

# Life cycle sustainability assessment (LCSA) for selection of sewer pipe materials

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**Abstract** Sewer systems, over their life cycle, suffer deterioration due to aging, aggressive environmental factors, increased demand, inadequate design, third party intervention, and improper operation and maintenance activities. As a result, their state and overall long-term performance can be affected, which often requires costly and extensive maintenance, repair, and rehabilitation. Furthermore, these pressures can enhance the risk of failures (e.g., sewer leakage) which in turn can have serious impacts on the environment, public safety and health, economics, and the remaining service life of these assets. Effective asset management plans must be implemented to address long-term sustainability principles, i.e., economic growth, human health and safety, and environmental protection, simultaneously. The aim of this paper is to evaluate and compare four typical sewer pipe materials [i.e., concrete, polyvinyl chloride (PVC), vitrified clay, and ductile iron] and identify sustainable solutions. Two comprehensive life cycle sustainability assessment (LCSA) frameworks were applied. The first LCSA framework was based on the integration of *emergy synthesis*, life cycle assessment (LCA), and life cycle costing (LCC). In this framework, *emergy synthesis* has been applied to integrate the results from environmental analysis (i.e., LCA) and economic analysis (i.e., LCC) to an equivalent form of solar energy: a solar *emergy joule*. The second LCSA framework was based on a conventional, multi-criteria decision-making technique, i.e., the analytical hierarchy process, to integrate the results from environmental analysis (i.e., LCA) and economic analysis (i.e., LCC) and find the most sustainable

solution over the sewer pipe life cycle. The results demonstrate that PVC pipe is the most sustainable option from both environmental and economic view points and can ensure a more sustainable sewer system.

**Keywords** Sewer pipe materials · Life cycle sustainability assessment (LCSA) · *Emergy synthesis* · Multi-criteria decision-making (MCDM) method

## Introduction

Buried infrastructure, including water distribution and sewerage systems, is bloodlines of modern society that may cause significant environmental and economic impacts through their life cycle (Halfawy et al. 2008). The network of sewer pipes, which collects sewage from buildings and storm runoff and conveys the wastewater to locations of treatment or disposal, forms the main component of the underground sewer network infrastructure (Ariaratnam and MacLeod 2002).

In North America, a large portion of urban water infrastructure including water and wastewater piping networks of underground structures is reaching the end of their useful service life of 50–75 years (Younis and Knight 2010). Increasing needs for new urban water infrastructure are challenging, particularly in the presence of existing environmental constraints and limited funding. In the past, the problems caused by deteriorating sewer pipes were dealt with by adopting a reactive asset management approach,<sup>1</sup> whereby repair or rehabilitation was only done

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<sup>1</sup> In general, in a reactive asset management approach, a decision is made in case a failure happens. This approach is in contrast to proactive asset management where physical assets and their performance are monitored frequently and a decision is made before a failure happens (Schuman and Brent 2005).

once a pipe failed. Traditional infrastructure management only focused on maximizing the economic benefits (Mirza 2007) while ignoring the environmental impacts and long-term socio-economic consequences. However, this type of approach was deemed unsustainable due to consideration of short-term cost only.

Environmental performance and sustainable development are additional key aspects in effective maintenance of sewer systems (Mihelcic et al. 2003; Muga and Mihelcic 2008). The term “sustainability” in the context of infrastructure systems has been applied to refer to a broad variety of performance conditions or performance indicators that concern different groups, and may imply different meanings (e.g., see Ashley and Hopkinson 2002; Foxon et al. 2002; Haas et al. 2009; Ugwu et al. 2006; Venkatesh and Brattebø 2013). Despite the fact that a standard definition is elusive, sustainability evaluation has been defined more in the sense of taking a longer-term view of effects on future generations, well beyond the immediate business cycles, considering short- and long-term environmental impacts and socio-economic consequences (Ashley and Hopkinson 2002).

Sharma et al. (2009) discussed that alternative urban water infrastructure must be designed to address long-term sustainability, by providing reliable urban water services with minimum life cycle cost and environmental impacts. Thus far, very limited research has been reported in the context of sustainable assessment of sewer systems. For example, Dennison et al. (1999) compared the environmental impacts of alternative pipe materials, while Lundie et al. (2004, 2005) compared alternatives for wastewater, stormwater, and drinking water pipes. A few studies analyzed the sewer network only at the production and manufacturing stages of the life cycle (Herstein and Filion 2011). Extensive literature review highlights the need for innovative techniques to facilitate effective management of sewer systems to minimize the cost as well as to protect the environment and human health (HH).

In this paper, selection of sewer pipe material has been studied in the context of environmental and economic sustainability. For this purpose, two life cycle sustainability assessment (LCSA) approaches have been applied for sustainability assessment and decision-making for selecting sewer pipe material. The first LCSA framework, called Em-LCA, was introduced by Reza et al. (2013a, b). Em-LCA is based on the integration of emergy synthesis, life cycle assessment (LCA), and life cycle costing (LCC). In this framework, emergy synthesis has been applied to integrate the results from environmental analysis (i.e., LCA) and economic analysis (i.e., LCC) to an equivalent form of solar energy, called a solar emergy joule (seJ). The second LCSA framework is analytical hierarchy process (AHP)–LCA, which was previously introduced by Reza

et al. (2011). AHP–LCA is based on a conventional, multi-criteria decision-making (MCDM) technique, i.e., the AHP, to integrate the results from environmental analysis (i.e., LCA) and economic analysis (i.e., LCC) and find the most sustainable solution over the sewer pipe life cycle.

## Background information

The term “life cycle” refers to the major activities in the course of the product’s lifespan from its manufacture, use, and maintenance, to its final decommissioning and disposal. The LCA “cradle-to-grave” approach makes it a more holistic decision-making tool that can be used for selection of more sustainable urban water infrastructure (e.g., pipe material). LCA is a standard procedure for evaluating the environmental performance of human-dominated products and processes (Raugei et al. 2012a, b), and it has been widely used in diverse areas such as evaluating urban water infrastructure (e.g., see Filion et al. 2004; Stokes and Horvath 2009, 2010). LCA can help decision makers to select an urban water infrastructure product or material, such as sewer pipe, that results in the least impact to the environment. LCA methodology is based on the axiom that all phases in the life of a material or product cause environmental impacts and economic consequences and must therefore be analyzed, including raw materials acquisition, product manufacture, transportation, installation, operation and maintenance, and ultimately recycling and waste disposal (Lippiatt 2000).

In recent years, the aids of life cycle-based tools to support decision-making for sustainable products and processes have been discussed by several researchers (e.g., Bare 2014; Meyer and Upadhyayula 2014; Yeheyis et al. 2013). Life cycle technique can also be used to carry out LCSA of urban water infrastructure and sewer pipe (Heijungs et al. 2010). Accordingly, environmental LCA can be used to evaluate overall environmental impacts of different sewer pipe materials or products, while LCC techniques can be applied to estimate overall cost of different sewer pipe options. However, one of the main challenges of LCSA is how to integrate the result of LCA and LCC to find the most sustainable solution. Often, the environmental impacts are described in terms of physical units such as grams of chemical pollutants emitted to the air, kilometers of degraded streams, or the number of endangered species in a particular region, while the socio-economic impacts are commonly accounted for in \$ (Reza et al. 2013a). Nevertheless, to make a policy decision related to an urban water infrastructure such as sewer pipe, both environmental impacts and long-term economic consequences must be expressed by a unified measure to compare and evaluate equitably (Campbell et al. 2005). A

comprehensive effort has been made to standardize LCA and LCC by the International Organization for Standardization (ISO 14040 2006; ISO 14044 2006). However, there are still several technical issues in the application of LCA, particularly in impact assessment and product comparison (Reza et al. 2013a; Stewart et al. 1999).

Dealing with non-commensurate units of varying environmental impacts (e.g., grams of CO<sub>2</sub> emissions, kcal of energy consumption) and socio-economic costs is a major shortcoming of using LCA for the infrastructure sector (Brown and Buranakarn 2003; Reza et al. 2013a). Currently, there are three main approaches in the literature to characterize and compare the sustainability of an infrastructure product or system based on the LCA and LCC techniques:

- (1) Comparative sustainability assessment and selecting the most sustainable option based on initial results of standard LCA (and/or life cycle costing, i.e., LCC). This approach is only possible when the value of all (or most) life cycle impact categories (including upstream, downstream, and socio-economic impacts) in one alternative are less than the other alternatives (e.g., see this paper by Reza et al. 2013c). However, the LCA result for a building alternative is often a combination of pros and cons; a building material 'X' might have a large global warming potential effect while having excellent durability and recyclability potential as compared to a building material 'Y'.
- (2) Applying a multi-criteria decision analysis (MCDA) tool, e.g., AHP, PROMETHEE, ELECTRE, TOPSIS, etc. This method is very popular, and some recent application can be seen in Hahn (2014), Hossaini et al. (2014), Iwaro et al. (2014), Kucukvar et al. (2014a, b), Mattiussi et al. (2013), Myllyviita et al. (2014), Prado-Lopez et al. (2014), Reza et al. (2011), Scannapieco et al. (2014), and Yadollahi and Ansari (2014).
- (3) Decision-making based on a single indicator, e.g., embodied energy and carbon, material flow analysis, ecological footprint, emergy synthesis, and cost benefit. Some recent applications of this approach can be seen in Hu (2010), Mahlia and Iqbal (2010), Reza et al. (2013a, b), and Teng and Wu (2014).

In this paper, the two last approaches, i.e., applying a MCDA tool (AHP) and decision-making based on a single indicator (emergy) for selecting a sewer pipe material, will be explored.

## Methodology

The major steps of the methodology that has been used in this paper are:

- (1) Conducting standard LCA and LCC for evaluating environmental and economic impacts, respectively.
- (2) Performing emergy synthesis to unify the LCA and LCC results and to obtain overall impacts.
- (3) Applying AHP method to integrate the LCA and LCC results and to determine overall impacts.
- (4) Comparing results of emergy-based LCSA approach with AHP-based LCSA approach.

## LCA for sewer pipe

In the first step, LCA for all the selected materials is conducted. The selected materials for this study include concrete (CO), ductile iron (DI), polyvinyl chloride (PVC), and vitrified clay (VC), which represent 84 % of the total stock of sewers (Allouche et al. 2002). These materials are selected because they have comparable features in terms of quality and environmental characteristics. The functional unit had been defined as the 3 m length and 400 mm diameter of sewer pipes of different materials with the same design life of 100 years.

The inputs and outputs of all life cycle phases and relevant processes are compiled. The life cycle inventory (LCI) analysis requires collecting data for all process units and their associated energy and mass flows, as well as the data on emissions and discharges into the receiving air. Inventory analysis of a sewer system is very complex and involves dozens of individual unit processes as well as hundreds of related substances to quantify mass, energy, emission, information, and money flows through the extraction of raw resources, production processes, transportation, demolition, etc. SimaPro 7.1 is used for inventory analysis. This software uses various databases containing cradle-to-grave materials life cycle data. The LCI encompasses raw material extraction and production, transportation to a manufacturing company, pipe manufacturing, pipe installation, operation and maintenance, and disposal phases.

The life cycle impact assessment (LCIA) included resource depletion, energy consumption, and associated emissions for all phases of the life cycle of the sewer pipes. The environmental impacts are calculated for 3 m length and 400 mm diameter of sewer pipes of different materials with the same design life of 100 years. LCIA results for different sewer pipe materials have been summarized in Table 1.

## LCC for sewer pipe

The life cycle cost for pipe material selection consists of three main components: capital cost; maintenance, repair, or replacement cost; and end of life cost. In this study, the

**Table 1** LCIA results of sewer pipe

	Manufacturing					Construction				
	Resource use (kg)	Energy consumption (GJ)	Global warming potential (kg CO <sub>2</sub> eq)	Acidification (kg SO <sub>x</sub> eq)	Smog potential (kg NO <sub>x</sub> eq)	Resource use (kg)	Energy consumption (GJ)	Global warming potential (kg CO <sub>2</sub> eq)	Acidification (kg SO <sub>x</sub> eq)	Smog potential (kg NO <sub>x</sub> eq)
CO	24,224.3	1.24	39.02	0.98	0.27	3,375	0.40	7.98	0.20	0.06
PVC	5,966	1.23	24.19	0.61	0.17	3,375	0.30	3.62	0.09	0.03
VC	24,136	3.68	61.46	1.55	0.43	3,375	0.38	5.04	0.13	0.03
DI	14,949	5.72	139.50	3.51	0.97	3,375	0.35	7.06	0.18	0.05
O & M										
	Resource use (kg)	Energy consumption (GJ)	Global warming potential (kg CO <sub>2</sub> eq)	Acidification (kg SO <sub>x</sub> eq)	Smog potential (kg NO <sub>x</sub> eq)	Resource use (kg)	Energy consumption (GJ)	Global warming potential (kg CO <sub>2</sub> eq)	Acidification (kg SO <sub>x</sub> eq)	Smog potential (kg NO <sub>x</sub> eq)
CO	3,777	0.35	5.87	0.15	0.04	2,822	0.02	4.91	0.12	0.03
PVC	6,838	0.60	23.92	0.60	0.17	2,422	0.05	0.98	0.02	0.01
VC	3,689	0.33	5.87	0.15	0.04	2,904	0.02	122.94	3.09	0.85
DI	3,602	0.32	5.87	0.15	0.04	2,923	4.13	88.73	2.23	0.62

LCIA functional unit had been considered as the 3 m length and 400 mm diameter of sewer pipes of different materials with design life of 100 years

capital cost was defined as the total initial investment incurred at the beginning of the life cycle of the pipe. It consists of material cost and pipe installation cost. Maintenance cost is the common cost of maintenance until the pipe is replaced. The present value of total life cycle cost (TLCC) is calculated by adding the installation cost to the present value of a growing annuity of maintenance activities. The formula is:

$$TLCC = C_i + \Sigma C_{mrr} + C_e, \tag{1}$$

where the TLCC in present value is a summation of capital cost ( $C_i$ ), which includes the initial cost or cost of material; installation, maintenance, repair, and replacement cost ( $C_{mrr}$ ), which includes life cycle costs paid for maintenance, repair, and replacement of a pipe; and end of life cost ( $C_e$ ), which includes cost of disposal and/or recycling of a pipe. When choosing between two mutually exclusive alternatives with significantly different service life, an adjustment should be made to ensure equal comparison. The net present values of the competing alternatives should be adjusted using an equivalent annual annuity (EAA) approach (ISO/DIS 15686-5 2004). The EAA approach calculates the constant annual cash flow generated by a project over its lifespan. The present value of the constant annual cash flows is exactly equal to the project's net present value. Using this method, the annual investment cost required for each alternative can be calculated using the following equation:

$$PW = A \cdot \frac{(1 + r)^n - 1}{r(1 + r)^n}, \tag{2}$$

where the present worth annuity (PW) is a function of annualized total cost ( $A$ ), discount rate ( $r$ ), and service life years ( $n$ ). In this study, the discount rate of 4.17 % is used, which is obtained from the Canadian Government securities provided by the Bank of Canada (2012). In order to compare alternatives with unequal service lives, the number of service life years for the alternative with the highest EAA should be selected as the functional unit, and the TLCC for other alternatives will be normalized based on the selected functional unit. The various life cycle cost data used in this study are given in Table 2.

### Emergy-based LCSA approach

The first LCSA approach applied in this paper is based on the use of emergy synthesis in order to unify the results of LCA and LCC. Emergy synthesis was proposed and developed by H.T. Odum in 1980 as a way of understanding the behavior of self-organized systems, valuing ecological products and services, and analyzing ecological and economic systems together (Hau and Bakshi 2004). Campbell (1998) explained emergy as a real measure of

**Table 2** Lifecycle cost data for different pipes

Parameters	CO	PVC	VC	DI
Discount rate, $r$ (%)	4.17	4.17	4.17	4.17
Service life, $n$ (years)	114	75	136	100
Initial cost, $C_i$				
Material cost (\$/m length)	83.9	172.04	201.25	254.06
Installation cost (\$/m length)	204	204	204	204
Maintenance, repair and replacement cost, $C_{mrr}$				
Root (chemical treatment, \$/m/year)	0.912	0.912	0.912	0.912
Sludge maintenance (\$/m/year)	0.59	0.59	0.59	0.59
Grease (pressurized cleaning/jetting, \$/m/year)	0.29	0.29	0.29	0.29
Debris (flushing, \$/m/year)	0.298	0.298	0.298	0.298
Repair cost (\$)	10 % of initial cost	10 % of initial cost	10 % of initial cost	10 % of initial cost
Replacement cost (\$)	100 % of initial cost	100 % of initial cost	100 % of initial cost	100 % of initial cost
EoL cost, $C_e$ (\$)	30 % of initial cost	20 % of initial cost	15 % of initial cost	35 % of initial cost

relative importance that can express different forms of environmental, economic, and human systems in terms of equivalent ability to do work (Reza et al. 2013a). Information about energy synthesis, its theoretical basis, and its method is summarized in “Appendix” section.

Several new studies have been introduced by energy and LCA practitioners in the direction of integrating and combining LCA and energy synthesis (e.g., Zhang et al. 2010a, parts I and II; Reza et al. 2013a, b). Raugei et al. (2012a, b) discussed the potential added value of integrating LCA and energy synthesis. In a recent study by Reza et al. (2013a), energy synthesis has been used as a complement to standard LCA to evaluate long-term sustainability of roadway systems. In this study, the Em-LCA approach proposed by Reza et al. (2013a) has been applied and investigated for sustainability assessment of sewer pipe material. The following is a brief summary of major steps that are applied in the energy-based LCSA.

*Defining scope and system boundary*

Defining the system boundary is a primary requirement of energy analysis. Particularly to obtain a well-integrated result, the boundary of energy accounting (EMA) should be set in accordance with the LCA scope. As illustrated in Fig. 1, the complete life cycle of sewers from cradle-to-grave is covered in this analysis. In the energy-based life cycle approach, fluxes in each stage of a sewer life cycle are transformed into their energy equivalent. The boundary consists of major flows contributing at different stages of the sewer life cycle, which include raw material extraction, manufacturing of materials, construction, operation and maintenance, and demolition (cradle-to-grave).

In this study, the energy-based LCSA technique has been developed to consider three major impact categories:

*resource inputs or upstream impacts*, including the work of an ecosystem that would be needed to replace renewable and non-renewable resources; *waste and emission or downstream impacts*, including the energy equivalent of HH and natural capital loss as a result of life cycle emission; and *associated economic impacts*, including life cycle monetary cost related to human labor and services. Tables of the actual flows of materials, labor, and energy are constructed from the diagrams and all flows are evaluated. The different units for each flow were multiplied by the transformities, which are obtained from the literature to convert them to solar energy.

*Data analysis and impact assessment*

In this step, the inflows and outflows of the sewer systems obtained from SimaPro LCI and LCC have been simulated as energy pathways in the sewer system diagram to show the flows and their interaction. Figure 2 shows the *energy system diagram* for the sewer system. The system diagram consists of major flows contributing at different stages of sewer life cycle, which include resource extraction, manufacturing of materials, construction, operation and maintenance, and demolition (cradle-to-grave). Relationships between components and pathways of resource flows are drawn in this step. The sewer system has been assumed as a thermodynamic engine that consumes resources to produce specific services; produces emissions to air, water, and land; and maintains its performance as a public infrastructure.

Considered flows have different forms of energy, material (natural resources), human work, machinery, and service. The dashed line shows the recycle scenario at the end of a sewer life cycle. Flows of money in the system are illustrated as dashed lines with a \$ sign. The energy system

**Fig. 1** System boundary based on cradle-to-grave LCA

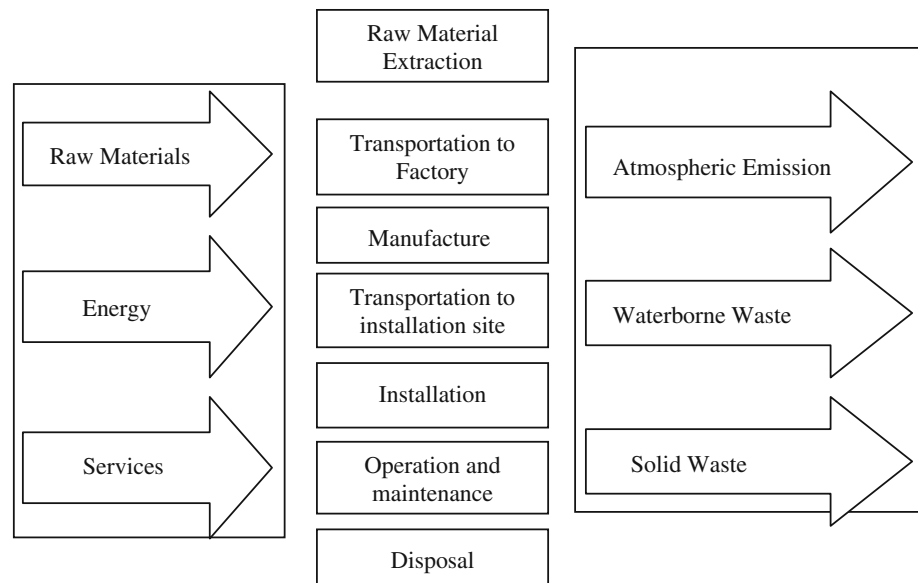


diagram is drawn based on the symbols of the energy systems language given by Odum (1996).

After developing the energy system diagram for each sewer pipe, a description of different pathways from the product system diagram is transferred to the emergy evaluation table, where the calculations needed to quantitatively evaluate these pathways are compiled. Generally, the emergy evaluation table has six columns: column 1: note, column 2: item, column 3: raw data, column 4: transformity or specific emergy, column 5: reference, and column 6: emergy.

*Evaluating the impacts of resource use* In this step, all inventory data related to resource consumption that were obtained from LCI needs to be compiled. Then, *unit emergy values* (UEVs) or *solar transformity* for each inventory item must be extracted from the emergy database (i.e., Odum 1996) and adopted based on the selected global biosphere emergy baseline.<sup>2</sup> Then, using UEV of each input pathway, all resource inputs in the inventory are converted into emergy values. Finally, the total solar emergy,  $U$ , can be derived from Eq. (1):

$$U = \sum_i \text{UEV}_i \times E_i, \quad (3)$$

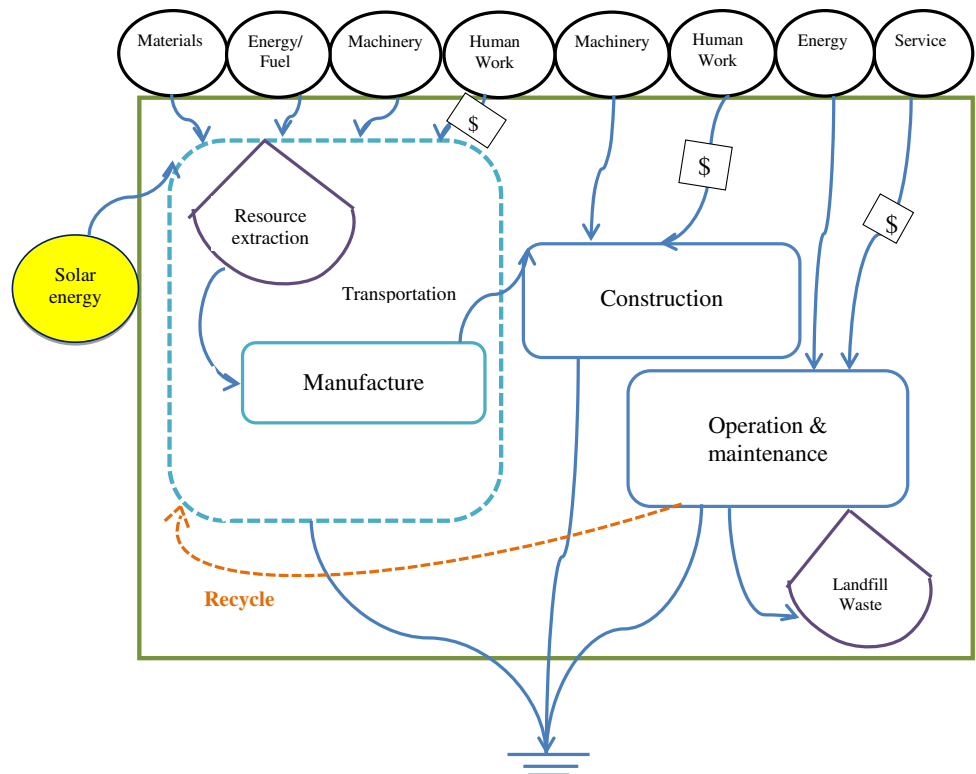
where  $E_i$  is the actual energy content of the  $i$ th independent input flow to the process and  $\text{UEV}_i$  is the unit emergy value (UEV) or solar transformity of the  $i$ th input flow (Pulselli et al. 2007).

<sup>2</sup> Global biosphere emergy baseline is the total emergy driving the biogeosphere. So far a few different global biosphere emergy baselines have been suggested by emergy practitioners. In this research, the sum of solar, tidal, and deep heat sources is considered to be equal to the value of  $15.83\text{E}+24$  seJ/year as suggested by Odum and Brown (2000).

Emergy calculations of resource use or upstream impacts for various pipes have been summarized in Tables 3, 4, 5 and 6. As was summarized in these tables, each inventory item has been transferred from raw units to solar energy. Column 1 includes the names of the inventory items and unit in joules or kg. Column 2 is the UEVs used for emergy calculations, expressed in seJs/J or kg. UEVs are collected from the EMA database (Odum 1996). The amount of each inventory item has been summarized in columns 3–6 for each life cycle stage. The total life cycle input to each inventory item is summarized in column 7. Column 8 indicates the solar emergy or upstream impact of a given flow, calculated by multiplying the total amount of each inventory item by its related UEV (column 2 multiplied by column 7).

*Evaluating the impacts of emissions* In this step, absolute values of emissions (only air emissions are considered in this study) from LCI are converted to emergy values. A number of methods have been developed in the previous studies for assessing the environmental impact of emissions. It is a very useful step to integrate such methods within a procedure capable of describing and quantifying the actual damage to populations or assets in emergy terms. Emissions can cause ecological losses through acidification, eutrophication, or ecotoxicity that may result in loss of species and fish mortality. In addition, emissions can lead to some socio-economic losses, such as HH effects and land occupation (Zhang et al. 2010a). The consequences of airborne and waterborne emissions and solid waste generation can be quantified based on the natural and human capital losses caused by emissions (Bakshi 2000, 2002; Reza et al. 2013a).

**Fig. 2** System diagram of a sewer lifecycle



Knowledge of ecosystem self-organization as well as loss of ecosystem components is required to evaluate the ecological impacts in terms of energy loss (EL; Bakshi 2000). In this study, a preliminary damage assessment of losses is performed according to the framework of the Eco-indicator 99 assessment method. According to the Eco-indicator 99, ecological impacts or natural capital losses can be addressed by potentially disappeared fraction (PDF)<sup>3</sup> of species in the affected ecosystem (Bakshi 2002), while the human capital losses can be expressed as disability adjusted life years (DALYs)<sup>4</sup> per unit emission. Then the emission impacts on ecosystem quality (EQ) and HH represented by PDF and DALY can be converted to a corresponding EL as proposed by Liu et al. (2011).

EL in support of local ecological resources can be measured using Eq. (4):

$$EL_{EQ} = \sum m_i \times PDF (\%) \times E_{bio}, \tag{4}$$

where  $EL_{EQ}$  represents energy equivalent of loss of regional natural resources due to given emission,  $m_i$  is the amount of

$i$ th chemical released, PDF (%) represents the potentially disappeared fraction calculated as  $PDF \text{ m}^2 \text{ year/kg}$ , and  $E_{bio}$  is the unit of annual energy allocated to regional natural capital (this value for Canada and the province of BC is calculated by Hossaini and Hewage 2013).

In the same way, EL in support of human resources (considering all their complexity such as education, culture, quality of life, etc.) can be calculated as proposed by Liu et al. (2011):

$$EL_{HH} = \sum m_i \times DALY \times E_p, \tag{5}$$

where  $EL_{HH}$  represents energy equivalent of loss of human resources due to given emission  $m_i$ , DALY represents the disability adjusted life years per unit emission (year/g), and  $E_p$  is the total annual energy per population (annual energy per population for Canada is  $1.73E+17 \text{ seJ/year/pop}$  Hossaini and Hewage 2013). Energy equivalent of air emissions downstream impacts and EL (loss of human health  $EL_{HH}$  and ecosystem quality  $EL_{EQ}$ ) for the different pipe materials have been summarized in Tables 7, 8, 9 and 10.

*Evaluating the impacts of life cycle monetary costs* In this stage, economic aspects will be accounted for as the emergy required to support labor and/or services.<sup>5</sup>

<sup>3</sup> The PDF can be interpreted as the fraction of habitats or species that has a high probability of no occurrence in a region due to unfavorable conditions caused by product life cycle impacts, e.g., acidification and eutrophication.

<sup>4</sup> DALY is the number of disability years caused by exposure to an emission (chemicals or pollutants) multiplied by the “disability factor”, which is a number between 0 and 1 that describes severity of the damage (0 being perfectly healthy and 1 being fatal; Agrawal et al. 2014).

<sup>5</sup> According to Brown et al. (2012) labor can be define as an activity that is directly applied to a process, while services can be recognized as activities that are indirectly applied to a process from the larger scale of the economy.

**Table 3** Emergy equivalent of resource use for concrete sewer pipe

Resources (unit)	UEV (seJ/unit) <sup>a</sup>	Production	Construction	Maintenance	EoL	Total	Emergy (seJ) <sup>b</sup>
Cement (kg)	3.04E+12	6.59E+01	–	6.59E+01	–	1.32E+02	4.01E+14
Sand (kg)	1.12E+12	1.19E+02	–	1.19E+02	–	2.37E+02	2.66E+14
Water (kg)	1.95E+09	3.30E+01	–	3.30E+01	–	6.60E+01	1.29E+11
Gravel (kg)	1.12E+12	1.85E+02	–	1.85E+02	–	3.69E+02	4.14E+14
Concrete mixer fuel (J)	1.13E+05	2.64E+08	–	–	–	2.64E+08	2.98E+13
Electricity (J)	2.00E+05	7.65E+08	–	–	–	7.65E+08	1.53E+14
Excavator fuel use (J)	1.13E+05	–	–	–	–	3.38E+08	3.82E+13
Compactor fuel use (J)	1.13E+05	–	1.69E+08	1.69E+08	–	2.48E+08	2.80E+13
Demolition fuel use (J)	1.13E+05	–	1.24E+08	1.24E+08	–	2.46E+08	2.78E+13
Truck (dump) fuel (J)	1.13E+05	2.11E+08	1.06E+08	5.29E+07	2.11E+07	3.91E+08	4.42E+13

<sup>a</sup> UEV for each inventory item extracted from the emergy database (Odum 1996) and adopted based on the global biosphere emergy baseline of 15.83E24 seJ/year as suggested by Odum and Brown (2000)

<sup>b</sup> The functional unit had been considered as the 3 m length and 400 mm diameter of sewer pipes of different materials with design life of 100 years

**Table 4** Emergy equivalent of resource use for PVC sewer pipe

Resources (unit)	UEV (seJ/unit) <sup>a</sup>	Production	Construction	Maintenance	EoL	Total	Emergy (seJ) <sup>b</sup>
PVC resin (kg)	5.87E+12	4.06E+01	–	4.06E+01	–	8.11E+01	4.76E+14
Calcium carbonate (kg)	1.12E+12	1.93E+00	–	1.93E+00	–	3.85E+00	4.32E+12
Stabilizer (kg)	6.38E+11	1.31E+00	–	1.31E+00	–	2.63E+00	1.68E+12
PVC manufacture fuel (J)	1.13E+05	1.13E+09	1.13E+09	–	–	2.27E+09	2.56E+14
PVC extruder fuel (J)	2.00E+05	7.10E+07	–	7.10E+07	–	1.42E+08	2.84E+13
Excavator fuel use (J)	1.13E+05	–	169,405,714.3	3.39E+08	–	5.08E+08	5.74E+13
Compactor fuel use (J)	1.13E+05	–	1.24E+08	2.48E+08	–	3.72E+08	4.20E+13
Truck (dump) fuel (J)	1.13E+05	2.30E+07	1.15E+07	1.15E+07	2.30E+06	4.83E+07	5.46E+12
Recycling fuel (J)	2.00E+05	–	–	–	3.82E+07	3.82E+07	7.65E+12
Disposal fuel (J)	1.13E+05	–	–	–	5.34E+06	5.34E+06	6.03E+11

<sup>a</sup> UEV for each inventory item extracted from the emergy database (Odum 1996) and adopted based on the global biosphere emergy baseline of 15.83E24 seJ/year as suggested by Odum and Brown (2000)

<sup>b</sup> The functional unit had been considered as the 3 m length and 400 mm diameter of sewer pipes of different materials with design life of 100 years

**Table 5** Emergy equivalent of resource use for VC sewer pipe

Resources (unit)	UEV (seJ/unit) <sup>a</sup>	Production	Construction	Maintenance	EoL	Total	Emergy (seJ) <sup>b</sup>
Clay (kg)	1.96E+12	2.94E+02	–	2.94E+02	–	5.88E+02	1.15E+15
Barium (kg)	1.68E+12	1.32E+01	–	1.32E+01	–	2.64E+01	4.44E+13
Calcite (kg)	1.95E+09	6.91E+00	–	6.91E+00	–	1.38E+01	2.70E+10
Diesel (J)	1.13E+05	2.21E+09	–	–	–	2.21E+09	2.49E+14
Electricity (J)	2.00E+05	6.52E+08	–	–	–	6.52E+08	1.30E+14
Excavator fuel (J)	1.13E+05	–	1.69E+08	1.69E+08	–	3.39E+08	3.83E+13
Compactor fuel (J)	1.13E+05	–	1.24E+08	1.24E+08	–	2.48E+08	2.80E+13
Truck (dump) fuel (J)	1.13E+05	1.65E+08	8.26E+07	4.13E+07	1.65E+07	3.06E+08	3.45E+13
Recycling fuel (J)	2.00E+05	–	–	–	5.69E+09	5.69E+09	1.14E+15

<sup>a</sup> UEV for each inventory item extracted from the emergy database (Odum 1996) and adopted based on the global biosphere emergy baseline of 15.83E24 seJ/year as suggested by Odum and Brown (2000)

<sup>b</sup> The functional unit had been considered as the 3 m length and 400 mm diameter of sewer pipes of different materials with design life of 100 years



**Table 6** Emery equivalent of resource use for DI sewer pipe

Resources (unit)	UEV (seJ/unit) <sup>a</sup>	Production	Construction	Maintenance	EoL	Total	Emery (seJ) <sup>b</sup>
Cast iron (kg)	4.15E+12	2.12E+02	–	2.12E+02	–	4.25E+02	1.76E+15
Carbon (kg)	1.68E+12	7.70E+00	–	7.70E+00	–	1.54E+01	2.59E+13
Silicon (kg)	1.95E+12	6.34E+00	–	6.34E+00	–	1.27E+01	2.47E+13
Coal (kg)	4.00E+04	5.03E+09	–	–	–	5.03E+09	2.01E+14
Electricity (J)	2.00E+05	4.37E+08	–	1.37E+08	–	5.74E+08	1.15E+14
Excavator fuel (J)	1.13E+05	–	1.69E+08	1.69E+08	–	3.39E+08	3.83E+13
Compactor fuel (J)	1.13E+05	–	1.24E+08	1.24E+08	–	2.48E+08	2.80E+13
Truck (dump) fuel (J)	1.13E+05	1.19E+08	5.95E+07	2.98E+07	1.19E+07	2.20E+08	2.49E+13
Recycling fuel (J)	2.00E+05	–	–	–	3.98E+09	3.98E+09	7.96E+14
Disposal fuel (J)	1.13E+05	–	–	–	1.38E+08	1.38E+08	1.56E+13

<sup>a</sup> UEV for each inventory item extracted from the emery database (Odum 1996) and adopted based on the global biosphere emery baseline of 15.83E24 seJ/year as suggested by Odum and Brown (2000)

<sup>b</sup> The functional unit had been considered as the 3 m length and 400 mm diameter of sewer pipes of different materials with design life of 100 years

Accordingly, it was assumed that sewer pipe life cycle consists of investing emery ( $F$ ) from the economic system due to different activities such as extracting and refining the resources, manufacturing and producing goods, and providing labor and services for construction, rehabilitation, and maintenance. According to Ulgiati and Brown (2012), if we trace back far enough through the web of energy and material flows of a system, it can be revealed that all the money invested in a process is used to purchase labor and services (indirect labor). They emphasize that it is not necessary to assess the monetary value for each input item in the supply chain, and services can be accounted for from the price of final inputs to the foreground (e.g., price of extracting and refining the resources as well as manufacturing and producing a material can be considered as total material cost).

According to Odum (1996), the work of labor can be valued based on level of training and education where data are available. However, analyses in different national economies of the training and education necessary for labor have not been yet conducted. Therefore, in practice, the emery required to support labor and/or services can be obtained by multiplying the salaries paid (or total cost of services) by emery cost factor, i.e., the UEV of currency (seJ/GDP) in a given economy (Ulgiati and Brown 2012). This is based on the assumption that salaries can reflect the level of training and education of different labor inputs (Ulgiati and Brown 2012). Accordingly, using the emery technique to account for TLCC adds further essential information about the *structure, infrastructures, and socio-economic development of a society in which a process takes place and how it affects the performance and the cost of the process under investigation* (Ulgiati and Brown 2012).

In this stage, the results from LCC that have been presented in Table 2 are converted to emery value. Life cycle costs have been calculated based on average cost of materials and services in Canada. The impacts of life cycle costs are considered emery investment from the economic system due to different activities such as extracting and refining the non-renewable resource, manufacturing and producing goods, and providing services for construction, rehabilitation, and maintenance. Emery value for life cycle costs and services is accounted by multiplying the absolute \$ values by Canadian currency (Canada Emery/GDP is 4.22E+12 seJ/CAD Hossaini and Hewage 2013). The associated life cycle costs of the different pipes have been converted to the emery values and summarized in Tables 11, 12, 13 and 14.

*Fellow summary and calculating the yield emery value*

In this step, the emery value of different items of each sewer pipe is added up and summed for each group of impacts (upstream impacts, downstream impacts, and monetary cost). Then the overall impact or yield emery value can be obtained by summing the total emery value of all groups of impact for each sewer pipe material.

AHP-based LCSA approach

The second LCSA approach applied in this paper is based on the use of AHP in order to aggregate and combine the results of LCA and LCC. AHP is a MCDM technique developed by Saaty (1980) and thus far has successfully been implemented in various engineering applications. Background information about MCDM and AHP, and their theoretical basis and method, was summarized in the

**Table 7** Emery equivalent of air emissions for Concrete sewer pipe

Airborne pollution	Damage category	DALY (kg) <sup>a</sup>	PDF (%) <sup>a</sup>	Production	Construction	Maintenance	EoL	Total effects	Emery loss (seJ) <sup>b</sup>	
									EL <sub>HH</sub>	EL <sub>EQ</sub>
Global warming potential (kg)	Climate change	2.10E-07	–	3.90E+01	7.98E+00	5.87E+00	4.91E+00	5.78E+01	2.10E+12	–
NO <sub>x</sub> emission (kg)	Respiratory disorder	8.87E-05	5.71	2.71E-01	5.54E-02	4.07E-02	3.41E-02	4.01E-01	6.15E+12	1.27E+09
SO <sub>x</sub> emission (kg)	Respiratory disorder	5.46E-05	1.04	9.81E-01	2.01E-01	1.48E-01	1.23E-01	1.45E+00	1.37E+13	8.36E+08

<sup>a</sup> Eco-indicator 99 (Goedkoop and Spriensma 2000)

<sup>b</sup> The functional unit had been considered as the 3 m length and 400 mm diameter of sewer pipes of different materials with design life of 100 years

**Table 8** Emery equivalent of air emissions for PVC sewer pipe

Airborne pollution	Damage category	DALY (kg) <sup>a</sup>	PDF (%) <sup>a</sup>	Production	Construction	Maintenance	EoL	Total effects	Emery loss (seJ) <sup>b</sup>	
									EL <sub>HH</sub>	EL <sub>EQ</sub>
Global warming potential (kg)	Climate change	2.10E-07	–	2.42E+01	3.62E+00	2.39E+01	9.77E-01	5.27E+01	1.91E+12	–
NO <sub>x</sub> emission (kg)	Respiratory disorder	8.87E-05	5.71	1.68E-01	2.51E-02	1.66E-01	6.78E-03	3.66E-01	5.61E+12	1.16E+09
SO <sub>x</sub> emission (kg)	Respiratory disorder	5.46E-05	1.04	6.08E-01	9.10E-02	6.02E-01	2.46E-02	1.33E+00	1.25E+13	7.62E+08

<sup>a</sup> Eco-indicator 99 (Goedkoop and Spriensma 2000)

<sup>b</sup> The functional unit had been considered as the 3 m length and 400 mm diameter of sewer pipes of different materials with design life of 100 years

**Table 9** Emery equivalent of air emissions for VC sewer pipe

Airborne pollution	Damage category	DALY (kg) <sup>a</sup>	PDF (%) <sup>a</sup>	Production	Construction	Maintenance	EoL	Total effects	Emery loss (seJ) <sup>b</sup>	
									EL <sub>HH</sub>	EL <sub>EQ</sub>
Global warming potential (kg)	Climate change	2.10E-07	–	6.15E+01	5.04E+00	5.87E+00	1.23E+02	1.95E+02	7.10E+12	–
NO <sub>x</sub> emission (kg)	Respiratory disorder	8.87E-05	5.71	4.27E-01	3.50E-02	4.07E-02	8.53E-01	1.36E+00	2.08E+13	4.28E+09
SO <sub>x</sub> emission (kg)	Respiratory disorder	5.46E-05	1.04	1.55E+00	1.27E-01	1.48E-01	3.09E+00	4.91E+00	4.64E+13	2.82E+09

<sup>a</sup> Eco-indicator 99 (Goedkoop and Spriensma 2000)

<sup>b</sup> The functional unit had been considered as the 3 m length and 400 mm diameter of sewer pipes of different materials with design life of 100 years

“Appendix” section. Integration of AHP and LCA provides a LCSA framework that is consistent with decision-making for sustainable infrastructure asset management. In recent years, AHP has been applied by few researchers as part of the LCSA approach for selecting more sustainable infrastructure or construction alternatives (e.g., Reza et al. 2011). AHP is a systemic method to solve complex decision-making problems involving few alternatives with numerous criteria. The process of comparing the relative importance or preference of a parameter (objectives or criteria) with respect to other parameters is based on pair-wise comparisons. In this paper, AHP has been done by the following five stages as proposed by Zahedi (1986):

(1) Break down a problem into a hierarchy of ultimate goal, (sub)criteria,<sup>6</sup> and alternatives.

- (2) Collect basic input data for all (sub)criteria and alternatives to make pair-wise comparisons.
- (3) Evaluate the relative weights of each (sub)criterion. A linguistic measure of importance used for pair-wise comparisons is provided in Table 15 (Saaty 1980). According to a nine-point intensity scale, a decision maker is able to generate pair-wise comparisons among (sub)criteria and alternatives and derive relative importance of a factor.
- (4) Aggregate weights and scores to establish a ranking of alternatives. The aggregated scores are in the range of [0 1]. The alternative with the maximum value will be considered a preferred alternative.
- (5) Study reliability and validity of data using sensitivity analysis.

In this paper, LCIA results have been characterized and classified as general categories or (sub)criteria, that are hierarchically structured and developed. Figure 3 provides three levels of the proposed hierarchical model. The goal of

<sup>6</sup> The term “(sub)criteria” in this manuscript implies both criteria (main sustainability criteria, i.e., environmental and economic factors) and sub-criteria (main sustainability criteria have been subdivided into several sub-criteria, e.g., resource depletion).

**Table 10** Emergy equivalent of air emissions for DI sewer pipe

Airborne pollution	Damage category	DALY (kg) <sup>a</sup>	PDF (%) <sup>a</sup>	Production	Construction	Maintenance	EoL	Total effects	Emergy loss (seJ) <sup>b</sup>	
									EL <sub>HH</sub>	EL <sub>EQ</sub>
Global warming potential (kg)	Climate change	2.10E-07	-	1.40E+02	7.06E+00	6.46E+00	8.87E+01	2.42E+02	8.78E+12	-
NO <sub>x</sub> emission (kg)	Respiratory disorder	8.87E-05	5.71	9.68E-01	4.90E-02	4.48E-02	6.16E-01	1.68E+00	2.57E+13	5.30E+09
SO <sub>x</sub> emission (kg)	Respiratory disorder	5.46E-05	1.04	3.51E+00	1.77E-01	1.62E-01	2.23E+00	6.08E+00	5.74E+13	3.50E+09

<sup>a</sup> Eco-indicator 99 (Goedkoop and Spriensma 2000)

<sup>b</sup> The functional unit had been considered as the 3 m length and 400 mm diameter of sewer pipes of different materials with design life of 100 years

**Table 11** Emergy equivalent of lifecycle costs for concrete sewer pipe

Services	UEV (seJ/CAD) <sup>a</sup>	Production	Construction	Maintenance	Total	Emergy (seJ) <sup>b</sup>
Initial cost	4.22E+12	2.52E+02	6.12E+02	-	8.64E+02	3.64E+15
Maintenance cost	4.22E+12	-	-	8.69E+01	8.69E+01	3.67E+14
Repair cost	4.22E+12	-	-	8.64E+01	8.64E+01	3.64E+14
Replacement cost	4.22E+12	-	-	2.86E+00	2.86E+00	1.21E+13

<sup>a</sup> Canadian emergy money ratio (EMR) reported by Hossaini and Hewage (2013)

<sup>b</sup> The functional unit had been considered as the 3 m length and 400 mm diameter of sewer pipes of different materials with design life of 100 years

the study is defined at the first level. In the second level, sustainability criteria, and environmental and economic factors are considered. Each of these main criteria is subdivided into several sub-criteria based on LCIA damage categories and life cycle cost categories. After constructing the hierarchy, pair-wise comparisons are performed at each level in the hierarchy using a reciprocal matrix (refer to the “Appendix” section) to include relative importance of all criteria and sub-criteria. The criteria and sub-criteria are compared according to their relative importance and with respect to the parent elements in the adjacent upper level. Applying AHP and pair-wise comparison matrices, the relative importance weight is assigned to each (sub)criterion or damage category.

In this research, it was assumed that the main criteria i.e., environmental and economic impacts, are equally important. Pair-wise comparison among different sub-criteria (i.e., among five damage categories and among three life cycle cost categories) has been carried out according to the linguistic measure of importance table proposed by Saaty (Table 15). For instance, Table 16 represents the principal matrix of comparison, which contains the comparison between environmental sub-criteria in relation to the overall objective of the problem (i.e., the selection of a sustainable sewer material). A local priority vector was generated for the matrix of judgments in Table 15 by normalizing the vector in each column of the matrix (i.e., dividing each entry of the column by the column total) and then averaging over the rows of the resulting matrix (Saaty 1980). Finally, the relative importance weights of different environmental criteria are shown in the last column.

According to LCIA results (Table 1), it can be observed that different sewer alternatives have varying levels of impact with respect to different (sub) criteria. Accordingly, the relative weights have been assigned to each sewer pipe alternative with respect to their upper level sub-criteria (i.e., damage categories and life cycle cost categories), by normalizing their impact values (the smaller the impact the bigger the weight has been assigned). Finally, by aggregating weights, a set of alternatives ranking can be achieved based on the cumulative effects of different life cycle impacts and costs and calculating the overall weight or sustainability index. Table 17 shows the relative importance weight of different (sub)criteria as well as overall weights or sustainability index of the four sewer pipes.

**Results and discussion**

In this study, four types of sewer materials, namely, CO, PVC, VC, and DI were analyzed based on the life cycle approach. Environmental impacts associated with sewer materials were calculated for every stage of life cycle. Economic impacts over the life cycle of sewer pipes were calculated using the LCC method. All the impacts were aggregated using two LCSA approaches. The results are discussed in the following sections. In this section, the results from each LCSA approach are explained and the pros and cons of each method are discussed.

**Table 12** Emergy equivalent of lifecycle costs for PVC sewer pipe

Services	UEV (seJ/CAD) <sup>a</sup>	Production	Construction	Maintenance	Total	Emergy (seJ) <sup>b</sup>
Initial cost	4.22E+12	5.16E+02	4.12E+02	–	9.28E+02	3.92E+15
Maintenance cost	4.22E+12	–	–	8.69E+01	8.69E+01	3.67E+14
Repair cost	4.22E+12	–	–	1.13E+02	1.13E+02	4.76E+14
Replacement cost	4.22E+12	–	–	3.47E+01	3.47E+01	1.47E+14

<sup>a</sup> Canadian emergy money ratio (EMR) reported by Hossaini and Hewage (2013)

<sup>b</sup> The functional unit had been considered as the 3 m length and 400 mm diameter of sewer pipes of different materials with design life of 100 years

**Table 13** Emergy equivalent of lifecycle costs for VC sewer pipe

Services	UEV (seJ/CAD) <sup>a</sup>	Production	Construction	Maintenance	Total	Emergy (seJ) <sup>b</sup>
Initial cost	4.22E+12	6.04E+02	6.12E+02	–	1.22E+03	5.13E+15
Maintenance cost	4.22E+12	–	–	8.69E+01	8.69E+01	3.67E+14
Repair cost	4.22E+12	–	–	1.22E+02	1.22E+02	5.13E+14
Replacement cost	4.22E+12	–	–	3.27E+00	3.27E+00	1.38E+13

<sup>a</sup> Canadian emergy money ratio (EMR) reported by Hossaini and Hewage (2013)

<sup>b</sup> The functional unit had been considered as the 3 m length and 400 mm diameter of sewer pipes of different materials with design life of 100 years

**Table 14** Emergy equivalent of lifecycle costs for DI sewer pipe

Services	UEV (seJ/CAD) <sup>a</sup>	Production	Construction	Maintenance	Total	Emergy (seJ) <sup>b</sup>
Initial cost	4.22E+12	7.62E+02	6.12E+02	–	1.37E+03	5.80E+15
Maintenance cost	4.22E+12	–	–	8.69E+01	8.69E+01	3.67E+14
Repair cost	4.22E+12	–	–	1.37E+02	1.37E+02	5.80E+14
Replacement cost	4.22E+12	–	–	1.98E+00	1.98E+00	8.36E+12

<sup>a</sup> Canadian emergy money ratio (EMR) reported by Hossaini and Hewage (2013)

<sup>b</sup> The functional unit had been considered as the 3 m length and 400 mm diameter of sewer pipes of different materials with design life of 100 years

### Emergy-based LCSA approach

Emergy synthesis was applied for assessing energy and material inflows to every stage of life cycle for selected sewer pipes. Figure 4 compares upstream impacts of different resource categories (resource use categories are explained in “[Emergy-based LCSA approach](#)” section) of the different materials of sewer pipes. According to this figure, DI pipe is more resource-intensive based on material extractions and fuel consumption, while PVC pipe is least resource-intensive among all pipes.

In addition, Figs. 5 and 6 compare different downstream impact categories (explained in “[Emergy-based LCSA approach](#)” section) of the different pipe materials. According to these figures, DI pipe causes more natural and human capital losses due to emission to air. PVC pipe shows least ELs following CO and VC pipe, respectively.

Life cycle costs were also calculated based on average cost of labor and services in Canada. The impacts of life

cycle costs are considered as emergy investment from different activities such as extracting and refining the resource, manufacturing and producing goods, and providing labor and services for construction, rehabilitation, and maintenance. Figure 7 compares the emergy cost of different pipes. According to this figure, DI pipe is the most costly alternative pipe material. The emergy cost of CO pipe is less than all other pipes. Figure 8 compares the total emergy value of the four different pipes. According to this figure, PVC pipe causes less overall environmental and economic impact through its life cycle, followed by the CO pipe.

### AHP-based LCSA approach

As discussed in “[AHP-based LCSA approach](#)” section, the normalized importance weights of sub-criteria are combined to obtain the final weights of all the alternatives used in the third level of the AHP model. Finally, the ranking of

**Table 15** Fundamental scale for developing priority matrix (Saaty 1980)

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one activity over other
5	Strong importance	Experience and judgment strongly favor one activity over other
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of highest possible order of affirmation
1, 2, 4, 6, 8	Intermediate values	

alternatives is conducted and the impacts of various (sub)criteria are assessed and aggregated as a single sustainability measure. The overall weights or sustainability index of different pipes are compared in Fig. 9. As shown in this figure, CO pipe turns out to be the most preferable material among the other materials, with an overall weight of 0.27, followed by overall weight of 0.26 for PVC pipe.

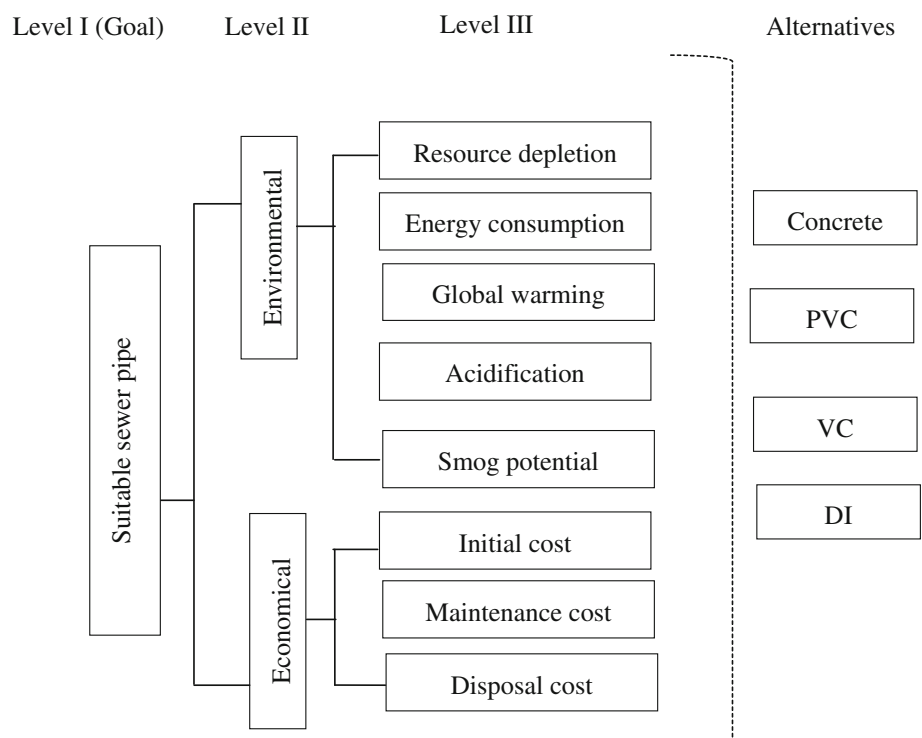
Discussing the results of two LCSA approaches

By comparing the results from both LCSA approaches, it can be realized that the final results of the methods are not quite in agreement. While the emergy-based LCSA method promotes PVC pipes, the AHP-based method suggests that CO pipes can be a slightly more preferable option among other pipe materials. One of the main reasons is because the assignment of weight in AHP involves human

subjectivity and it could be very sensitive to decision maker preference. In fact, the proximity of the overall weights of concert and PVC pipes indicate that a slight change in relative importance weight among different (sub)criteria can change the rank of PVC and concert pipes relatively.

To better understand the sensitivity of the AHP results, a sensitivity analysis can be conducted in which different weighting schemes can be applied to re-evaluate each alternative. In this research, the analysis is repeated in two further trials. In the second trial, environmental impact is given priority and its weight was assumed to be 0.75 compare to 0.25 for economic cost. In the third trial, economic impact is given priority and its weight was assumed to be 0.75 compare to 0.25 for environmental impact. The weighting schemes for the three trials for each alternative have been indicated in Fig. 10. The results show that the

**Fig. 3** Hierarchy model for AHP-based LCSA approach



**Table 16** Pair-wise matrix and priorities for environmental sub-criteria

Sub-criteria	Resource use	Energy consumption	Global warming potential	Smog potential	Acidification	Relative priority
Resource use	1	1/3	1/4	3	3	0.13
Energy consumption	3	1	1/2	4	5	0.28
Global warming potential	4	3	1	5	7	0.47
Smog potential	1/3	1/4	1/5	1	3	0.08
Acidification	1/3	1/5	1/7	1/3	1	0.04

**Table 17** Overall weights of the four sewer pipes using AHP method

Main criteria	Weight	Sub-criteria	Weight	Weight of alternatives				Final weights			
				CO	PVC	VC	DI	CO	PVC	VC	DI
Environmental impacts	0.5	Resource use	0.13	0.19	0.28	0.19	0.26	0.01	0.02	0.01	0.02
		Energy consumption	0.28	0.38	0.35	0.1775	0.07	0.05	0.04	0.02	0.01
		Global warming potential	0.47	0.40	0.23	0.1124	0.09	0.09	0.05	0.02	0.02
		Acidification	0.08	0.38	0.42	0.1124	0.09	0.01	0.01	0.01	0.01
		Smog potential	0.04	0.38	0.39	0.1124	0.09	0.02	0.02	0.02	0.01
Economic impacts	0.5	Initial cost	0.67	0.18	0.24	0.2653	0.29	0.06	0.08	0.08	0.10
		O & M cost	0.24	0.20	0.28	0.2215	0.24	0.02	0.03	0.02	0.03
		EoL cost	0.09	0.30	0.29	0.06	0.47	0.01	0.01	0.01	0.02
		Total weight						0.27	0.26	0.19	0.22

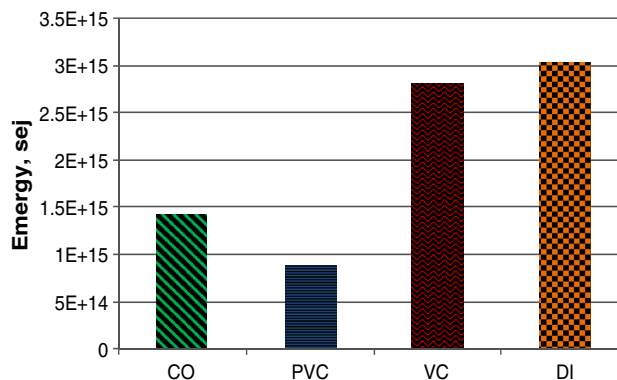
CO remains the most preferable option in the second trial, while the PVC pipe turns out to be the most preferable option of the third trial.

Interestingly, the change of ranking in the third trials can be explained with respect to the energy results. Comparing Figs. 5, 6, 7 and 8 and the results of energy analysis, it can be realized that all sewer pipe alternatives cause more economic impacts than environmental impacts through their life cycle. So by prioritizing the economic impacts, PVC pipe turns to be the most preferable option for both LCSAs.

Another important result to emerge from the energy analysis is that the effects of upstream impacts are significantly greater than the effect of downstream impacts in a sewer pipe life cycle. However, often LCA studies consider downstream impacts to be more or equally as important as upstream impacts. For example, both the EPA Science Advisory Board and the BEES Stockholder Panel defined significant higher weights for the global warming effect as compared to resource and fuel consumption.

## Conclusions

This paper explored two LCSA frameworks; energy-based and AHP-based LCSA were applied to evaluate and

**Fig. 4** Upstream impacts for various pipes

compare four typical sewer pipes materials and to identify the most sustainable option. Life cycle environmental impacts and economic costs of common sewer materials in Canada were studied.

Evidence from this study indicates that by applying energy synthesis, it is possible to tangibly evaluate the contribution of environmental and economic impacts in an energy-based unit. The most significant characteristic of the energy synthesis is that it can create a relation between economic and ecological systems. Therefore, by applying energy-based LCSA, it is possible to determine an overall,

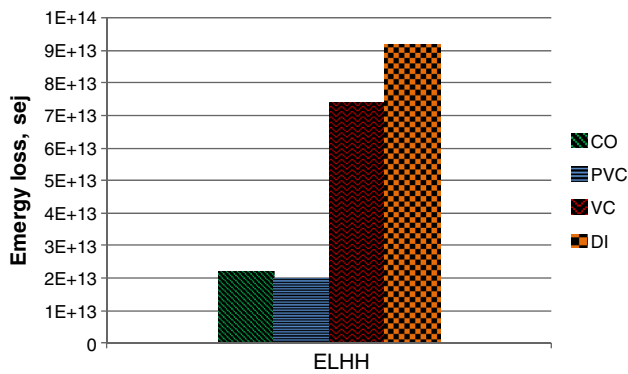


Fig. 5 Energy loss (loss of human health  $EL_{HH}$ ) of different pipes

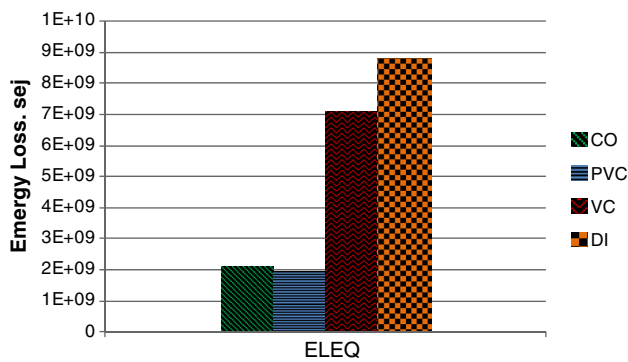


Fig. 6 Energy loss (loss of ecosystem quality  $EL_{EQ}$ ) of different pipes

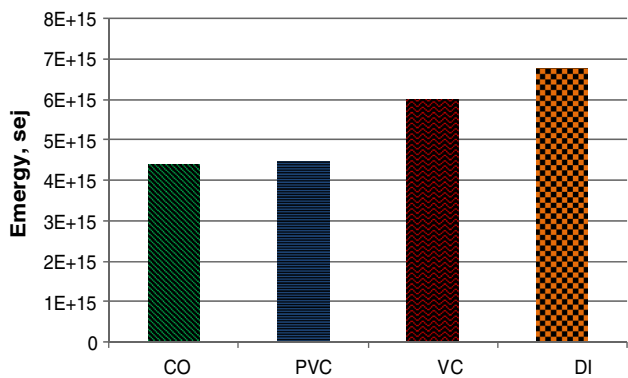


Fig. 7 Energy life cycle cost of different pipes

unbiased and unified measure to find the most sustainable option with minimum subjectivity.

A controversial aspect of emergy synthesis used in the emergy-based LCSA framework is the lack of research characterizing and documenting uncertainties in the emergy evaluation process. In a recent study, Reza et al. (2013b) discussed different sources of uncertainty in UEVs

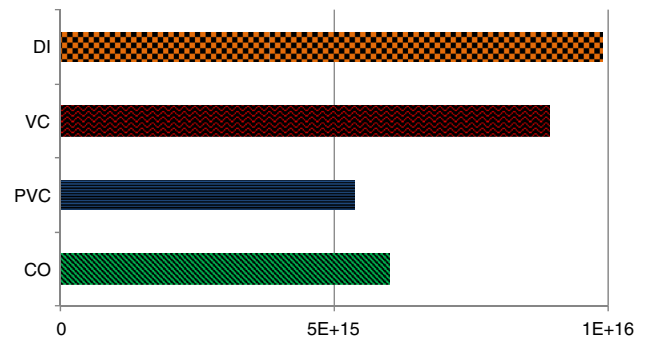


Fig. 8 Total energy of different pipes

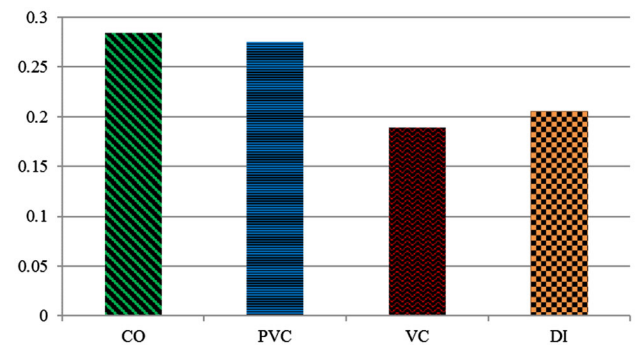


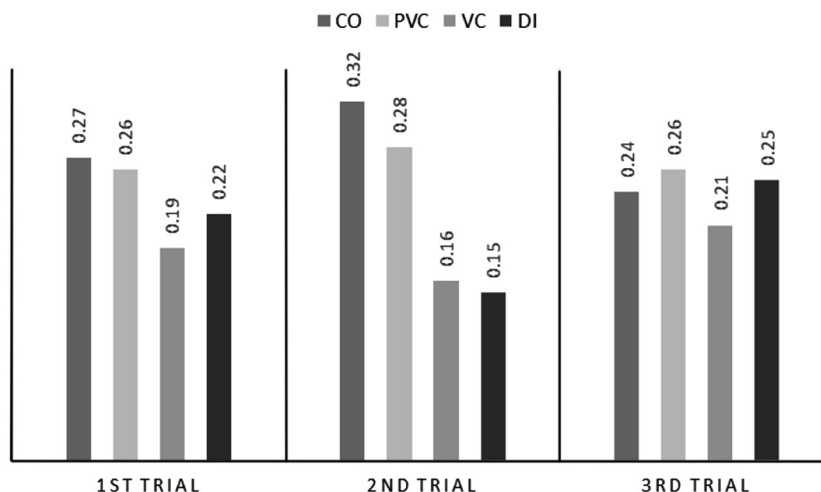
Fig. 9 Relative weights based on environment and economic criteria

and explored the utility of fuzzy-based methods to propagate uncertainty in emergy synthesis. A number of possible future studies are apparent in order to propagate uncertainty and variability of UEVs, as well as some other variable parameters such as national emergy per GDP, DALY, and PDF.

The AHP-based LCSA framework can be applied when decision makers want to involve their judgment in the sustainability evaluation process. However, the results of this research support the idea that the final results of the AHP-based method are still based on subjective evaluations, as this method leaves the choice of assigning relative importance weights among different environmental and economic impacts to the analyst. In other words, weighting aggregation techniques usually ignore fundamental essence and usefulness of various energy and resources related to ecological services, biodiversity, carbon sequestration, and hydrological functions.

Overall, both LCSA frameworks have several pros and cons. While the emergy-based LCSA framework can provide a unified and unbiased measure, the AHP-based LCSA framework benefits from a simple and flexible MCDM technique that can be adjusted by decision makers' preferences. The emergy-based LCSA framework has the

**Fig. 10** Relative weights of different sewer alternatives in different trial



capability to estimate and integrate a wide range of sustainability objectives over the life cycle of a sewer pipe system. Part of those sustainability objectives and their related impacts (e.g., work of ecosystems to provide ‘freely available’ services and products, downstream ecological and HH impacts, and effect of economic system to support labor and services) were ignored in other previous LCA and LCC studies, energy research, and other LCSA approaches related to sustainability assessment of urban water infrastructures. However, energy synthesis used in the energy-based LCSA framework is based on thermodynamic theories and convert environmental impacts and economic costs to seJs, which can be difficult to apprehend by decision makers without in-depth ecological knowledge. In addition, UEVs that are used to convert environmental and economic impacts can be uncertain based on different geographical, temporal, and climatic scenarios. On the other hand, AHP results can be highly subjective and very sensitive to decision maker judgment and preference.

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**Appendix**

Emergy synthesis

Emergy synthesis is one of the environmental accounting methods that take into account the contribution of ecological products and services. Emergy can be defined as the available solar energy used up directly or indirectly to create a service or product and can be used to assess natural inflows and services within a system (Odum 1996). For instance, many joules of sunlight are required to make 1 J of fuel, several joules of fuel are needed to make a joule of electricity, many joules of electricity are required to

support information processing in a university, and so forth. Because different kinds of energy are not equal in contribution, work is made comparable by expressing each in units of one form of energy previously required (Odum and Brown 2000). According to Odum (1996), in order to account for the existence of energies of different qualities, they must be considered in terms of one type of energy. The type of energy chosen as reference was solar energy, because it is basically the source of almost all flows in the biosphere.

The emergy of different products is calculated by multiplying mass (g) or energy quantities (J) by transformity, which is a transformation coefficient. Transformity is one example of a UEV and is defined as the emergy per unit energy. In the literature, emergy values and transformities are reported in scientific form (e.g., 3.42E+12 seJ/kg). For ease of use, emergy values can be reported using metric prefix of ‘tera’ (10<sup>12</sup>). Transformity is an intensive quantity and is measured in seJ/J (emergy per unit energy). It represents the inverse of an efficiency comparing two similar processes; a higher transformity means that more emergy is need to produce the same amount of output. Therefore, the transformity is a measure of hierarchical position in energy transformation chains (Zhang et al. 2006).The emergy of different product is calculated by multiplying mass (g) or energy quantities (J) by transformity, which is a transformation coefficient. The solar emergy *U* of a flow coming from a given process is

$$U = \sum_i UEV_i \times E_i, \tag{6}$$

where *E<sub>i</sub>* is the actual energy content of the *i*th independent input flow to the process and UEV<sub>*i*</sub> is the unit emergy value or solar transformity of the *i*th input flow (Pulselli et al. 2007).

It is common to measure solar transformity in seJ per joule of product (seJ/J) with a base that 1 emjoule is



equivalent to 1 J of solar energy and transformity of solar energy is 1 seJ/J (Ulgiati et al. 1995). The solar transformity of the sunlight absorbed by the earth is 1.0 by definition. Solar transformities represent the position of any product or service in the hierarchical network of the earth’s biosphere (Odum 1996). For instance, if 6,000 solar emjoules are required to generate 30 J of natural gasoline, then the solar transformity of that gasoline is 200 seJ/J (6,000/30 seJ/J). Solar energy is the largest but most dispersed energy input to the earth. The higher the transformity of an item, the more available energy of another kind is required to make it (Brown and Ulgiati 2004). For convenience, it is very common to use transformity values derived from other studies. The use of emergy method is easy and its goal is to support designer’s decisions in the development/assessment of more sustainable products or process. Emergy method normalizes all the attributes of the system in a common metric unit, called solar emergy (Tilley and Swank 2003).

Multi-criteria decision-making (MCDM)

In the last three decades, MCDM research in different disciplines has expanded extensively. Hwang and Yoon (1981) reviewed and summarized MCDM methods and applications. In a MCDM process, a decision maker is required to choose among quantifiable or non-quantifiable and multiple criteria (Pohekar and Ramachandran 2004). Several MCDM methods have been applied in life cycle approach, like ELECTRE (Roy 1991), PROMETHEE (Brans et al. 1984) and GAIA (Brans and Mareschal 1994), AHP (Saaty 1980), and TOPSIS (Yoon and Hwang 1985).

The MCDM methods are capable of performing the solution procedure regardless of the functional relationship for the objectives and constraints, and secondly, the number of attributes and alternatives applicable to the model is computationally limitless. However, the MCDM methods have two weak points. First, the MCDM methods are lacking in the delivery of the absolute optimum; however, they are capable of deciding over the best options among selected alternatives. Second, if the weights of the criteria are not properly assigned, it may fail to reveal “true” decisions. AHP that was used in this study has been successfully implemented in various engineering applications, especially for infrastructure management.

AHP is a systemic method commonly used for decision-making (Sadiq et al. 2004; Saaty 1997). AHP can solve complex decision-making problems involving few alternatives with numerous criteria. The process of comparing the relative importance or preference of a parameter (objectives or criteria) with respect to other parameter is based on pair-wise comparisons. One of the major advantages of AHP is using pair-wise comparisons to determine

weights and derive priority index in comparison to other weighting methods where weights are assigned arbitrarily. AHP can use subjective assessment of relative weights (importance, likelihood, or preference) to a set of priority ratio scale and overall scores (Sadiq et al. 2003).

Usually a hierarchical model is developed to degenerate complex problems into simpler and manageable elements which create different hierarchical layers or levels. The first level of each hierarchy is a goal or an objective, whereas at the last level there is an evaluation of alternatives. The intermediate layers contain criteria and sub-criteria (Tsfamariam and Sadiq 2006).

Saaty (1980) proposed pair-wise comparisons at each level in the hierarchy using a reciprocal matrix. The pair-wise judgment matrix thus developed, indicates dominance or relative importance of one element over another (Saaty 1980). The result of the pair-wise comparison on *n* criteria is summarized in an *n* × *n* matrix as follows:

$$A = \begin{bmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \dots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{bmatrix}, \quad a_{ii} = 1, \quad a_{ji} = 1/a_{ij}, \quad a_{ij} \neq 0. \tag{7}$$

Each element *a<sub>mnn</sub>* in the upper triangular matrix expresses the importance intensity of a criterion (or property) *m* with respect to another criterion *n*. The weights of the criteria in each level of the hierarchy are determined by taking the geometric mean of each column of the final judgment matrix and then normalizing the derived matrix. Finally, the weights at the lowest level will be obtained by multiplying the weights of the corresponding criteria in higher levels from the highest level to that level. In a case of *n* criteria, a set of weights in each level of hierarchy could be written as follows:

$$W = (w_1, w_2, \dots, w_n) \quad \text{where} \quad \sum_1^n w_n = 1. \tag{8}$$

There are several mathematical techniques that can be used to calculate the vector of priorities (*weights*) from matrix, such as eigenvector, geometric mean, and arithmetic mean. Preliminary investigation has been shown that there is no significant difference based on the selection of a specific technique. Normalization based on geometric means of the rows has been recommended because it provides an easy approach to obtain approximate priorities (weights; Saaty 1990). In this method, the normalization is required for each column of the matrix and then averaging over each row. One of the common issues in generating pair-wise comparison matrix is non-consistency; that is  $\forall i, j: a_{ij} \neq w_i/w_j$ . To ensure consistency in the pair-wise

comparisons and associated weight estimation, a consistency value is recommended. In pair-wise comparison matrices, the eigenvalue  $\lambda$  and eigenvector  $W$  (priority vector) value may help solving eigenvalue Eq. (3).

$$(A - \lambda)W = 0. \quad (9)$$

In Eq. (3),  $W$  is the priority vector which is associated with the matrix of comparisons and  $n$  is the dimension of this matrix. Saaty (1980) recommended a maximum eigenvalue  $\lambda_{\max} > n$  for inconsistent matrices. If consistency index (CI) is sufficiently small, the estimate of the weight  $w$  is acceptable. The CI is defined as following:

$$CI = (\lambda_{\max} - n)/(n - 1), \quad (10)$$

where CI is consistency index that indicates whether a decision maker assigns consistent values (comparison) in a set of evaluation (Tesfamariam and Sadiq 2006). The final inconsistency in pair-wise comparison is computed using consistency ratio (CR).

$$CR = CI/RI, \quad (11)$$

where RI is the random index, determined by averaging CI of a randomly generated reciprocal matrix (Saaty 1980).

It is noted that making a comparison between different criteria is a challenging task. There is no widely agreed method to determine the relative importance of different impacts. Decision-making based on AHP technique can cause confusion and does not deal effectively with redundancy of selected criteria. Normalization of different attributes may fail to find the true solution of the alternatives. For this reason, more advanced method needs to be developed that can address the dilemma of non-commensurate units in MCDM problems.

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