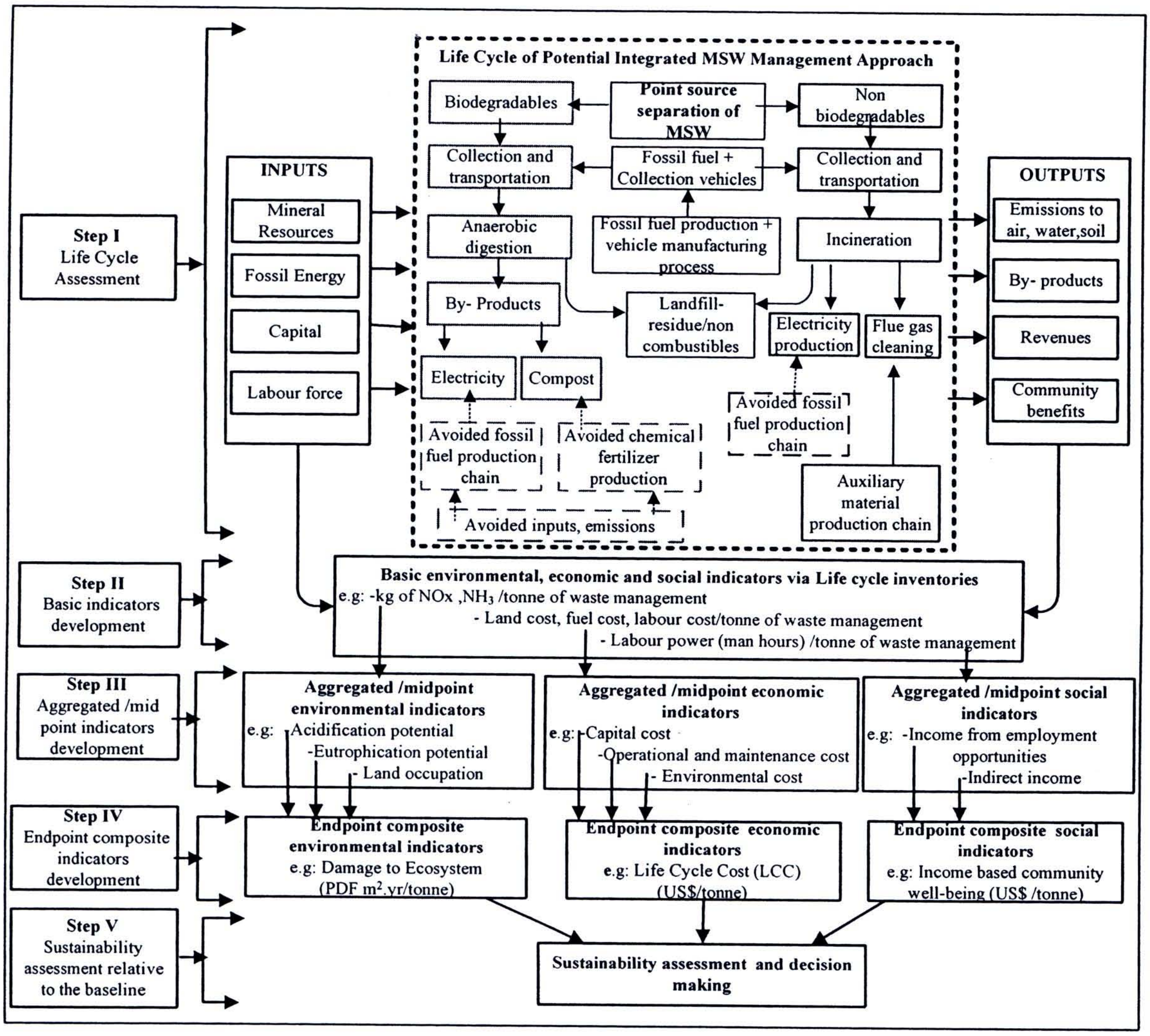

Figure 4.1: Conceptual framework for life cycle sustainability assessment

4.1.2 Assessment of environmental sustainability

4.1.2.1 Identification of midpoint indicators for sustainability assessment

Environmental sustainability can be achieved through the reduction of resource consumption and environmental pollution. To measure the effects of MSW management on environmental degradation, the most relevant midpoint environmental indicators were identified in Chapter 3. Furthermore, to quantify the relevance of midpoint indicators, mathematical formula derived (see Table 4.1) considering all the phases of life cycle. This set of indicators would be appropriate for scientific decision making.

Table: 4.1 Selected midpoint indicators to quantify environmental damages associated with life cycle emissions/resources consumption

Major emissions/ resources consumption from the different life cycle phases of MSW management	Midpoint Indicator	Unit of measurement	General formula to quantify the magnitude of impacts	References for background information
CH_4 → landfill/open dumps CO_2, N_2O, CO → Transportation, energy and auxiliary material production, incineration	Global warming potential	kg CO_2 eq.	$X_{Gross} = \sum(Q_i EM \times EF_i) + \sum(Q_i T \times EF_i) + \sum(Q_i TF \times EF_i)$	IPCC, 2006; Guinée et al., 2001; Nielsen and Hauschild, 1998; Tchobanoglous et al., 1993
NH_3, H_2S → Landfills/open dumps, anaerobic digestion, NOx, SOx → Fuel production, incinération HCl, HF → Fuel production	Acidification potential	kg SO_2 eq.	$X_{Net} = X_{Gross} - \sum(Q_i PA \times EF_i)$ *Here* X = GWP, POFP, EP, AP, HTP	
NH_3, NO_2^-, NO_3^-, PO_4^{-3} → Landfill/open dumps, Anaerobic digestion NOx → Transportation, energy and auxiliary materials production, incineration,	Eutrophication potential	kg PO_4^{3-} eq. or kg NO_3^-eq	GWP – Global warming potential POFP – Photo – Oxidant Formation Potential EP – Eutrophication Potential	
VOCs → Landfill/open dumps, anaerobic digestion, aerobic composting, CO, NOx → Transportation, energy and auxiliary materials production, incineration,	Photo oxidant formation potential	kg C_2H_4 eq.	AP – Acidification Potential HTP – Human Toxicity Potential Q_i – Magnitude of substance *i* from EM - Energy and Material production, T – Transportation, TF – Treatment Facility, PA – Potential Avoidance.	
VOCs, NH_3 → Landfill/open dumps, anaerobic digestion, composting , NOx, SOx, PM_{10} → Transportation, energy and auxiliary materials production, incineration,	Human toxicity potential	kg 1-4 DB eq	EF_i – Equivalency Factor of i[th] substance	
Crude oil → Diesel production for transportation, waste handling and processing machineries Coal, natural gas, crude oil → Electricity and thermal energy required for recycling, operating machinery	Abiotic resource depletion potential	kg Sb eq.	$AR_{Gross(i)} = AR_{EM(i)} + AR_{T(i)} + AR_{TF(i)}$ $AR_{Net(i)} = AR_{Gross(i)} - AR_{REM(i)} = m_i$ $AR_{Gross(i)}$ –Gross Abiotic Resource i, $AR_{REM(i)}$ is abiotic resources i conservation from Recovered Energy and Materials. m_i- net quantity of resource i extracted. $ADP_i = \frac{DR_i}{(R_i)^2} \times \frac{(R_{ref})^2}{DR_{ref}}$ Where; ADP_i- Abiotic Depletion Potential of resource *i*, R_i – Ultimate reserve of resources i (kg), DR_i – Extraction rate of resources *i* (kg.y^{-1}), R_{ref} – Ultimate reserve of the reference resource (antimony kg), DR_{ref} – Extraction rate of the reference resource (kg.yr^{-1}) $ADP = \sum_i ADP_i \times m_i$	Guinée, 2001; Oers et al., 2002; Saxena et al., 2009
Land occupation and land transformation → Treatment facilities, final disposal, transportation, fossil fuel mining for energy	Land occupation (LO)/(Ecological Footprint -EF)	m^2.yr	$LO_{Direct(Local)} = \sum_a A_a \times t_a$ LO_{Direct} - Direct land occupation, A_a - occupation of area by local land use type *a* , t_a-occupation time (years) $LO_{Gross} = LO_{EM} + LO_T + LO_{TF}$ $LO_{Net} = LO_{Gross} - LO_P$ $LO_{EM, T, TF, P}$ – Land occupation for energy and material production, transportation, treatment facility, by-products	Rapport, 2000; Huijbregts et al., 2008; Wackernagel et al., 2005; Hanafiah et al., 2010

4.1.2.2 Development of endpoint composite indicators for environmental sustainability assessment

The endpoints approach classifies flows into various environmental themes and three major composite indicators can be developed for modeling the damage to each theme: human beings, natural environment and resources (see Figure 4.2). The Eco-indicator 99 and ReCiPe models were used to correlate the midpoint and endpoint indicators via the damage-oriented method (Goedkoop et al., 2008). At the endpoint level, depletion of bioproductive land and available abiotic resources were identified as the most crucial ultimate environmental damages which arise due to MSW management. "Damage to ecosystem" and "damage to abiotic resources" were therefore selected as the major composite indicators for environmental sustainability assessment (see Figure 4.2). Even though "damage to human health" is caused by environmental emissions, this indicator can be considered as a social indicator too since safeguarding human health would be of interest to society as a whole (Finnveden et al., 2009).

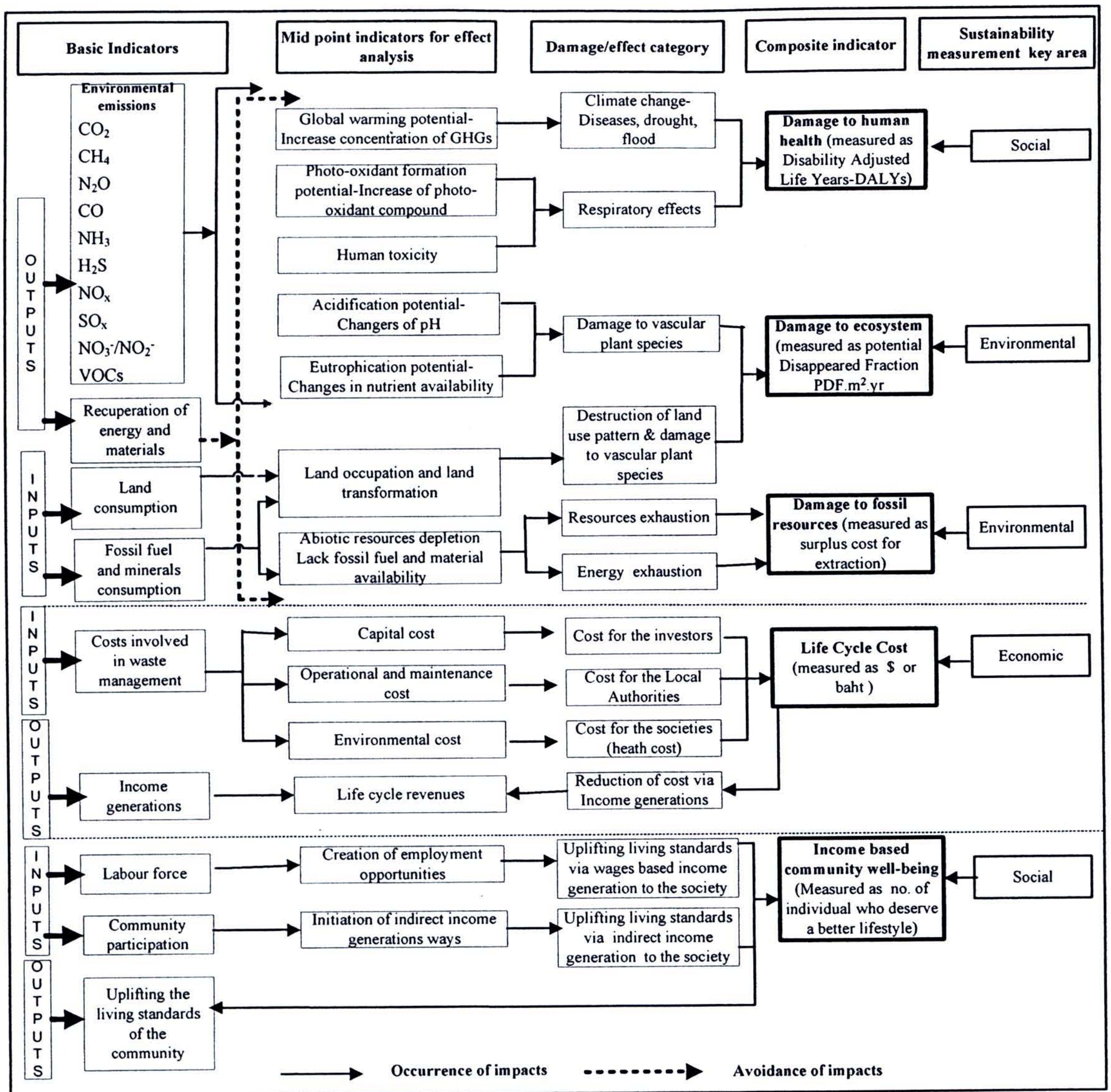

Figure 4.2: Correlation between basic, midpoint and endpoint composite indicators with respect to most relevant environment, economic and social aspects

Composite Indicator – Damage to Ecosystem

The ecosystem damage refers to the effect on the biodiversity caused by the pollutant emissions or the occupancy of the ecological environment. There are two major ways, in which MSW management activities can cause ecosystem damage. The local effects on the ecosystem are caused by acidifying and eutrophying substances emissions from MSW management and land occupation/land conversion. These damages are proportionately equal to the Potentially Disappeared Fraction (PDF) of species. PDF measures the fraction of species that are threatened or that disappear from given area during a certain time (PRé

Consultants, 2001; LiJing et al., 2008; Goedkoop et al., 2008). PDF of different land use types can be calculated as below:

PDF $= \frac{S_{reference} - S_{use}}{S_{reference}}$ Where, $S_{reference}$ – Species diversity on the reference area type, S_{use} – Species diversity on the converted or occupied area.

Damage to ecosystem by acidifying and eutrophying substances

There is a potential of releasing significant amount of acidifying and eutrophic substance emissions during degradation process of MSW as well as from the energy and raw materials production. Based on eco-indicator 99 guidelines (PRé Consultants, 2001), damage to ecosystem (PDF.m^2.yr) caused by acidification and eutrophication can be quantified as below:

$$DE_{Acidification/eutrophication} = \sum_i m_i \alpha_i$$

Where m_i – mass of the emission i for entire lifecycle (kg), α_i – damage factor to the ecosystem from impact factor i (PDF.m^2.yr/kg). The derived values of damage factor (α_i) to ecosystems from major acidifying and eutrophying substances such as SO_x, NO_x, and NH_3 are 1.04, 5.71 and 15.56 PDF.m^2.yr/kg respectively, if 60% of deposition in natural area (Pré Consultants, 2001).

-Land occupation/transformation

The major damage to ecosystem is caused by land occupation (directly or indirectly) and land conversion (changes of land use type). The damage can be quantified by using the general formula as below.

Land occupation (LO) / transformation = A (m^2) × T (years)

Damage to Ecosystem (PDF.m^2.yr) from land occupation $= \sum_a PDF_a \times LO_{Local(a)}$

where A – Area of land, T – time duration of land occupation/transformation, PDF_a – PDF of land use type a, $LO_{local(a)}$- Land occupation (m^2.yr) of land type a for MSW transportation, treatment and disposal, greenhouse gas absorption, etc.

Damage factors for occupation of different land use types are presented in ReCiPe model (Goedkoop et al., 2008). In fact, damage factors for occupation of mix plantation, urban area/dumpsite, coniferous plantation, monoculture broad leaf plantation, intensive crops, and broad leafed plantation are 0.66, 1.19, 0.47, 0.19, 1.12 and 0.27 PDF.m^2.yr respectively.

There are three major stages noticible in relation to the damage caused by local land consumption of MSW management activities. To calculate these damages, PDF at different stages of land consumption, such as land transformation, occupation and restoration period, should be taken into account considering the species variation potential (see Figure 4.3) and time duration of land use (T).

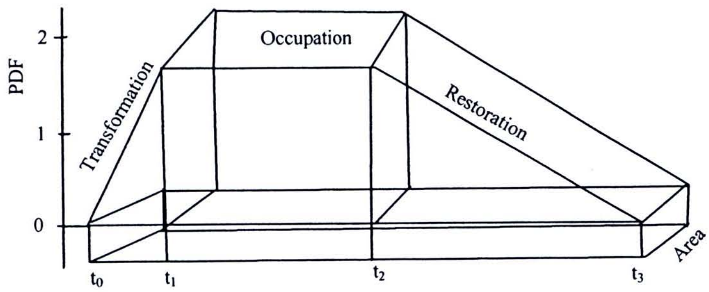

Figure 4.3: Variation of PDF with land transformation, occupation and restoration

Based on the ReCiPe model guidelines on variation of PDF with respect to time (Goedkoop et al., 2008), damage to ecosystem by land transformation (e.g. design/construction phase of landfill), occupation (e.g. operation phase of landfill) and restoration (e.g. after landfill closure) can be quantified using formula below;

$$DE_{\text{Transformation}} = A_{trans} \times T_{trans} \times \left[\frac{1}{2}(PDF_{(t_1)} - PDF_{(t_0)})\right].$$

$$DE_{\text{Occupation}} = A_{Occu} \times T_{occu} \times PDF_{(t_1)}$$

$$DE_{\text{Restoration}} = A_{Resta} \times T_{Resta} \times \left[\frac{1}{2}(PDF_{(t_3)} - PDF_{(t_2)})\right]$$

Therefore, total damage to ecosystem can be calculated at local level considering all the damages caused to ecosystems due to acidification, eutrophication and land occupation and land conversion.

Damage to ecosystem $(PDF.m^2_{local}.yr)$ = $DE_{\text{Acidification/eutrophication}} + DE_{\text{Transformation}} + DE_{\text{Occupation}} + DE_{\text{Restoration}}$

Furthermore, to do a meaningful comparison on damage to ecosystem in different nations, local damage to ecosystems $(PDF.m^2_{local}.yr)$ can be converted as damaged biocapacity at the global scale by multiplying the appropriate equivalence factor and yield factor of the land use types (Wackernagel et al., 2005; Scotti et al., 2009; Hanafiah et al., 2010). The formula below was derived to quantify the ultimate damage to ecosystem at global scale.

Damage to Biocapacity (gha.yr) = Damage to Ecosystem ($PDF.m^2_{local}.yr$) /10,000 × Equivalence Factor (gha/ha) × Yield Factor (dimensionless).

Yield factors are needed for normalizing the land types available to world average equivalents using locally derived yield factors. These are multipliers, which express the extent to which local bioproductivity is more or less than that of the world average for that land type (Scotti et al., 2009; Schaefer, 2006). The equivalence factors are needed to represent the world's average potential productivity of a given bioproductive area relative to the world average potential productivity of all bioproductive areas (Huijbregts et al., 2008; Wackernagel et al., 2005).

Finally, this composite indicator can be used to answer one central sustainability question: 'how much of the bio-productive capacity of the biosphere is used by different MSW management technologies?'

Composite indicator - Damage to abiotic resources

Damage to abiotic resources caused by fossil fuel and mineral utilization can be considered as one of the major damages to the environment (Omer, 2008) and MSW management activities consume significant amount of fossil resources (see Figure 4.2) in the form of diesel fuel, electricity and thermal energy consumed in various activities such as transportation, pre-processing and treatment of waste. In the midpoint impact assessment level several attempts have been made in developing various abiotic resource depletion models (Guinée and Heijungs, 1995; Steen, 2000; PRé Consultants, 2001). However, to measure the fossil fuel and mineral resources consumption effects on sustainability in a tangible way, endpoint damage assessment would be appropriate. To this end, in this research, a formula was developed to account for the depletion of abiotic resources, expressed in monetary terms, based on the ReCiPe model concept. It would be an appropriate tool since it was developed based on the concept of marginal increase in costs to the society due to the continuous extraction of resources and its scarcity (Goedkoop et al., 2008). For instance, for the next 1000 Giga barrel of crude oil extraction, the price will need to increase 30 dollars per barrel.

The marginal cost increase (MCI) is the factor that represents the increase of the cost of a reference commodity r ($/kg), due to an extraction. The unit of the marginal cost increase is dollars per kilogram per kilogram ($\$/kg^2$).

$$MCI_r = \frac{\Delta Cost_r}{\Delta Yield_r}$$

The total additional cost to society due to an extraction of a significant amount of fossil fuel can thus be calculated by multiplying the marginal cost increase per kg by the annual consumed amount times future value of a dollar for extraction compared to the base year. The damage is defined as the additional costs society has to pay as a result of an extraction.

$$D_r = MCI_r \times P_r \times (1+d)^t$$

The damage D_r is expressed in $/kg, P_r is the global production amount of the reference resource per year (kg/yr), d is the inflation rate and t is the time interval that should be taken into account.

For instance, MCI_r and D_r calculation for reference resource (Oil, crude, feedstock, 42 MJ per kg, in ground) is shown in Table 4.2. In order to calculate endpoint impact, midpoint characterization factors ($CF_{mid.i}$) for i[th] resources are needed relative to the reference resource. In fact, in the ReCiPe model, the midpoint characterization factors for metals are derived as Fe-equivalents. For fossil fuels, the midpoint characterization factors are derived relative to the energy content of reference resources which would be "Oil, crude, feedstock, 42 MJ per kg, in ground" (Goedkoop et al., 2008). The derived mid point characterization factors for crude oil (42MJ/kg), hard coal (18MJ/kg), brown coal (8MJ/kg), natural gas (36.6MJ/kg) are 1.0, 0.19, 0.24,0.43 and 0.87 respectively.

To calculate the endpoint damage caused from the consumption of different fossil fuels, the following formula can be used.

Damage to abiotic resources ($/kg) $= CF_{mid.i} \times D_r$

By using this concept, potential damage caused to abiotic resources can be calculated in terms of money for all the fossil fuel and mineral consumption of a particular MSW management system. Thus, this composite indicator will be beneficial for sustainability assessment and decision-making process

Table 4.2: Calculation of MCI_r and D_r for the reference resource

Description	Value	Unit
Volume of one oil barrel in liters	160	L
Estimated production cost increment	30	$/barrel in year 2000
Mass of oil in one barrel	136	kg
Production cost increment per kg oil extraction	0.22	$/kg (from year 2000 to 2010)
Production amount in base year 2000 (based on ReCiPe Model)	3.43E+12	kg
MCI_r	6.43E-14	$/kg/kg
Average inflation rate of Middle East countries	5	%
Time period between current year and the base year	10	from base year (2000 to 2010)
Future value of 1 dollar for year 2010	1.63	$ (relative to base year 2000)
Damage of 1 kg of crude oil extraction (D_r)	0.36	$/kg (year 2010)

4.1.3 Assessment of economic sustainability

Economy is a very important decisive factor for MSW management, and it is important to analyze this aspect as systematically as environment is analyzed using LCA (Reich, 2005). In order to measure the economic feasibility, at design phase, overall cost and benefits of the proposed MSW management should be taken into account including all phases of the life cycle (Ngoc and Schnitzer, 2009). Significant amount of revenues from the proposed MSW management system should be obtained to recover the cost of the municipalities to delivering the service (Den Boer et al., 2007). Even though there are economic methods like cost benefit analysis to assess the financial feasibility, there are several characteristics with these methods that make them less suitable for a combination with LCA (Reich, 2005). Thus, to quantify all the cost and revenues for the entire life cycle, a relevant economic indicator would be the life cycle cost which covers all the costs incurred by the intended waste management system.

Composite indicator - Life Cycle Cost (LCC)

LCC represents the physical chain of material flows related to a product, from resource extraction to waste management (Gluch and Baumann, 2004). Sustainability of any MSW management method depends on the total cost of the facility (Lutz et al., 2006) and LCC for MSW management system involves evaluation of all the costs related to design and construction of facility, collection and transportation, processing, operation, maintenance and support and final material disposal. Therefore, detailed financial analysis via LCC analysis would be the appropriate method for evaluating overall financial aspect of any MSW management system (Reich, 2005). Also it would be a very good indicator to make decisions on cost effectiveness and economic sustainability of the system (Reich, 2005; Utne, 2009). However, LCC analyses should be done early in the system development process, because the outcome of life cycle cost estimation cannot be influenced very much when the design is completed (Gluch and Baumann, 2004).

All cost elements should be identified in a systematic manner, in particularly, there should be a relationship between the cost categories and the sustainability attributes. Therefore, total capital expenditure, operation and maintenance cost and environmental cost (monetary value for the environmental emissions) must be incorporated in the LCC analysis (see Figure 4.2 and Table 4.3).

Present value calculation has to be done, especially for capital cost to allow the summation of initial and future costs (Utne, 2009; Goedecke et al., 2007; Lutz et al., 2006). In order to calculate the present worth of cost of capital (P), the following formula can be used (Heredia, 1996).

$$P = \left[1 - \frac{(1+r)^n}{(1+i)^n}\right]\left[\frac{1+r}{1-r}\right]a$$

Where, r: inflation rate, i: prevailing interest rate, n: number of years, a: initial cost.

Operation and maintenance cost would be the major share of LCC for a local authority mainly due to high collection and transportation fee. To calculate life cycle operation and maintenance cost, labour cost, utilities, operating supplies, accident risk expenditure, insurance, taxes, etc. should be accounted for.

Even though local authorities are not concerned about the environmental cost yet, it should be taken into account for LCC cost estimation since the community people may have to bear the costs in the form of health costs cause due to the environmental pollution. There are different approaches for environmental cost estimation based on damage assessment of emissions (ECON'95), on willingness-to-pay (Steen, 2000), and on the value judgments of a democratic society through their reflection on the government's tax and fee systems, represented by EcoTax'99 (Reich, 2005). In this study, environmental costs were calculated based on the default values of emissions and resources consumption reported in the Swedish EPS model (Steen, 2000) and presented as willingness to pay (WTP) of the society. These are actually based on what society is willing to pay in order to avoid human health impacts due to pollutants. In developing Asian countries, society may not necessarily be willing to pay this amount of money in advance to avoid impacts since they are more concerned in spending money for the basic needs. However, these costs must anyhow be paid indirectly for medical treatment of health impacts from pollution. Thus, despite socio-economic and cultural differences between Sweden and developing Asian countries like Thailand, Sri Lanka and India, people in all the countries will have to pay some amount of money sooner or later, directly or indirectly for the health issues. Using this reasoning, the Swedish EPS model was adapted to studied Asian countries using the hypothesis that the WTP is proportional to the per capita income (GDP expressed in terms of purchasing power parity – GDP (PPP)) (Nguyen and Gheewala, 2008). For instance, the following equation can be used to estimate WTP for Thailand.

$WTP_{Thailand} = WTP_{Sweden} \times$ Per capita GDP(PPP)$_{Thailand}$/Per Capita GDP(PPP)$_{Sweden}$

Per capita GDP(PPP)$_{Thailand}$/Per capita GDP(PPP)$_{Sweden}$ is the "income elasticity of WTP" and the derived value is 0.21 (GDP(PPP) of Thailand 8400 US$, GDP(PPP) of Sweden, 38200 US$) (CIA, 2008).

Considering all those cost factors, a common formula can be developed to calculate LCC as shown in Table 4.3.

Table 4.3: Formula derived for LCC assessment

Indicators	General Formula	References for background information
Life Cycle Cost (LCC) ($/tonne)	$LCC_{Gross} = CE + OMC + EC$, $LCC_{Net} = LCC_{Gross} - LCR$ According to EPS model, $EC = \sum(WTP_i \times Q_i)$ Where CE – Capital Expenditure, OMC – Operational & Maintenance Cost, EC – Environmental Cost, LCR – Life Cycle Revenue, WTP_i – Willingness to Pay for emissions of i^{th} substance, Q_i – Magnitude of substance *i*	Gluch and Baumann, 2004. Utne, 2009. Goedecke et al., 2007. Lutz et al., 2006. Reich 2005. Steen, 2000

In order to make final decision on economic feasibility proposed MSW management methods, life cycle revenues from the sale of different by-products should also be included to estimate net LCC (see Table 4.3). Such LCC analysis for a particular MSW management system would provide useful information in terms of long term cost-effectiveness.

4.1.4 Assessment of social sustainability

In relation to sustainable development and policy making, there has been an increasing interest for the inclusion of social aspects as part of the LCA framework (Jørgensen et al., 2008; Finnveden et al., 2009). Social life cycle assessment (Hunkeler, 2006) is a tool that enables assessment of the overall social benefits/effects that can be expected from a particular system.

There is a wide range of social impacts, both positive and negative, of associated with MSW management. For instance, properly designed MSW management systems have the potential of uplifting the community well-being by providing significant number of employment opportunities, mitigating health damages, generating additional income to the households from selling recyclables, etc. In contrast, poorly designed MSW management practices create huge threat to human health due the emissions as well many other negative impacts and lack of benefits to the community people at times resulting in public opposition (Shekdar, 2008; Giusti, 2009). Therefore, assessment of major positive and negative social impacts of intended MSW management facilities is necessary.

Composite Indicator - Damage to human health

Damage to human health is one of the major issues associated with exposure to pollution from MSW management systems. In fact, health issues are associated with every step of the handling, treatment and disposal of MSW, both directly (exposure to hazardous substances in the waste via recovery and recycling activities and other occupations in the waste management industry or exposure to emissions from incinerators and landfill sites, vermin, odous and noise) or indirectly (e.g. via ingestion of contaminated water, soil and food) (Giusti, 2009). The disability adjusted life years (DALYs) concept developed by WHO and the World Bank can be used to quantify the damage to human health (PRé Consultants, 2001).

To aggregate different types of damages to human health, a tool for comparative weighting disabilities is needed. This represents the years of life lost (YOLL) and years lived disabled (YLD) due to the impacts caused by emissions. The actual impact depends on the fate of a pollutant in the natural environment and its effect on human well being. As reported, the major health impacts from MSW management emissions are infectious diseases, cardiovascular diseases, respiratory diseases and cancer. These diseases are caused as the ultimate damage of MSW emissions based midpoint impacts such as global warming; photo-oxidant formation and human toxicity (see Figure 4.2). DALYs can be taken as an endpoint impact to estimate the overall heath damages, in which ultimate effects of several midpoint impacts categories have been accounted. In the literature, several methodologies have been proposed for calculating the impacts of emissions on human health (Steen, 2000; PRé Consultants, 2001). The Swedish EPS model expresses more clear correlation between environmental pollutions and human health damages with respect to the potential severity of emissions on health in various ways. Aggregation of different health effects can be achieved through the use of indicators positioned at the end of the cause-effect chain. For instance, global warming can affect health damages in several ways, such as malnutrition, heat stroke, drowning, malaria, dengue, cholera and tick-borne diseases, etc. Damage factors are derived as mortality/severe morbidity and morbidity values relative to different type of diseases which can be resulted by the same or different pollutants (Steen, 2000).Therefore, this model can be used to explain the seriousness of impacts easily as permanent life loss or disability.

Overall health damage from a particular disease can be calculated as:

DALYs (person-years) = Mortality (YOLL) + Severe Morbidity (YLD) + Morbidity (YLD)

For instance, total DALYs from climate change issues (heat stress, starvation, flooding, malaria) caused by 1 kg of CO_2 is 1.80E-06 person-years (Steen, 2000). Similarly, health damages caused due to all the midpoint impacts based diseases can be estimated. The generic formula for calculating overall damage to human health considering all possible health impacts is shown in Table 4.4.

Composite Indicator -Community well-being (Income based measures)

The concept of community well-being is one of the frameworks for social sustainability assessment. Poverty alleviation and economic development are the major aspects towards improving well-being of the community. As reported, unemployment situation in local community have been affected the physical and mental health and mortality of the individual to the extent. In addition, unemployment may lead to increased levels of tension, conflicts, decreased physical and mental health of family members, violence in the home, affects levels of crime in society, etc. (Jørgensen et al., 2008).

Appropriate MSW management systems can enhance the living standards due to local economic growth by facilitating employment as well as other income generation opportunities (see Figure 4.2). In fact, there is a potential of earning significant amount of money by selling point source separated recyclables. In addition, providing employment opportunities for skilled workers may facilitate the enhancement of the living standard of the individual as well as her or his family members as it helps to improve family income and subsequent poverty reduction. Thus, creation of employment opportunities and household income increment indeed positively correlates with nutrition, clothing, shelter, sanitation, health and literacy level and happiness which are functions of variables of well-being.

Facilitating more job opportunities in terms of quality (trained personnel) and quantity would be a good approach to obtain community appreciation (Den Boer et al., 2007). Prior estimation of potential skilled employment opportunities for intended MSW management at the design phase will be a good indicator to show the future social benefits and for convincing the community. Potential generation of employment opportunities is calculated by using a general formula which is developed based on social life cycle assessment concept (Hunkeler, 2006). The formula developed herein focuses on the work hours required for one tonne of MSW management.

$$\text{PEO (working hours/tonne)} = \frac{(SLR_C \times TA_C) + (NCV \times SLR_{\text{per vehicle}}) + SLR_{TF} + SLR_I}{Tonnes\,/\,day}$$

PEO: Potential employment opportunities, SLR_C: Skilled labour requirement for collection (labour hours/area), TA_C:Total area of collection (area/day), NCV: No. of collection vehicles (vehicles per day), $SLR_{\text{per vehicle}}$: Skill labour requirement per vehicle (labour hours/vehicle), SLR_{TF}: Skilled labour requirement for treatment facility (labour hours/day),

SLR_I: Skilled labour requirement for indirect activities (e.g. administration, fuel production, auxiliary material production) (labour hours/day).

To calculate the number of individuals who may have a "good life" as a result of improving income based well-being from MSW management systems, total income generation potential from one tonne waste can be divided by average cost of living (see Table 4.4).

Table 4.4: Formula derived for social indicators

Composite Indicators	General formulae	References
Disability Adjusted Life Years (DALY)	$Damage\,(DALYs) = \sum_i (G_i \sum_a H_{mortality\cdot a} + G_i \sum_a H_{severe\,morbidity\cdot a} + G_i \sum_a H_{morbidity\cdot a})$ G_i is the amount of pollutant i emitted from entire life cycle . $H_{mortality a}$, $H_{severe\,morbidity\,a}$, $H_{morbidity\,a}$ is the damage factor to human health due to disease pathway a, from pollutant i .	Steen, 2000 PRé Consultants, 2001 Somerford and Katzenellenbogen, 2004
Income based community well-being	Up-lifting living standards (no.of individuals/tonne) $= \frac{\sum_i (PEO_i \times TW_i) + I_{informal}}{COL}$ PEO_i: Potential employment opportunities for i^{th} level (labour hrs/tonne), TW_i: Rate of wages ($/hour) of i^{th} level , $I_{informal}$: Income generation from indirect activities ($/tonne) , COL: cost of living ($/person)	Den Boer et al., 2007 Hunkeler, 2006

4.1.5 Further research for improvement of the concept

This research focused on broadening the traditional environmental LCA towards a more comprehensive sustainability assessment, including economic and social aspects within a single conceptual framework. Within this common framework, novel relationships were identified between the effects of life cycle inputs/outputs and the three pillars of sustainability. To assess sustainability, a set of midpoint and endpoint indicators were developed. The developed midpoint and endpoint indicators would be useful to quantify the environmental, economic and social effects in order to compare the magnitude of sustainability aspects of different MSW management options and to select the most promising approach.

-Development of baseline: However, a scientifically sound baseline is necessary at the decision-making stage to compare the magnitude of impacts relative to the baseline and to determine whether or not they are acceptable, especially for decision making on single treatment method. This baseline would help decision-makers and policy-makers to find the exact answer to the question of "is this MSW management system sustainable? However, development of such a baseline to represent a critical threshold value of sustainability status is still a challenging issue and further research is needed.

-Quantification of sensitivity of three pillars on overall sustainability: The set of developed composite indicators would be useful to quantify the sustainability level of three different pillars. However, when it comes to decision and policy making stage, the decision makers would like to know the most sensitive pillar to reach the maximum sustainability. In order to magnitude the sensitivity of each pillar on overall sustainability, all the three arenas of sustainability should be ought into a common unit. Therefore, weighting and further aggregation of the developed composite indicators would seem to facilitate the decision making process. The one possible approach is converting all the end results of composite indicators to monetary values. However, there are some limitations of such approaches such as it may introduce additional uncertainty in the calculations. Some information would invariably be lost as is the case whenever data are aggregated. Taking into account all of these considerations, weighting and aggregation of three pillars have to be done, and further research is required.

4.1.6 Concluding remarks

This part of the research provides a wider understanding about sustainable development and a transparent approach to assess the three-dimensional sustainability of MSW management systems via life cycle thinking. Most relevant midpoint indicators are identified and mathematical formulas developed to quantify the impacts since these indicators would be useful for the scientific decision making process. Moreover, to assess the overall sustainability of particular MSW management systems in a more tangible way, endpoint composite indicators are explored by combining various sustainability aspects based on a complex concept.

The basic advantages of the developed composite indicators are that they are closer to the actual damage and thus easier to comprehend at the decision making stage and to convince the stakeholders. They have developed by aggregating the most crucial ultimate damages/effects of multidimensional aspects of MSW management systems, which cannot be fully captured by any individual midpoint indicators. Thus, the set of robust composite indicators would be very useful as an appealing tool for policy makers to support policy implementation. Moreover, these indicators would be very useful for prior evaluation of three-dimensional sustainability of alternative MSW management options and then for decision-making with respect to planning and implementation of sustainable MSW management projects in the near future.

It is noteworthy to mention that the developed methodology can be adapted not only for waste management but also for any other field to identify the critical sustainability aspects and then to develop indicators. Also, the set of developed endpoint composite indicators can be directly applied to assess the three-dimentional sustainability of any other projects e.g. renewable energy project, when one identifies the similar trend of ultimate damages/effects occurrence possibilities.

The major limitation of application of these indicators in waste management or any other field is extensive data requirements to perform detail life cycle inventories with respect to three pillars of sustainability and that whole process would be expensive and time consuming.