SELECTION OF SEWER PIPE MATERIALS: COMPARING TWO LIFECYCLE APPROACHES

by

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ABSTRACT

Sewer systems are subjected to deterioration due to aging, aggressive environmental factors, increased demand, inadequate design, improper operation and maintenance activities. As a result their current-state and overall long-term performance are affected, which often requires costly and extensive maintenance, repair and rehabilitation. Therefore, it becomes a challenging task for the decision-makers to make a decision that improves design, construction, operation and maintenance activities.

The main aim of this study is to evaluate different materials of sewer pipes (i.e., concrete, polyvinyl chloride, vitrified clay and ductile iron) and identify sustainable solutions using both an emergy-based lifecycle approach and a traditional lifecycle approach.

Emergy method converts all forms of lifecycle inflows (such as energy, raw resources, labour, money, services and information) to an equivalent form of solar energy, named solar emergy joule (sej), which does not require any multi-criteria method to aggregate non-commensurate values. On the other hand, in traditional lifecycle approach, analytical hierarchical process method has been used to integrate environmental and economic impacts of different pipes. Analysis based on emergy-based LCA approach is useful and more credible, as it measures the contribution of environmental and economic impacts in a common unit which removes the multi-criteria dilemma. The analysis results demonstrate that PVC pipe is the most sustainable option from both environmental and economic points of view and can guarantee a more sustainable sewer system.

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LIST OF SYMBOLS AND ABBREVIATIONS

ACP	Acidification potential
AHP	Analytical hierarchy process
ASCE	American society for civil engineers
ASTM	American society for testing and materials
CI	Consistency index
CO	Concrete
CO_2	Carbon dioxide
CCTV	Closed circuit television
CR	Consistency ratio
DIP	Ductile iron pipe
EMA	Emergy analysis
EP	Eutrophication potential
GDP	Gross domestic product
GWP	Global warming potential
IC	Initial cost
ISO	International Standardization Office
KWh	Kilo-watt hour
LCA	Lifecycle analysis
LCI	Lifecycle inventory
LCC	Lifecycle costing
MCDM	Multi criteria decision making
MIIP	Nitrogen oxides
NO_x	Nitrogen oxides
PVC	Polyvinyl chloride
RI	Random index
Sej	Solar emergy joule, solar emjoule
SO_x	Sulfur oxides
STC	Statistics Canada
TBL	Triple bottom line

TFN	Triangular fuzzy number
TOE	Ton of equivalent
US EPA	United States Environmental Protection Agency
VC	Vitrified clay

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Dedicated to my parents

1 INTRODUCTION

1.1 Background

Buried infrastructure including water distribution and sewerage systems are the bloodline of modern society and have a significant impact on the economic, environmental, and social aspects of our day to day lives (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 & MacLeod, 2002). The main purposes of sewer systems are to:

1) ensure public health
2) protect natural water bodies from pollution, and
3) provide a high level of protection against urban flooding (Ertl & Haberl, 2006).

In developed countries, mainly in Europe, North America and Oceania, the sewer networks are serving about 90% of the population (WHO, 2011). By virtue of their function and capital-intensive nature, wastewater collection and conveyance systems are considered extremely important components of the buried infrastructure (Hahn et al., 2002). However, in North America, a large portion of municipal water and wastewater piping networks of underground structures are near to the end of their useful service life of 50-75 years (Younis & Knight, 2010). Sewer systems during their service life may subject to deterioration due to aggressive environmental conditions, increased demand, inadequate design, and improper operation and maintenance that undermine their structural integrity. This results in structural failures and collapses and leads to difficult and expensive emergency repair work.

In the past, the problems caused by deteriorating sewer pipes were dealt with by adopting a reactive approach, whereby repair or rehabilitation was only done once a pipe failed. Traditional infrastructure management only focused on maximizing economic benefits (Mirza, 2007) while ignoring the environmental and social impacts. However, this type of approach was deemed unsustainable due to only consideration of direct cost. For effective maintenance of sewer systems, environmental performance and sustainable development are key aspects to be considered and are of utmost importance.

Sustainable development also referred to as the Triple Bottom Line (TBL) approach, as defined by the United Nation in 1987, is a pattern of resource use that "aims to meet human needs while preserving the environment, so that these needs can be met not only in the present, but also for generations to come." During the 2005 World Summit, it was noted that achieving sustainable development goals requires reconciliation of environmental, social and economic equity aspects in projects. Attempts to improve social, economic, and environmental indicators have turned the attention to better infrastructure management. However, research on sustainable development in the area of buried infrastructure has not yet been fully appreciated.

Very little research has been reported in the context of management of sewer systems. An 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 public health. In this study, sewer system has been studied in the context of environmental and economic sustainability; however, social impacts were not addressed due to lack of sufficient data.

1.2 Research objective

A traditional lifecycle approach includes lifecycle assessment (LCA) to evaluate environmental impacts and lifecycle cost analysis (LCC) to evaluate economic impacts. Traditional lifecycle approach requires a weighting scheme for multi-criteria decision making (MCDM) to evaluate overall impacts.

The main objective of this study is a quantitative assessment of sustainability for sewer systems by using an emergy-based lifecycle approach (EM-LCA) and comparing the results with traditional lifecycle approach. Emergy concept will be coupled with the lifecycle approach to evaluate and quantify the lifecycle impacts (environmental and economic) in an energy-based unit. The result of this research will be useful to guide decision makers to select suitable sewer pipe that has the least environmental impacts and is economically beneficial.

1.3 Thesis outline

This thesis is organized into five chapters. Following the introduction chapter, Chapter 2 presents a detailed literature review of related topics that includes: general discussion on sewer pipes, lifecycle assessment and lifecycle costing in the context of sewer pipes, emergy accounting and emergy-based LCA and finally uncertainty analysis. Chapter 3 discusses the methodology for developing an emergy-based lifecycle approach. In Chapter 4, the results are discussed in the context of a comparison with traditional lifecycle approach and uncertainty characterization in emergy analysis. Finally, chapter 5 provides conclusions and makes recommendations for further research.

2 LITERATURE REVIEW

2.1 Background

According to Statistics Canada (2011), Canadian construction industry contributes about 4 to 6% of Canada's GDP that has grown 42.7% in the last decade. On the other hand, the amount of energy use and GHGs emissions from the construction industry has increased from 8.9% to 11.7% during the period of 1990 to 2010 (Nyboer & Kamiya, 2012). As a result, there is a dire need for research in sustainable and green construction practices to respond to the increasing demand of the growing Canadian population. Numerous research initiatives have been undergoing to develop new methods, frameworks and tools for evaluating the 'greenness' of infrastructures worldwide. Sewer networks systems are a very important underground infrastructure that should also be investigated considering the environmental and economic impacts.

The aim of this chapter is to provide background information related to the different aspects of this research. To fully appreciate the multi-disciplinary nature of this research, a comprehensive literature review encompassing topics such as the role of sewer systems in the well-being of urban environments, types of sewer systems, and their structure and materials is discussed. Along this line, a short historical background is presented on the evolution of these underground systems. Lifecycle approaches, multiple-criteria decision making (MCDM) and emergy concepts are discussed in later sections.

2.2 Sewer systems

The earliest existence and use of sewer systems can be traced back as far as 4000 BC in Mesopotamia (present day Iraq) and 3000-2000 BC in the city of Mohenjo-Daro in Pakistan. In Europe, the Minoans put sewer systems into use as early as 3000-100 BC in the Isle of Crete (Greece). In Rome, the first sewers were constructed between 800 and 735 BC. Sewer systems at this time were primarily used to drain water from the streets during precipitation (rainfall or snowmelt). It was not until the mid-19th century that the importance of sewer systems for disposal of human waste and other domestic wastes was fully recognized (Schladweiler, 2008). In Europe and Americas, this recognition came against the backdrop of a series of deadly cholera epidemics (e.g., in early 1800s in Paris and London) due to filthy water (e.g., water used in flushing toilets, kitchen water) flowing from houses and building up on the streets and surrounding areas that polluted sources of potable water (e.g., water wells, streams). This emphasized the need for conveying waste water away from houses, buildings, and treating waste water before discharging them into rivers, streams etc. Schladweiler (2008) presents a detailed historical account of the use and development of sewer systems since the ancient times to the present.

Today, sewer systems are a standard feature of any urban environment. Following their use since the ancient times, sewer systems drain two types of water from their sources to treatment sites or points of disposal: a) wastewater – this is also known as foul sewage; it includes water flushed down from toilets and the water that drains from showers, bathtubs, kitchen sink, washing machines, and other domestic sources, and also includes water from businesses and industries that contains dissolved or suspended matter; b) stormwater – this is the rainfall or snowmelt that runs off impervious surfaces like rooftops, roads, parking lots, etc. Wastewater, if not drained properly, could cause pollution and create health risks. Meanwhile, stormwater, if not drained properly, has the potential of causing flooding leading to potentially catastrophic damages and further health risks.

2.3 Types of sewer systems

Historically, sewer systems are primarily used to convey and drain stormwater to receiving water bodies (Schladweiler, 2008). In the past, domestic wastewater was normally stored in subsurface cesspools under houses and buildings. These cesspools were then cleaned up from time to time. The cleaning was very expensive, and poorly maintained cesspools also emitted foul odors. Leaking and overflowing cesspools can contaminate water wells, resulting in catastrophic cholera epidemics (e.g., London episodes in 1847). As cities continued to grow and their population densities increased, the use of cesspools became extinct in large urban areas.

During the late 1800s, two potential approaches were adopted to combat the problems related to cesspools and to drain wastewater away from buildings and water wells:

1) Combined sewers: Cities with existing sewers also drain stormwater.

2) Separate sewers: Cities build systems to deal with sanitary sewage and stormwater separately. These two basic types of sewer systems developed in many modern cities.

2.3.1 Combined sewer system

A combined sewer system (CSS) is designed to collect and convey both wastewater (originating from domestic, commercial, and industrial sources) and stormwater (generated from rainfall and snowmelt) in the same conduit. Figure 2-1 shows a schematic diagram of a combined sewer system.

Normally, combined sewers transport all the wastewater (domestic and stormwater) towards a downstream point (e.g., the waste water treatment plant, WWTP), where it is treated and then discharged into a receiving water body. However, in the event of heavy rainfall or snowmelt, the volume of collected water in a combined system can exceed the capacity of the sewer system and/or the wastewater treatment plant. Due to this, combined sewer systems are designed to overflow occasionally and discharge excess water directly into nearby streams or rivers.

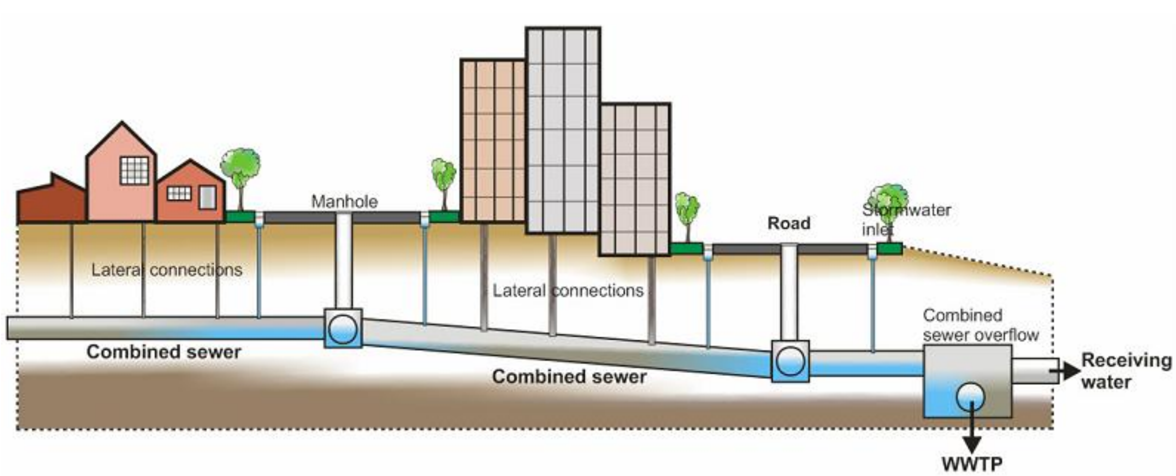

Figure 2-1: Combined sewer system (Ana, 2009)

The volume of water released into receiving water bodies is termed combined sewer overflow (CSO) and the structure that controls it is referred to as the CSO structure. Since the water flowing through the system is a mixture of wastewater and stormwater, CSOs contain not only stormwater but also untreated and waste, toxic materials and debris. This can cause a major water pollution concern in the nearby receiving water bodies (US EPA, 2008).

2.3.2 Separate sewer system

A separate sewer system (SSS) is designed to collect and convey wastewater and stormwater using two separate lines. Figure 2-2 shows a schematic view of a separate sewer system.

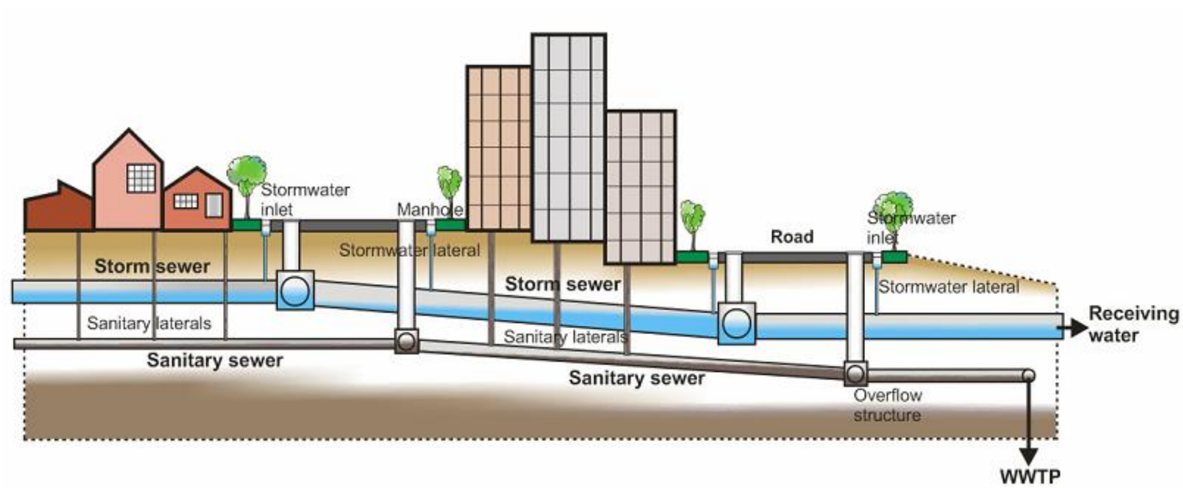

Figure 2-2: Separate sewer system (Ana, 2009)

In SSS, the wastewater from houses and buildings is drained by sanitary lateral pipes into a network of so-called sanitary sewers. The collected foul sewage is then transported to the WWTP for treatment before being disposed of into a receiving water body. Meanwhile, the stormwater from rooftops, roads, parking areas and other impervious areas enters the stormwater inlets and drains through the stormwater laterals into a network of so-called storm sewers. The collected stormwater is then conveyed and disposed of directly to the nearest receiving water bodies without treatment. Since the average wastewater flow is only a small portion of an average storm flow, sanitary sewers are smaller in diameter as compared to storm sewers. One advantage of SSS over CSS is the elimination of CSOs, which can be a major source of pollution in receiving water bodies. On the flip side, SSS is more expensive and complicated to build compared to CSS since two parallel pipes have to be constructed in close proximity.

2.4 Sewer construction material

There are several different pipe materials available for sewer systems, each with unique characteristics required for different conditions. Until 1850, sewers were generally constructed using brickwork. Over time, because of aging, these sewers have suffered extensive structural damage. Although some sewer systems still contain brick works, very few are left today.

In the middle of the nineteenth century, more and more clay pipes were used to build the sewer system. Concrete pipes were introduced during the early part of the twentieth century. Modern sewers include polyvinylchloride, fiberglass, high-density polyethylene, ductile iron, steel and reinforced concrete. In general, sewer pipe materials can be divided into two main categories based on their load carrying capacity: (1) Rigid pipes and (2) Flexible pipes. Rigid pipes are defined as those pipes designed and installed on the basis of an established relationship to minimum crushing strength. Commonly specified rigid pipe material includes asbestos cement (AC), concrete (CO), cast iron (CI) and vitrified clay (VC) (ASCE, 1999). Flexible pipes are defined as those pipes designed and installed on the basis of established pipe stiffness and limiting vertical deflection. Ductile iron (DI), fabricated steel, polyethylene, and polyvinyl chloride (PVC) are a few examples of flexible sewer pipe materials. The distribution of different pipe materials in Canada is shown in Figure 2-3.

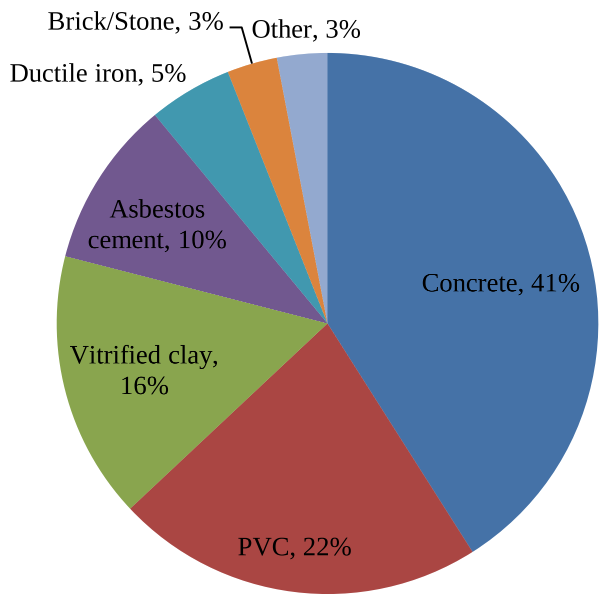

Figure 2-3: Distribution of sewer pipe materials in Canada (Allouche et al., 2002)

Windsperger et al. (1999) reported that, concrete, PVC, vitrified clay, and ductile iron have comparable characteristics in terms of quality and environmental characteristics. Concrete is favorable for its structurally rigid, self-supporting, and construction adaptability characteristics. Ductile iron (DI) pipe is well known for its high resistance to abrasion while vitrified clay and PVC pipe are preferable for their corrosion resistant quality. Thus, selecting the best material from a list of comparable pipe materials is always a challenging question. The sewer pipe materials selected for this study are briefly described in the following section:

2.4.1 Concrete

Concrete pipes can be non-reinforced, reinforced or pre-stressed. Circular concrete pipes vary in diameter from 100 mm to 610 mm for non-reinforced concrete and 300 to 3660 mm for reinforced concrete. Laying lengths of concrete pipes also vary widely, ranging from 1.2 m to 7.4 m, depending on the manufacturer. Cast-in-place reinforced concrete pipes are also used when standard pipes are not available or to deal with special circumstances. Due to their size, abrasion resistance, strength and cost, concrete pipe is suited for storm sewer construction. Their vulnerability to corrosion, however, limits their application in sanitary sewer constructions.

2.4.2 Brick masonry

This material type was used in the construction of large diameter sewers before concrete came into common use. However, due to high material and labour cost, its use today is limited. One of the problems with brick sewers is the disintegration of the mortar joints due to corrosion, leading to their collapse.

2.4.3 Vitrified clay

Vitrified clay pipes are composed of crushed and blended clay that are formed into pipes, then dried and fired in a succession of temperatures. The final firing gives the pipes a glassy finish. Vitrified clay pipes have been used for hundreds of years and are strong, resistant to chemical corrosion, internal abrasion, and external chemical attack. They are also heat resistant. These pipes have an increased risk of failure when mortar is used in joints because mortar is more susceptible to chemical attack than the clay. Joints of other pipes like ductile iron or PVC are chemically more stable. It has been seen that the thermal expansion of vitrified clay pipes is less than many other types (such as DI and PVC).

2.4.4 Ductile iron

Ductile iron (DI) pipes supersede cast iron (CI) pipe industry. Improvements in the metallurgy of cast iron in the 1940's increased the strength of cast iron pipe and added ductility, an ability to slightly deform without cracking. This was a major advantage and ductile iron pipe quickly became the standard pipe material for high pressure service for various uses (water, gas, etc.). This material is highly resistant to acids and alkalis making it suitable for handling wastewater with high acid concentration. Its disadvantage is its limited range of sizes and strength, and its brittleness.

2.4.5 Polyvinyl chloride

Plastics are generated from synthetic resins of high molecular weight. Plastics used in the manufacturing of pipes, belong principally to the polyvinyl chloride (PVC) and cellulose acetate types. PVC pipes are available in diameters from 100mm to 610mm and in laying lengths from 3.0m to 6.0m. The material is chemically inert to most acidic and alkaline wastes. This material is an attractive alternative for use in sewer systems due to its high durability, light weight, high strength-to-weight ratio, long laying lengths, watertight joints and smooth interior surface. However, PVC can undergo excessive deformation under loading, especially when installed improperly or subjected to high temperature wastes. In addition, it can turn brittle under very cold temperatures.

2.5 Current state of sewers in Canada

Most of Canada's modern infrastructure was being installed between the 1950-1970s in response to the "baby boom", rapid urbanization and high immigration rates (Mirza & Sipos, 2008). Investment in this new infrastructure was very high in those years, but maintenance was deferred intermittently over the past 30 years, and deterioration of these assets advanced at an accelerated rate (Mirza, 2007).

According to a recent Canadian Infrastructure Report Card, water and wastewater systems comprise approximately 30 percent of Canada's infrastructure stock (CIRP, 2012). The 84 municipalities (a total population of 19 million in 2009) that provided responses to the wastewater questionnaire reported a total of 50,025 km of sewer pipes. The network reported is composed primarily (78 %) of small, i.e., local collection pipes (< 450 mm in diameter). In 2010, Statistics Canada estimated that sanitary and storm sewers had passed 53 percent of their useful life nationwide. Figure 2-4 shows the overall physical condition of sewer systems in Canada (CIRP, 2012).

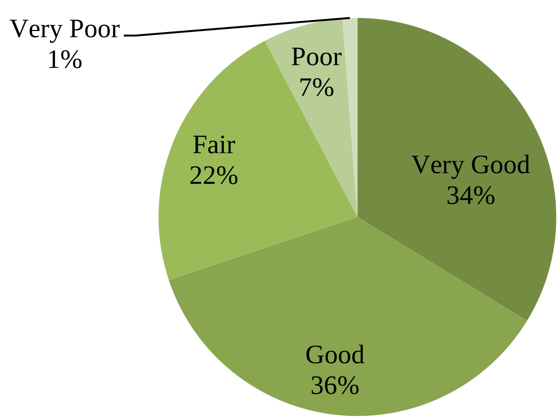

Figure 2-4: Physical condition of sewer systems in Canada (adapted from CIRP, 2012)

It can be seen that 33.7% of sewer networks are in *very good* condition while ~30% of pipes are in *fair* to *very poor* condition. The replacement cost of small sewers is about 39 billion and it is about 9 billion for large sewers (CIRP, 2012). Owing to the importance of sewer networks in urban environments, the current state of the networks and the enormous cost of replacement of these systems, actions are needed to be taken considering the overall lifecycle of the sewer systems to restore and/or improve these systems and to prolong their service lives.

2.6 Traditional lifecycle approach

The term "lifecycle" refers to the major activities in the course of the product's life-span from its manufacture, use, and maintenance, to its final disposal, including the raw material acquisition required manufacturing of the product. At each phase in their lifecycle, products interact with the environment (extraction or addition of substances), and with the economic (the costs to produce, or the profit to sell a product) and social systems (the personnel needed to transport from factory to a shop). Over the lifecycle, decisions are made by industry based upon information at all stages of the lifecycle. Incentives are given by governments to produce, reuse, and recycle products and services with the right energy and resource efficiency and with the lowest environmental impacts possible.

In a life cycle economy, decisions are made based upon all stages of the life cycle. In this economy, consumers will choose between different brands of a product, after balancing these products' environmental impacts such as potential contribution to climate change, social consequences, such as poor workers' rights, and price. In this study, two components of the lifecycle approach, namely, lifecycle assessment (LCA) for evaluating environmental impacts and lifecycle costing (LCC) for evaluating the economic consequences are discussed.

2.6.1 Lifecycle assessment (LCA)

Common lifecycle assessment (LCA) approach for assessing industrial systems is "cradle-to-grave". Cradle-to-grave is the full LCA approach from resource extraction ('cradle') to use phase and disposal phase ('grave'). However, cradle-to-cradle is a specific LCA approach in which the end-of-life disposal step for the product is a recycling process. It is a method used to minimize the environmental impacts of products/ processes by employing sustainable production, operation, and disposal practices. LCA evaluates all stages of a product's life from the perspective that they are interdependent, meaning that one operation leads to the next. LCA enables the estimation of the cumulative environmental impacts resulting from all stages in the product lifecycle, often including impacts not considered in more traditional analyses (e.g., raw material extraction, material transportation, and ultimate product disposal).

The United States Environmental Protection Agency (USEPA, 1995) defined LCA "as a methodology for estimating the environmental burdens of processes and products (goods and services) during their lifecycle from cradle-to-grave". The Society of Environmental Toxicology and Chemistry (SETAC, 1993) defined LCA "as a process to evaluate the environmental burdens associated with products, processes, or activities by identifying and quantifying energy and material used and waste released to the environment; to assess the impact of this energy and material uses and release to the environment; and to identify and evaluate opportunities to affect environment improvements".

The fundamental aim of LCA is to facilitate in making policy decisions (Raugei et al., 2012). LCA can help decision-makers select the product or process that result in the least impact to the environment. This information can be used with other factors, such as cost and performance data to select a product or process. LCA identifies the transfer of environmental impacts from one media to another (e.g., eliminating air emissions by creating a wastewater effluent instead) and/or from one lifecycle stage to another (e.g., from use and reuse of the product to the raw material acquisition phase).

A typical LCA includes: raw material extraction, manufacturing, distribution, use, maintenance, end-of-life (EoL), and disposal phases for a product/ process/ services. Figure 2-5 shows a generic lifecycle assessment supply chain of a product.

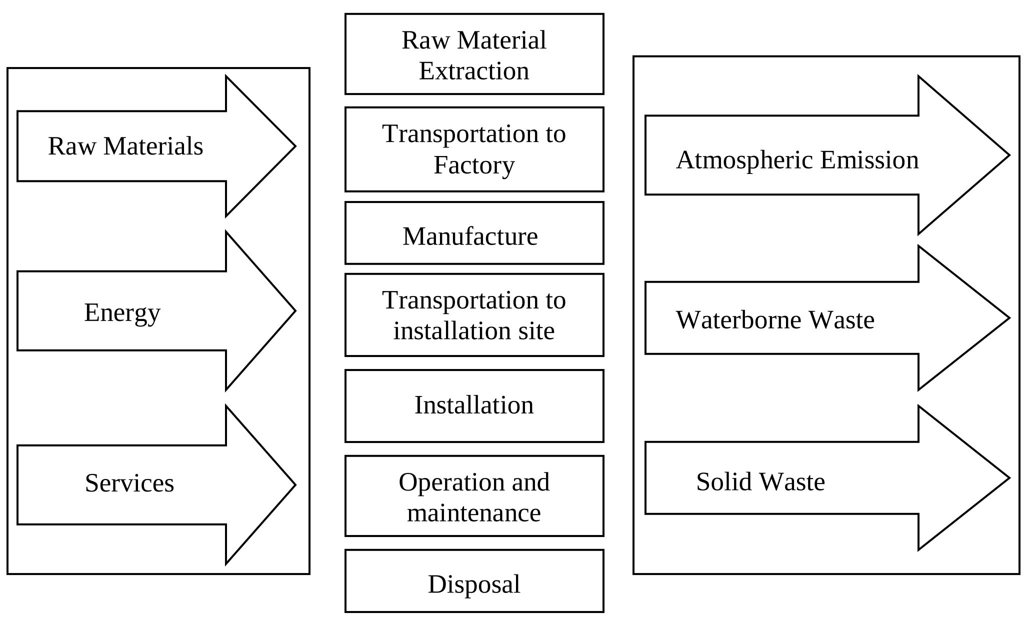

Figure 2-5: System boundary of LCA

A comprehensive effort has been made towards the standardization of LCA by the International Organization for Standardization (ISO). However, the final results of LCA are still based on subjective evaluations that leave the choice of the impact assessment method to an analyst (Ulgiati et al., 2006). SETAC, ISO 14040 and CML (Center of Environmental Sciences of Leiden University) have provided best management practices and guidelines for an LCA framework. Though these organizations worked independently, general consensus on the structure of the LCA framework describes the following four phases (Fava, 2006):

- Goal and scope definition
- Lifecycle inventory (LCI)
- Impact assessment (evaluation)
- Improvement assessment (interpretation)

Figure 2-6 illustrates the steps for the lifecycle assessment.

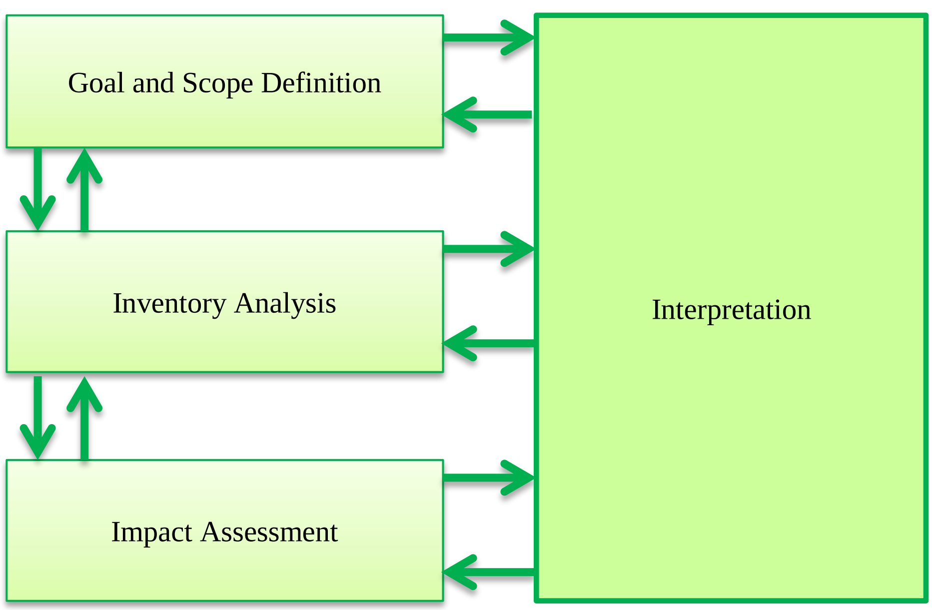

Figure 2-6: LCA standard steps

2.6.1.1 Goal and scope definition

Goal and scope definition is the first phase of LCA. The subsequent steps of LCA should be consistent with the defined goal and scope. ISO 14041 states that the goal of any study shall unambiguously state the intended application, the intended audience, and the reasons for carrying out the study. The scope defines the important elements of the methodology used in LCA. Since LCA is an iterative process, the initial definitions can still be modified in the later stage when more information is available. Elements that should be considered and stated clearly are as follows:

(a) Defining the purpose: This step helps to obtain the existing process/ product information and analyze process/ product improvement strategies.

(b) Setting the scope and depth: A decision has to be made regarding how many factors and processes need to be investigated in the study.

(c) Establishing LCA functional unit: A measure of performance of the selected system needs to be defined (SETAC, 1993).

2.6.1.2 Lifecycle inventory analysis (LCI)

The lifecycle 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 waters, soil, and air. In this phase, the system boundaries are established, and the system is described through a process flow chart (Khan et al., 2001). Usually the outcome of this phase is an inventory table. The functional unit defined in the first step is ascribed to each factor (Belemhof, 1995).

2.6.1.3 Lifecycle impact assessment

Lifecycle impact assessment (LCIA) aggregates the information obtained in the inventory (Tukker, 2000). Various impacts are characterized and grouped into generalized categories in this stage. Impact assessment or evaluation involves two steps:

(a) Classification: Various impacts are characterized and grouped into generalized categories, e.g., three main sustainability assessment criteria, environment, economics and social development (Khan et al., 2001).

(b) Aggregation: In this step, cumulative environmental effects on humans and the ecosystem are estimated. Then the impacts of various (sub) criteria are aggregated into a single index using relative weights assigned to them. This step is also called the valuation phase, which is the most challenging and controversial step of the LCA technique, because it involves human subjectivity (Khan et al., 2004). The valuation involves a structured description of the hierarchical relationships among the problem elements, beginning with an overall goal statement to developing a decision tree. Weights can be estimated based on an expert panel.

2.6.1.4 Improvement assessment

The purpose of this phase is to recommend any possible improvement in the system. This phase is also referred to as interpretation in ISO 14040. In addition, identification of significant issues and evaluation to reach conclusions and drafting the final report are integral parts of this phase.

2.6.2 Lifecycle costing (LCC)

Lifecycle costing (LCC) is another major component of lifecycle approach. LCC of an asset is the total cost of owning, operating, and maintaining an asset over its lifespan. This concept is very popular in infrastructure management for alternative selection because the comparison is made based on the "dollar" value. In civil engineering, LCC analysis has been used in the application of value engineering (Dell'Isola, 1997) and asset management (Arditi & Messiha, 1999; Shahata & Zayed, 2008; Wirahadikusumah, 1999). Though LCC analysis has many benefits to offer, but it also requires intensive data input. The first important information required for LCC model is the cost information, including initial (construction) cost and the recurring future maintenance cost. Construction cost can be easily obtained from historical data or solicited from contractors; however, it is not easy to determine the cost and the timing of maintenance activity. In most LCC analysis, annual maintenance costs are assigned as a percentage of construction cost (Rahman & Vanier, 2004). However, this is not the case in real practice where maintenance activity is only conducted periodically or as needed. Since maintenance history is rarely available, another potential way to improve the model is by incorporating information from condition assessment. While this data may not include historical maintenance, it does show the prevalence of pipe condition that requires certain type of maintenance. Therefore the probability of occurrences of maintenance activities can be calculated.

Another important data for LCC analysis is the expected service life of sewer systems. Ideally, the service life of a sewer is predicted using a deterioration model based on agency owned data. When this is not possible, experts' (i.e., engineers, asset owners) opinion or research findings from industry or government agencies can be used (FHWA, 2002). Some available examples of industry manuals developed for the estimation of useful life include: the International Infrastructure Management Manual (NAMS/IPWEA 2000); Perrin (2004), and the Municipal Infrastructure Investment Planning (MIIP) of Canada (Newton & Vanier, 2006).

Lifecycle cost of sewer network systems can be broken down into following categories: a) Capital cost, b) Inspection cost, c) Maintenance cost, d) Repair cost, and e) Disposal cost.

2.6.2.1 Capital cost

Capital cost is the cost incurred in installing the complete system in place as per the design specifications. Major capital costs include pipe material cost and cost of installation.

Material cost: Sewer material cost is usually obtained from pipe manufacturing companies who make pipes for sewer applications. The pipe cost is usually given in dollars per unit length, traditionally in $/linear foot or $/linear meter plus the costs of the fittings, connections, and joints.

Installation cost: Installation costs include the costs incurred in transportation (pipes, equipment, and material), and labor utilized. Walski & Pelliccia, (1982) and Neelakantan et al., (2008) presented installation cost data for various diameter of sewer pipes. It should be noted that the installation cost varies with the installation depth, type of contractor, type of pipe, method of installation and many other factors.

2.6.2.2 Inspection cost

Cost estimates for some commonly used internal inspection and evaluation methods are shown in Table 2-1. The costs reported by Zhao et al. (2001) are based on the information collected from 10 Canadian municipalities and two consulting firms who participated in a one-year research project on condition assessment and rehabilitation of large sewers. Zhao & Rajani (2002) gave a range for internal inspection from $5.5/m to $28/m for sewers of 150 mm to 914 mm in diameter (Zhao et al., 2001). In the cost analysis, inflation was taken into account based on 10 year average, which is 1.9% annually (Bank of Canada, 2012).

Table 2-1: Cost of pipe internal inspection/evaluation

Inspection method	Cost (kWh kg^{-1})
CCTV	$2-$10/m
Combined sonar/CCTV	$7-$10/m
Person-entry	$2-$20/m
Stationary-camera	$100 per access hole
Rotary sonic device	$12-$15/m
I/I detection by smoke testing	$1.9-$3.8/m
I/I detection by dyed water test	$3.1-$6.3/m
I/I detection by water flooding	$3.1-$6.3/m

2.6.2.3 Maintenance cost

Maintenance cost is the cost incurred in maintaining sewer pipes and other components in the system. Maintenance activities in sewer systems typically include flushing sewage, quality monitoring, servicing valves and fire hydrants, conducting leak detection and prevention. It is difficult to accurately model and account for these maintenance costs for any municipality as it depends on various factors. It is reasonable to assume that the maintenance costs would be a quarter of the operational costs in a typical sewer system. Raymond et al. (1999) reported some maintenance costs based on the City of Ottawa's experience (Table 2-2). The cost for sewer cleaning is about \$0.08/mm ϕ/m pipe and the cost of Chemical Cleaning is about 4% of the replacement cost or \$22/m (Raymond, 1999).

Table 2-2: Maintenance cost data

Maintenance activities	Cost	Source
Sewer Cleaning	\$0.08/mm ϕ/m length	Zhao & Rajani (2002)
Chemical Cleaning	\$22/m	Raymond (1999)
Resin Injection	\$221/hr	Zhao & Rajani (2002)

2.6.2.4 Repair cost

Random leaks and breaks in sewers due to deterioration may result in flooding, service interruptions, water contamination and could also affect fire-fighting capabilities potentially leading to loss of life and property. The physical mechanisms that lead to pipe breakage are often very complex and not completely understood (Kleiner & Rajini, 2001). Subsequently, the physical modeling of deterioration is often not possible due to lack of quality data and understanding of structural deterioration. Statistical models are prominent and are often used in predicting future break rates.

Failure of a sewer calls for urgent and unplanned repairs; therefore the repair cost can vary drastically from case to case, depending upon many factors such as the location and extent of the failure, and the depth and size of the pipe. There are three such repairs reported in the Trenchless Technology Magazine. The average unit cost is \$5.01/mm ϕ/m, which is 3.6 times the average unit cost of \$1.38 /mm ϕ/m for non-emergency rehabilitation. Collins & Stude (1995) reported that the Metropolitan St. Louis Sewer District experienced one failure each year in its old brick sewers and the repair costs ranged from \$483,000 to \$2,400,000 each.

2.6.2.5 Disposal cost

Disposal cost is the cost incurred in disposing of the sewer system infrastructure after its intended useful period. It is not typical of sewer systems to replace them entirely at once. Moreover, sewer pipes are typically left in the ground when they are replaced using trenchless techniques which are the preferred choice of the municipalities these days.

2.7 Past relevant studies

Lifecycle approach is the most popular technique used in many studies involving selection among alternatives. However, research regarding lifecycle approach of buried infrastructure is very rare. Though the concept of lifecycle was established many years ago, it is not widely used in this sector. LCA has been conducted on mass and energy flows for buildings and buildings materials, in order to improve sustainability. However, relatively less attention has been paid so far to mass and energy flows of urban infrastructure and utility systems in particular, in spite of their significant contribution to the total mass.

The application of LCA for decision-making for water distribution systems has been reported in the literature. For example, Dennison et al. (1999) compared the environmental impacts of alternative pipe materials using LCA while Lundi et al. (2004, 2005) applied LCA to compare alternatives for wastewater, stormwater and drinking water pipes. A few studies analysed the sewer network only at the production and manufacturing stages of the lifecycle (Howard, 2009; Herstein & Filion, 2011). In these studies, environmental impacts of various sewer systems were analysed in the pipe manufacture stage only. Herz & Lipkow (2002) assessed mass and energy flows for different pipeline rehabilitation technologies and integrated into the decision process for network rehabilitation and site development. Tukker (2000) conducted a LCA study for various sewer materials. The LCA result summarized the impact analysis based on the data from manufacturing of each type of pipe.

The LCA method can be combined with economic impacts to provide more comprehensive assessment of system impacts. Lifecycle economic impacts are reported in literature for sewers, e.g., Syachrani (2010) developed a lifecycle cost (LCC) model for sewer asset management. Koo (2007) developed a lifecycle approach for sewer system considering the environmental and economic impacts simultaneously. In his study, a multi-criteria decision making (MCDM) technique has been used to implement lifecycle approach, which was found to be an effective technique to aggregate various impacts over the lifecycle of an asset.

2.8 Multi-criteria decision making (MCDM)

In the last three decades, multi-criteria decision-making (MCDM) research in different disciplines has grown exponentially. Hwang and Yoon (1981) are two of the pioneers who reviewed and summarized MCDM methods and applications. In order to arrive at more concrete solutions, a number of works have been aimed at accommodating multi-criteria decision-making (MCDM) models into engineering decision problems (Sen & Yang, 1998).

Figueira et al. (2005) surveyed 52 international leading experts who researched the state of the art in MCDM.

In a MCDM process, a decision-maker is required to choose among quantifiable or non-quantifiable and multiple criteria (Pohekar & Ramachandran, 2004). The objectives are usually conflicting and therefore, the solution is highly dependent on the preferences of the decision-maker leading to the generation of a compromised solution. MCDM process that aids the decision making process by considering a limited number of criteria and analyzing several alternatives (finite or infinite) is deemed a good framework.

Several MCDM methods have been applied in lifecycle assessment, like ELECTRE (Roy, 1991), PROMETHEE (Brans et al., 1984) and GAIA (Brans & Mareschal, 1994), AHP (Saaty, 1980), TOPSIS (Yoon & Hwang, 1985) and SAW. The summary of pros and cons of those MCDM methodologies is provided in Table 2-3. 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. In this study, AHP is used as a decision making technique as it has successfully been implemented in various engineering applications, especially for infrastructure management.

Table 2-3: Comparison of various MCDM methods (Pires et al., 2011)

MCDM	Description	Advantages	Disadvantages
SAW	Value based method Use of measurement of the utility an alternative (Cheng et al., 2003)	Easy to use and understandable Applicable when exact and total information is collected	Normalization is required to solve multidimensional problems
AHP	Use of value based, compensatory, and pairwise comparison approach Use of Hierarchical structure to present complex decision problem	Applicable when exact and total information is collected Decision problem can be fragmented into its smallest elements, making evidence of each criterion applied (Macharis et al., 2004) Applicable for either single or multiple problems, since it incorporates qualitative and quantitative criteria. Generation of inconsistency index to assure decision makers (Pohekar & Ramachandran, 2004)	Due to aggregation, compensation between good scores on some criteria and bad scores on other criteria can occur (Macharis et al., 2004) Implementation is quite inconvenient due to complexity (Tahriri et al., 2008) Complex computation is required Time-consuming
TOPSIS	Use of value based compensatory method Measures the distances of the alternatives from the ideal solution	Easy to implement understandable principle Applicable when exact and total information is collected	Normalization is required to solve multidimensional problem

	Selection of the one closest to the ideal solution (Cheng et al., 2002)	Consideration of both the positive and negative ideal solutions	
ELECTRE	Use of outranking method Use of indirect method that ranks alternatives by means of pairwise comparison	Applicable even when there are incomparable alternatives Applicable even when incorporation of uncertainties is required	Time consuming without use of specific software due to complex computational procedure (Cheng et al., 2002) May or may not reach the preferred alternative
PROMETHEE	Use of outranking method, pairwise comparison, and compensatory method Use of positive and negative preference flows for each alternative in the valued outranking	Applicable even when there is missing information Applicable even when simple and efficient information is needed (Queiruga et al., 2008)	Time consuming without use of specific software When using many criteria, it becomes difficult for decision maker to obtain a clear view of the problem (Macharis et al., 2004)

2.8.1 Analytic Hierarchy Process (AHP)

Analytic hierarchy process (AHP) was proposed by Saaty (1980). AHP is a systemic method commonly used for decision-making (Sadiq, 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 the AHP is using pair-wise comparisons to determine weights and derive a priority index in comparison to other weighting methods where weights are assigned arbitrarily. The 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 reduce complex problems into simpler and manageable elements that 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 (Tesfamariam & Sadiq, 2006). The AHP consists of the following five stages (Zahedi, 1986):

1. Break down a problem into a hierarchy of ultimate goal, (sub)criteria, 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 2-4 (Saaty, 1980). According to the nine-point intensity scale, a decision maker is able to generate

pairwise comparisons among (sub) criteria and alternatives and derive the relative importance of factors

4. Aggregate weights and scores to establish a ranking of alternatives. The aggregated score are in the range of [0 1]. The alternative with the maximum value will be considered as a preferred alternative

5. Study reliability and validity of data using sensitivity analysis.

Table 2-4: 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	

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

$$A = \begin{bmatrix} a_{11} & a_{12} & .. & a_{1n} \\ a_{21} & a_{22} & .. & a_{2n} \\ . & . & . & . \\ a_{n1} & a_{n2} & .. & a_{nn} \end{bmatrix}, a_{ii} = 1, a_{ji} = 1/a_{ij}, a_{ij} \neq 0 \qquad \text{Equation 1}$$

Each element a_{mn} 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 judgement 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:

$$W = (w_1, w_2, ..., w_n) \text{ where } \sum_1^n w_n = 1 \qquad \text{Equation 2}$$

There are several mathematical techniques that can be used to calculate the vector of priorities (*weights*) from the matrix, such as, eigenvector, geometric mean, and arithmetic mean. Preliminary investigation has 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 is an easy way to obtain approximate priorities (weights) (Saaty, 1990). In this method, the normalization is required for each column of the matrix and then averaged over each row. One of the common issues in generating a 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 λ and eigenvector W (priority vector) value may help solving eigenvalue Equation (3).

$$(A - \lambda)W = 0 \qquad \text{Equation 3}$$

In equation 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 consistency index is defined as following:

$$CI = (\lambda max - n)/(n - 1) \qquad \text{Equation 4}$$

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

$$CR = CI/RI \qquad \text{Equation 5}$$

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 out 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.

Recently, various models have been proposed to assess the economic, technical and environmental characteristics related to the infrastructure system. These models include, exergy analysis (Kaushik et al., 2011), embodied energy analysis (Ko et al., 2004), lifecycle assessment (LCA) (Herz & Lipkow, 2002), emergy accounting (EA) (Droguett, 2011), energy analysis (Boustead & Hancock, 1979), environmental risk assessment (Sadiq & Husain, 2005) and cost-benefit analysis (Ormsby, 2009). In this study, emergy- based lifecycle approach is explored and implemented for enhancing sustainability in sewer asset management and results have been compared with the traditional lifecycle approach which involves the use of AHP as MCDM method.

2.9 Emergy accounting

Emergy accounting (EMA) is one of the environmental accounting methods that take into account the contribution of ecological products and services. Emergy (spelled with an "m'") 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; Ridolfi & Bastianoni, 2008). For instance, many joules of sunlight are required to make one joule of fuel, several joules of fuel is needed to make a joule of electricity, many joules of electricity is 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 et al., 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, since it is basically the source of all flows in the biosphere.

Therefore, this methodology allows for the evaluation of a process on a common basis, and the solar base of emergy evaluation is the conversion of all process inputs, including energy of different types and energy inherent in materials and services, into emergy by means of a conversion factor called *transformity* (Zhang et al., 2006) as shown in Figure 2-7.

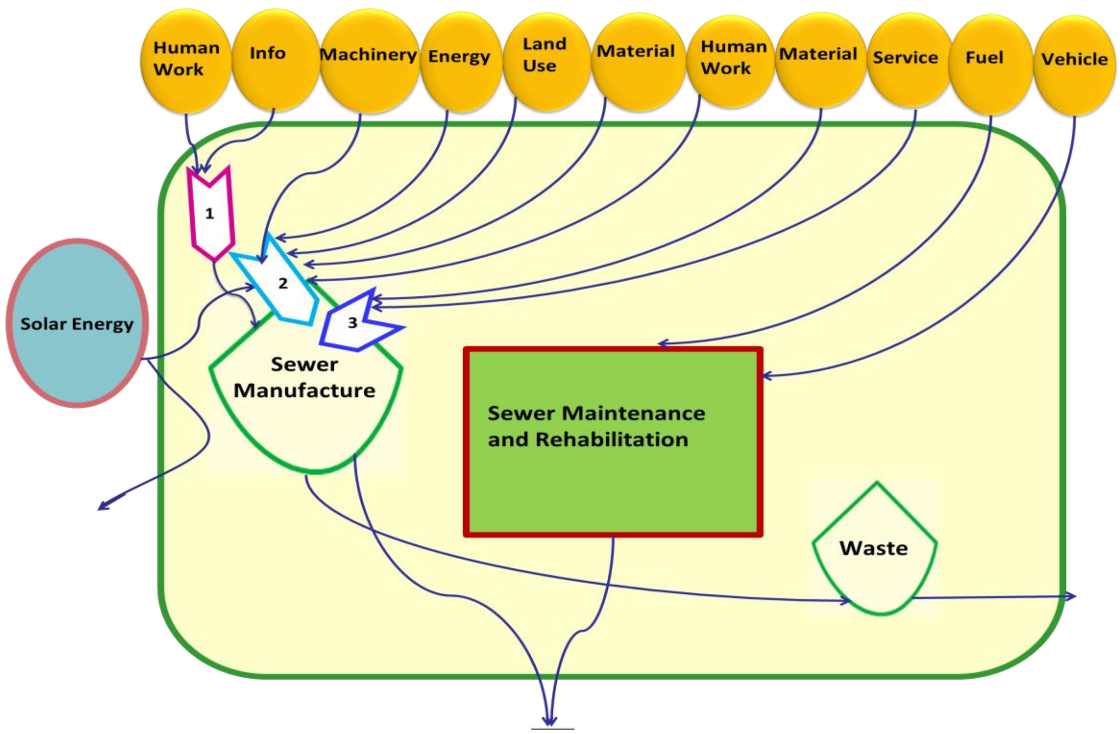

Figure 2-7: Emergy system diagram

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 unit emergy value 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^{12}). 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 B_k of the flow k coming from a given process is:

$$B_k = \Sigma_i Tr_i E_i \qquad \text{Equation 6}$$

where E_i is the actual energy content of the i^{th} independent input flow to the process and Tr_i is the solar transformity of the i^{th} input flow (Pulselli et al., 2007).

It is common to measure solar transformity in solar emergy joules 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 solar emjoules/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 et al., 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 & Swank, 2003).

Emergy synthesis offers original information about the relationship between a product or process and the environment, not captured by existing LCA indicators, which is particularly relevant to resource use and long-term sustainability, and which could be valuable for LCA. However there are differences in the conventions, systems boundaries and allocation rules between emergy and LCA, which require adjustments from the conventional application of emergy to achieve a consistent integration. Ingwersen (2010) provided three key points for the use of emergy in LCA:

- Emergy offers the most extensive measure of energy requirements. System boundaries in a cradle-to-cradle LCA typically begin with an initial unit process in which a raw material is acquired (e.g. extraction), and would include raw materials entering into that process, but would not include any information on the environmental processes creating those raw materials. Emergy traces energy inputs back further into the lifecycle than any other thermodynamic method, summing lifecycle energy inputs using the common denominator of the solar energy directly and indirectly driving all biosphere processes. Other thermodynamic methods including exergy do not include energy requirements underlying environmental processes (Ukidwe & Bakshi, 2004).
- When a resource is consumed in a production process, more energy is required to regenerate or replenish that resource. The emergy of a resource is this energy required to make it including work of the environment, and assuming equivalent conditions; this is the energy that is takes to replenish it. Sustainability ultimately requires that inputs and outputs to the biosphere or its subsystems balance out (Gallopin, 2003). As the only measure that relates products to energy inputs into the biosphere required to create them,

emergy relates consumption to ultimate limits in the biosphere by quantifying the additional work it would require from nature to replace the consumed resources.

- Emergy presents a unified measure of resource use. Comparing the impacts of use of renewable *vs*. non-renewable resources typically necessitates some sort of weighting scheme for comparison. Because there is less agreement upon characterization of biotic resources, these may not be included despite their potential relevance (Guinée, 2002). Using emergy, abiotic and biotic resources are both included and measured with the same units. As follows from its nature as a unified indicator, one which characterizes inputs with a single methodology to relate them with one unit (emergy uses sejs, or solar emjoules, which are sunlight-equivalent joules), no weighting scheme is necessary to join different forms of resources (e.g. renewable and non-renewable; fuels and minerals) to interpret the results.

2.10 Other environmental accounting methods

As mentioned earlier, there are many environmental accounting methods to analyze a system, among which exergy, emergy, embodied energy and lifecycle assessment (LCA) are used widely.

Exergy of a system is defined as the maximum useful work possible during a process. The main use of exergy has been seen in energy conversion systems such as power plants and in estimating the energy use in building. The major input to this system is fossil fuel and the major outputs are electricity. The most significant drawback of this method is that it does not account for “goods and services in the market or for information required” for the system operation (Meillaud & Brown, 2005).

Emboided energy is defined as the total energy, including fossil fuel, solar, nuclear etc. that was used to create any product, bring it to market and dispose of it. Therefore, embodied energy does not consider different types of flows used to make a product or service such as material, human work and information.

Traditionally, LCA method is often employed to assess the potential environmental impact of a product or process over its entire lifecycle, which includes resource extraction, transportation, manufacture, utilization, consumption, recycling and waste management (Dixon et al., 2003). The LCA method has been found to be a useful methodological tool in undertaking a quantitative environmental analysis of the entire process. However, it only focuses on the environmental impact of emissions while ignoring the contributions of ecological products and services. The main limitation of LCA is that it assesses all the impacts which are in mixed units. Thus the assessment method makes it difficult to conduct a comparative analysis between products or services (Brown & Buranakarn, 2003). LCA ignores ecosystem services and products, and the final results of this analysis depend on subjective evaluation (Ulgiati et al., 2006). In addition, the environmental impacts are usually 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. On the other hand, human related issues (socioeconomic impacts) are commonly accounted for in dollar value. However, to make a policy decision related to environmental systems, both environmental impacts and its associated socioeconomic consequences must be expressed by a unified measure to compare and evaluate equitably (Campbell et al., 2005).

For this reason, it is imperative to promote integration among methods that can potentially balance both the environmental impacts and socio-economic effects. Two different methods, i.e., EMA and LCA, can be combined to properly estimate the trade-off between human and natural service, as well as to evaluate current consumption methods of natural resource and environmental emission levels. Emergy method can overcome the limitations of LCA by normalizing all the attributes of the system in a common metric unit. Few studies have combined these two scientific tools to measure human impact on nature and the sustainability of a system, as exemplified by studies on two wine farms in Italy (Pizzigallo et al., 2008), in an urban residential area (Li and Wang, 2009), on bridge systems (Bahar et al., 2011), in stormwater management (Droguett, 2011). However, some studies point out the EMA method does not give enough consideration to the impacts of pollutants emission (Hau, 2004). This is not a flaw of emergy theory, because it is derived from natural ecosystems, and there are no wastes in natural ecosystem.

The typical emergy method does not consider the uncertainty in many of the numbers used to calculate the transformities. Averaged transformity of industrial and geological processes is frequently used in specific case studies with no knowledge of the degree of certainty of the resulting output. Therefore, the issue of uncertainty analysis should be addressed in emergy values to conduct a more reliable analysis.

2.11 Uncertainty analysis

In the practice of emergy evaluation, emergy results are not typically presented with uncertainty ranges. Odum believed that an emergy result was accurate within an order of magnitude (Brown, 2009). However, the lack of a clearly defined and systematic manner of characterizing the accuracy of emergy results has been a criticism of emergy work for decades (Ingwersen, 2010). A couple of notable first attempts at characterizing uncertainty in transformity or specific unit emergy values (UEVs) were performed by Campbell (2001) and Cohen (2003).

Campbell estimated the uncertainty in the transformity of global rainfall and river chemical potential based on differences in estimated global water flows. Cohen (2003) used a stochastic simulation technique to generate confidence envelopes for UEVs of various soil parameters. Both of these approaches were attempts to estimate ranges of specific emergy values, but neither fully characterized this uncertainty or proposed methods of propagating this uncertainty for use in future evaluations. A model for estimating uncertainty in emergy results can be useful for estimating ranges in emergy results within emergy and beyond for the estimation of the additional uncertainty related to emergy models in lifecycle results that use emergy as a unit of measurement.

The uncertainty in emergy values may exist on numerous levels. Classification of uncertainties, therefore, is helpful for identifying their sources. The classification scheme defined by the US EPA defines three types of uncertainty: parameter, scenario, and model uncertainty (Lloyd & Ries, 2007). There are additional elements of uncertainty (for example, calculation errors in evaluation, use of emergy for an inappropriate product or process) in the adoption of emergy analysis over the lifecycle. These errors are due to random calculation mistakes, human errors or methodological discrepancy.

The uncertainties involved in the input parameters propagate throughout the model and ultimately to the model output (Pasha & Lansey, 2011). As a result, model losses its capacity to represent the real situation. A range of techniques can be used to address parameter uncertainties in parameters that include probability theory, Bayesian theory, fuzzy set theory etc. In this study, uncertainty analysis using fuzzy-based techniques has been explored for modeling complex systems. This method can effectively handle uncertain and imprecise information (Ross, 1997). Fuzzy-based technique is suitable for the infrastructure management problem where data are scarce and are mainly collected through expert's opinions and deal with subjectivity of condition states which are qualitative terms (Rajani et al., 2006).

2.12 Fuzzy-based technique

Fuzzy-based techniques are a generalized form of interval analysis used to address uncertain and (or) imprecise information. Fuzzy sets qualify as fuzzy numbers if they are normal, convex and bounded (Klir & Yuan, 1995). A fuzzy number describes the relationship between an uncertain quantity X and a membership function μ. This function, which is comprised between zero and one, describes the possibility that the quantity X may take on a certain value x. Different shapes of fuzzy numbers are possible (e.g., bell, triangular, trapezoidal, Gaussian, etc.). In order to simplify the implementation, in this study, triangular fuzzy numbers (TFNs) were used. TFN is represented by three points (a, b, c) on the universe of discourse (scale X on which criterion is defined), representing the minimum, most likely, and maximum values, respectively. Figure 2-8 represents two membership functions associated with the unit emergy value of concrete production that is considered as uncertain.

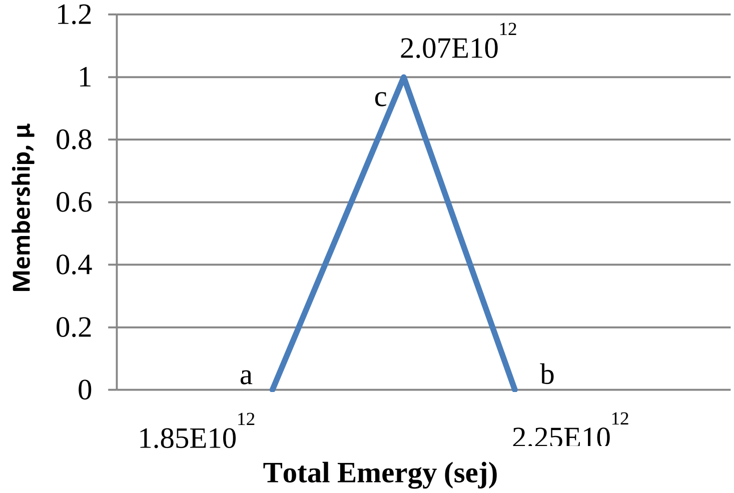

Figure 2-8: Representation of fuzzy triangular number

It is most likely that the unit emergy value lies between 1.85E10^{12} and 2.25E10^{12}. No preference can be expressed within this range. Values lower than or greater than these values, are considered impossible.

Another important concept related to fuzzy set is the introduction of the α -cut level. Each fuzzy number can be represented by α -cut (Dubois & Prade, 1988). The α -cut of a fuzzy set A is a crisp set A^{α} that contains all the elements of the universal set X whose membership grades in A are greater than or equal to the specified value of an α, i.e., $A^{\alpha} =\{ X|\mu_x > \alpha\}$(Klir & Yuan, 1995). Operations on the fuzzy number can be performed on the real number or the membership function (μ_x). Fuzzy operations are carried out on the fuzzy numbers using fuzzy arithmetic. Fuzzy arithmetic is based on two properties of fuzzy numbers (Klir & Yuan, 1995): (1) each fuzzy number can fully and uniquely be represented by its α -cut; and (2) α -cuts of each fuzzy number are closed intervals of real numbers for all $\alpha \in (0, 1)$. Hence, once the interval numbers are obtained, a well-established operation of interval analysis can be utilized (Ferson & Hajagos, 2004). Some commonly used fuzzy arithmetic operations are listed in Table 2-5.

Table 2-5: Common fuzzy arithmetical operations

Operators	Formulae	Results
Summation	A+B	$(a_1+b_1, a_2+b_2, a_3+b_3)$
Subtraction	A-B	$(a_1-b_3, a_2-b_2, a_3-b_1)$
Multiplication	A*B	$(a_1*b_1, a_2*b_2, a_3*b_3)$
Division	A/B	$(a_1/b_3, a_2/b_2, a_3/b_1)$
Scalar product	Q.B	$(Q*b_1, Q*b_2, Q*b_3)$

The procedure for calculating fuzzy α-cuts is reported in various literatures (e.g., Lee et al., 1994). Lee applied it to evaluate the risk related to the presence of nitrate in ground water. For k fuzzy variables X_1–X_k, and a model noted as $f(X_1,..., X_k)$, the procedure can be summarized as follows:

1. Select a value α of the membership function (a level of possibility).

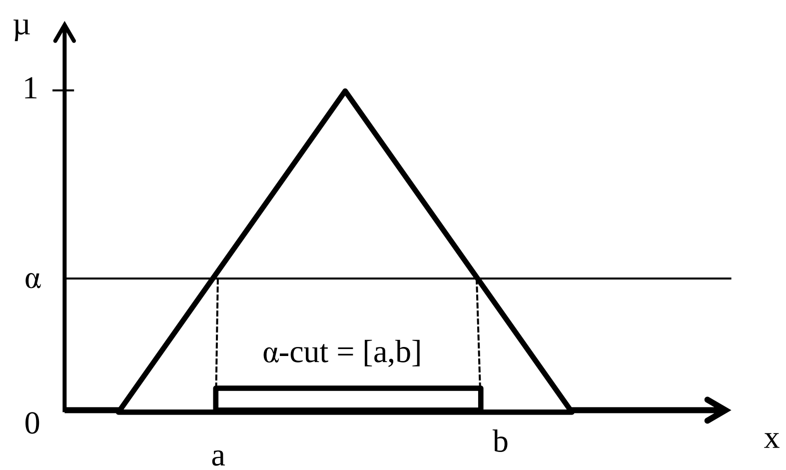

Figure 2-9: Illustration of α-Cut; i.e., all values comprised between a and b

2. Select for each fuzzy number X_1–X_k, the values a and b of the -cut for this value of α (as shown in Figure 2-9).

3. Calculate the min and max values of $f(X_1,...,X_k)$, considering all of the values located within the α-cuts for each fuzzy member.

4. Affect these min and max values to the lower and upper limits of the α-cut of $f(X_1,. ..,X_k)$.

5. Repeat the operation for another α -cut.

6. Built the fuzzy result of $f(X_1,...,X_k)$ using the min and max values of each α -cut of $f(X_1,...,X_k)$.

3 METHODOLOGY

In this chapter, the methodology for emergy-based lifecycle approach is proposed and developed. Lifecycle approach helps to develop an inventory of relevant energy and material inputs and environmental releases for each construction material. Emergy accounting requires the history of resources consumed to make that product or service. In this study, lifecycle approach combined with emergy analysis was used to quantify the type and quantity of resources of each sewer material, from cradle-to-cradle.

A step-by-step procedure for the integration of emergy analysis and the lifecycle approach is presented. Figure 3-1 defines the major steps of the proposed methodology to integrate emergy accounting with the lifecycle approach. This will help to evaluate emergy consumption of a sewer system over its lifecycle (cradle-to-cradle) by considering environmental and economic impacts which will result in more sustainable sewer infrastructure. The major steps of the methodology are:

- Conduct LCA and LCC (traditional lifecycle approach) for evaluating environmental and economic impacts, respectively
- Use AHP method to determine overall impacts based on traditional lifecycle approach
- Perform emergy calculations based on lifecycle inputs and outputs, and
- Compare results of emergy-based lifecycle approach with traditional lifecycle approach

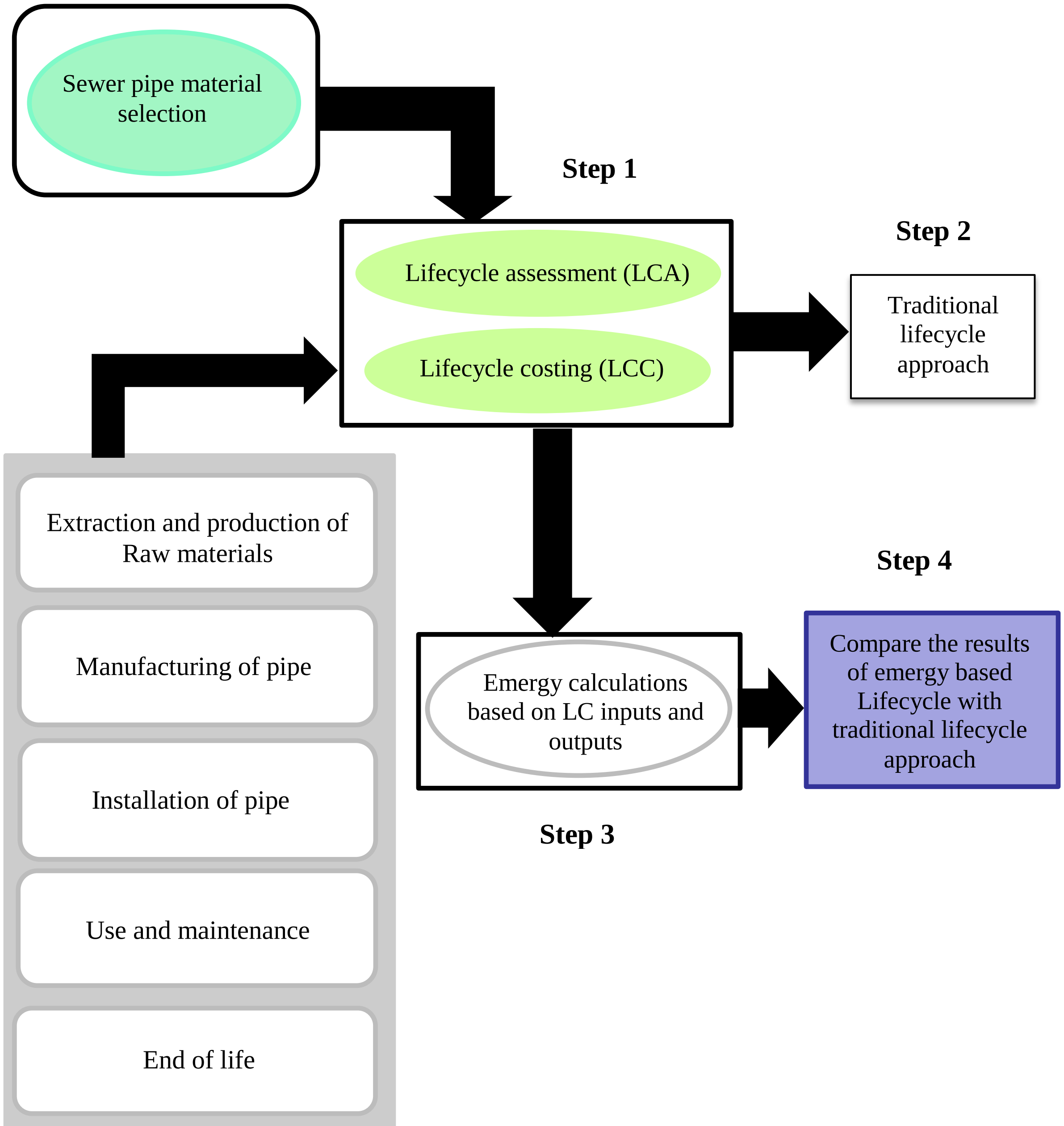

Figure 3-1: Steps for the proposed methodology

3.1 Lifecycle assessment (LCA) for sewer pipe

This is the first step of the proposed methodology. SimaPro is one of the leading tools in the field of LCA. It was used to perform LCA for major sewer materials in Canada (for inventory analysis and impact assessment). After selecting the materials, LCA for all the selected materials was conducted. SimaPro 7.1 was used for inventory analysis. It covers resource extraction and manufacturing stages in a lifecycle of a sewer. For other stages of the lifecycle data were collected from existing literature. As mentioned earlier, there are four major steps for developing the LCA model. The details of each step in the context of sewer infrastructure management are presented in the following sections.

3.1.1 Goal and scope definition

The selected materials for this study include concrete (CO), ductile iron (DI), polyvinylchloride (PVC) and vitrified clay (VC) and they represent 84% of the total stock of sewers (Allouche et al., 2002). These materials were selected because they have comparable features in terms of quality and environmental characteristics. To compare these materials lifecycle approach was employed, which evaluates the inputs and outputs of the system considering the environmental (LCA) and economic (LCC) impacts by examining each phase of the system's lifecycle.

The system boundary is one of the most important parameters that affect the results of an LCA. The system boundary of this study is defined in Figure 3-2. In this study, LCA encompasses raw material extraction and production, transportation to manufacturing company, pipe manufacturing, installation of pipe, operation, and maintenance and disposal phases. This study included resource depletion, energy consumption, and associated emission for all the phases of the lifecycle of the sewer pipes. The functional unit used for construction phase had been defined as the three meter length and 400 mm diameter of sewer pipes of different materials with different service life.

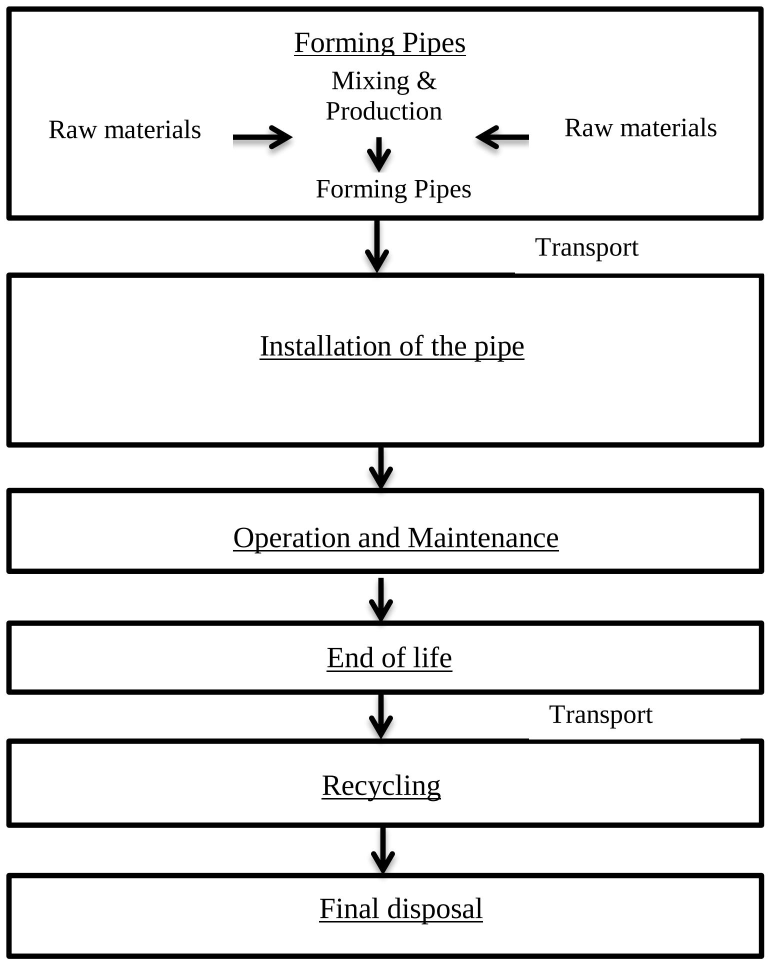

Figure 3-2: Assumed lifecycle of a sewer pipe

3.1.2 Lifecycle inventory (LCI)

To develop the lifecycle inventory, the system boundary was defined and inputs and outputs were determined (Figure 3-2). The data for flux in and out of the system were collected for all activities within the system boundary. LCI data was collected from pipe manufacturing companies and literature. Data for material production, pipe manufacturing, and transportation were collected from different pipe manufacturing companies (Hanson Pipes and Precast, Concast Pipe). Data related to energy consumption from different sources (e.g., natural gas, electricity) were also collected from pipe manufacturing companies. The estimation of emissions for fossil energy consumption and emission conversion factors is presented in Table 3-1. These emission conversion factors are based on study by Park et al. (2007). The conversion coefficients are based on the same physical energy unit, ton of oil equivalent (TOE). A TOE refers to the energy content of one metric ton of crude oil that is equivalent to 41.868 Giga Joule (APS, 2007).

Table 3-1: Environmental emission units of each energy source

Energy source	CO_2 (kg/TOE)	NO_X (kg/TOE)	SO_X (kg/TOE)
Coal	1,059	7.35	26.63
Gasoline	792	5.49	19.91
Diesel	837	5.81	21.05
Electricity	902	6.26	22.68

Energy and emissions estimations are extremely complex process depending on the level of accuracy of data. A high level of accuracy in data acquisition can guarantee high quality LCA; however, due to lack of data, most of the LCA is limited to the manufacturing stage when dealing with construction materials. Limited data are available for the construction stage of the sewer pipes. Due to various construction methods, it is always not possible to provide standardized energy consumption data for construction process. Energy consumption is affected by various factors such as the fuel efficiency of the equipment, job condition, productivity rates and construction schedule. Fuel consumption rates of equipment are collected from construction equipment site (http://www.constructionequipment.com/) (Table 3-2). This fuel consumption rate is under the normal working status. The typical production rate (80 feet/day) used by Koo (2007) was adapted in this research for the pipe installation method.

Table 3-2: Fuel consumption rate of construction equipment

Equipment	Fuel consumption rate
Excavator	10-12 gal/hour
Compactor	6-8 gal/hour
Medium size dump truck	5-7 mile/gal

3.1.3 Impact assessment

The next step after inventory analysis is the impact assessment. The purpose of this stage is to evaluate the significance of potential environmental impacts of the system, based on the LCI flow results. Typically, lifecycle impact assessment consists of the following components:

- Selection of impact categories, category indicators, and characterization models
- Classification stage: where the inventory parameters are sorted and assigned to specific impact categories
- Impact measurement: where the categorized LCI flows are characterized, using one of many possible LCA methodologies, into common equivalence units that are then aggregated to provide an overall impact category (ISO 14044, 2006).

In addition to these three steps, result should be normalized, grouped or weighted for better representation. Impacts are categorized as downstream or upstream. Downstream impacts cover the inflow of resources and energy to the system. Upstream impacts cover outflows of the system to different media (i.e., air, water and soil). The environmental impacts are calculated considering the complete lifecycle of the sewer including: 1) raw material extraction and production, 2) manufacture of pipe, 3) installation of pipe, 4) operation and maintenance, and 5) end of life.

3.1.3.1 Raw material extraction and production

The composition of raw materials for different pipes is given in Table 3-3. Energy required for production of the pipe materials and transport to the factory is also considered in this stage. The reference value for the energy consumption of concrete production was taken as 0.26 $kWhkg^{-1}$ (Baird et al., 2009). It was considered that this energy is provided 70% by fuel-oil or diesel and 30% by the electricity. The energy consumption for the PVC is 7.19 $kWhkg^{-1}$ which is provided entirely by diesel oil. The energy consumption for production of ductile iron is 6.70 $kWhkg^{-1}$ and utilizes 92% coal and 8% electricity. The energy consumption values for the materials are summarized in Table 3-4.

Table 3-3: Typical composition of various pipes

Sewer type	Material	Composition (%)
Concrete	Cement	16.39
	Sand	29.51
	Water	8.2
	Gravel	45.9
Polyvinyl chloride	PVC resin	92.6
	Calcium carbonate	4.4
	Stabilizer	3.0
Vitrified clay	Clay	93.6
	Barium	4.2
	Calcite	2.2
Ductile iron	Cast iron	93.8
	Carbon	3.4
	Silicon	2.8

Table 3-4: Energy consumption for extraction and production of materials

Material	Energy consumption (kWh kg^{-1})	Source
Concrete	0.26	(Baird et al., 2009)
PVC	7.19	(Baldasano & Parra, 2005)
Vitrified clay	1.95	(US EPA, 2007)
Ductile iron	6.70	(US EPA, 2007)

3.1.3.2 Manufacturing

Concrete pipes are normally processed by centrifuging or vibration. Ductile iron pipes are processed by centrifuging or vertical casting. The energy consumption data for manufacturing process was taken from pipe manufacturing companies. For extrusion of PVC, 0.45 kWh (kg material)$^{-1}$ energy is required, whereas to manufacture 1 metre of 400 concrete pipe, the consumption requirement is 60.4 kWh m^{-1}, and for 400 ductile iron pipe, the consumption rate is 12.7 kWh m^{-1} (Baird et al., 2009).

3.1.3.3 Installation of pipe

Most construction activities are carried out with heavy machinery. In the process of construction, energy is directly consumed by using construction machinery. Energy consumption of construction machinery can vary according to the scale, the deterioration of machinery, and the skill of the operators. In this study, simple the open cut method is considered for installation of all the pipes. The fuel consumption of all the construction machinery is provided in Table 3-2.

3.1.3.4 Operation and maintenance (O & M)

The operation of sewer pipe is simple. The fluid flows by gravity, and no propulsion systems are used in most of the cases. However, regular maintenance activities are required to maintain an ideal operating condition of sewer pipe. Since these maintenance activities are planned in advance, there is an uncertainty related to the exact timing of their occurrences. Hence, deterioration model development is necessary for predicting the expected service life. Service life is the period of time over which the asset is actually available for use and able to provide the required level of service at an acceptable risk (Marlow et al., 2009). The service life is adapted from the study by Newton and Vanier (2006), who reported the results in Municipal Infrastructure Investment Planning of Canada (MIIP) datasets. They estimated service life of different pipe materials which are shown in Table 3-5.

Table 3-5: Typical service life of various pipes (Newton and Vanier, 2006)

Material	Service life(years)
Concrete	114
PVC	75
Vitrified clay	136
Ductile iron	100

The categorical nature of a pipe grade makes it difficult to plot trends in pipe deterioration over time as there are many pipes at all condition states at given times. Figure 3-3 represents the deterioration models for various pipes (Newton & Vanier, 2006). These trends were analysed using regression models. Equations 7, 8, 9 and 10 express the service life of CO, PVC, VC and DI pipe respectively, which are given below:

$$y = e^{0.0112x} \qquad \text{Equation 7}$$

$$y = 0.001x^2 - 0.0203x + 1 \qquad \text{Equation 8}$$

$$y = e^{0.0108x} \qquad \text{Equation 9}$$

$$y = e^{0.0098x} \qquad \text{Equation 10}$$

where *y* is the structural pipe grade and *x* is the sewer pipe age. The model predicts a pipe will reach a completely failed state at condition state (5) among the five condition states where, 1 represents the best condition and 5 represents the worst or failing state. After reaching condition state 3, each pipe needs to be replaced. The mass and energy for the maintenance of sewer pipe is negligible compare to the total mass and energy. However, mass and energy flow for the replacement of pipe is calculated in this study.

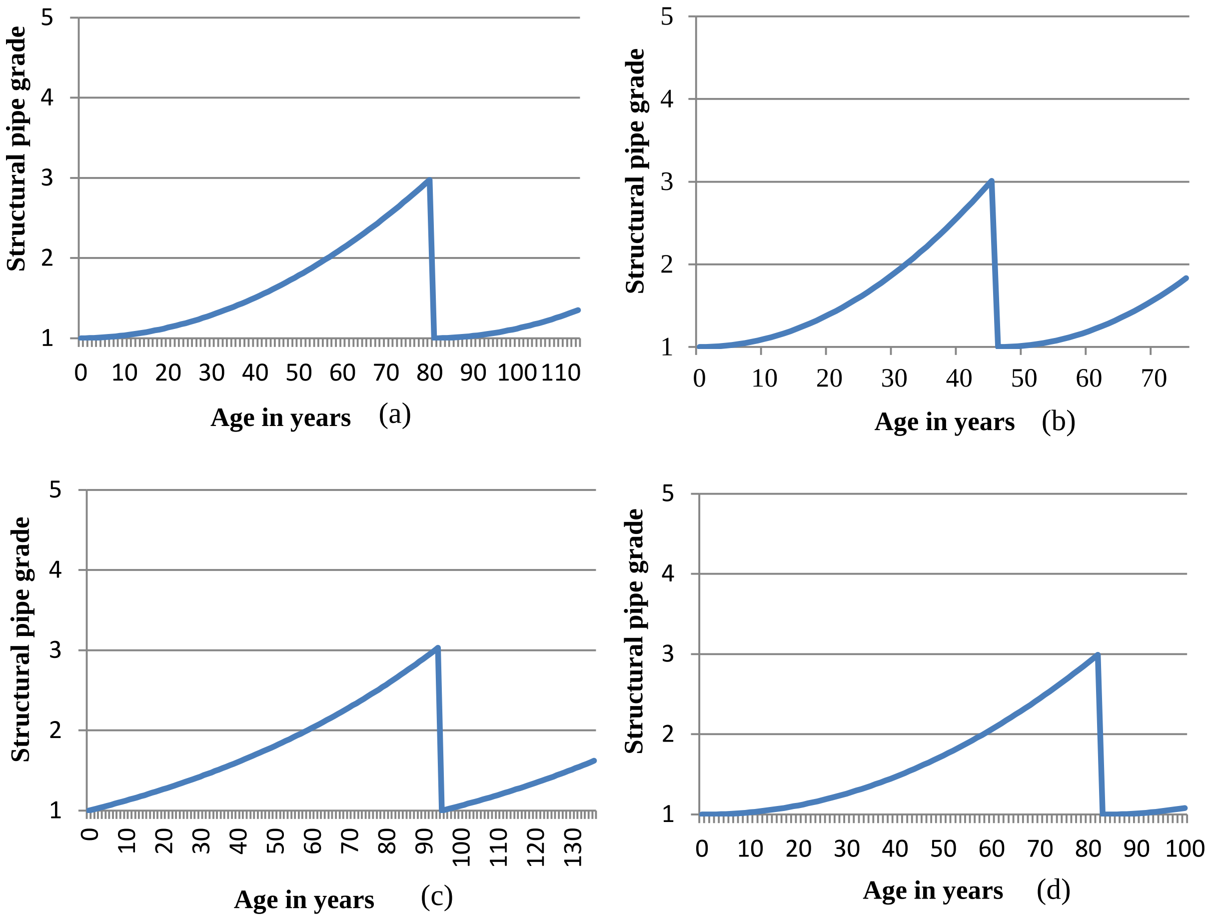

Figure 3-3: Deterioration curves with replacement (a) concrete, (b) PVC, (c) VC (d) DI

3.1.3.5 End of life (EoL)

Almost 97% of PVC and ductile iron pipes are recyclable. The remaining 3% is discarded as waste. Xiao et al. (2011) reported that aggregate can be built from recycled concrete. Recycled concrete can be 100% used in roadbed, parking lots and other applications as a granular material. Approximately, 0.155 KWh of energy is consumed for every kg of waste deposited in a disposal site (Choate & Ferland, 2004).

3.2 LCC for sewer systems

The lifecycle 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 capital cost was defined as the total initial investment incurred at the beginning of the lifecycle 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 lifecycle cost is calculated by adding the installation cost to the present value of a growing annuity of maintenance activities (Brigham & Ehrhardt, 2005; Fabricky & Blanchard, 1991). The formula is**:**

$$TLCC = C_i + \sum C_{mrr} + C_e \quad \text{Equation 11}$$

where *TLCC* is total lifecycle cost in present value, C_i is the initial cost and C_{mrr} is the cost of maintenance, repair and replacement and *Ce* is the end of life cost. 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 (Brigham & Ehrhardt, 2005). 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:

$$PW = A.\frac{(1+r)^n - 1}{r(1+r)^n} \quad \text{Equation 12}$$

where *PW* is the present worth annuity, *A* is the annualized total cost and *r* is the discount rate at *n* periods. Data for installation costs was obtained from a popular and often-used source in the literature. Neelakantan et al. (2008) presented installation cost data for various diameter pipes. Data for maintenance cost and suggested maintenance intervals were collected from the agency's sewer cleaning and inspection fact sheet (USEPA, 2009). It should be noted that the installation cost varies with the installation depth, type of contractor, type of pipe, method of installation and many other factors. However, the installation cost reported by Neelakantan et al. (2008) is adapted in this research in the model development. Table 3-6 and 3-7 present the installation cost and maintenance cost data of different pipe networks. Data for maintenance cost and suggested maintenance intervals (d years) were collected from the US EPA's sewer cleaning and inspection fact sheet (USEPA, 2009). All costs include labor cost, fringe benefits, equipment, material, and overhead for administrative services.

Table 3-6: Costs of installation of pipes for various diameters

Dia. (mm)	CO ($/m)	PVC ($/m)	VC ($/m)	DI ($/m)	Installation cost ($)
100	23.5	33.31	36.64	55.8	62.00
150	31.6	36.64	43.97	64.5	68.00
200	43.5	43.97	55.69	81.3	87.00
250	58.4	75.00	110.00	133.4	121.00
300	64.2	105.6	135.26	156.5	129.00
350	70.5	132.4	169.40	191.8	153.00
400	83.9	172.04	201.25	254.06	204.00

Table 3-7: Maintenance cost data (adapted from USEPA, 2009)

Type of maintenance	Interval (years)	Cost per unit length ($/m)
Root (chemical treatment)	5	$4.56
Sludge maintenance (rodding)	7	$4.13
Grease (pressurized cleaning/jetting)	7	$2.03
Debris (flushing)	7	$2.09

The end of life (EoL) cost of a structure, a system or a component is its remaining value at the end of the contract, or at the time it is replaced during the contract period. End of life cost can be based on the amount of resale value, salvage value, or scrap value, net of any selling, conversion, or disposal costs. End of life cost needs to be considered in order to have a more precise forecast of lifecycle cost. As a rule of thumb, the end of life cost of a system with remaining useful life can be calculated by linearly prorating its initial costs (Bhasker, 2007). For example, for a system with an expected useful life of 15 years, that was installed 5 years before the end of the contract, the EoL cost would be approximately two thirds of its initial cost. In this study, data for the end of life cost of the pipes were collected from the City of Kelowna. The various cost data which are obtained in this study are given in Table 3-8.

3.2.1 Discount rate (r)

Discount rate is a factor that takes into account the effect of time on the value of money. In the private sector, discount rate is defined as the financial advantage of one investment when compared to a risk free annual rate of return (Rahman & Vanier, 2004). Discount rate has two components: interest rate and inflation rate. Discount rate can be calculated as follow.

$$r = i + f \qquad \text{Equation 13}$$

where r is discount rate, i is interest rate, and f is inflation rate. In this study, the annual interest rate of 2.27% was used. This data was obtained from the current interest rate of 10 year Canadian Government securities provided by the Bank of Canada for 2012. For the inflation rate, due to the high fluctuation in recent years, the average rate of 10 years was used instead of the current inflation rate. The 10 year average is 1.9% annually (Bank of Canada, 2012). Therefore the discount rate can be calculated as:

$$r = 2.27\%+1.90\%=4.17\%$$

Table 3-8: Lifecycle cost data for different pipes

Parameter	**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, $ per meter length	83.9	172.04	201.25	254.06
Installation cost, $ per meter length	204	204	204	204
Maintenance cost, Cm				
Root (chemical treatment), $ per meter/yr	0.912	0.912	0.912	0.912
Sludge maintenance, $ per meter/yr	0.59	0.59	0.59	0.59
Grease (pressurized cleaning/jetting), $ per meter/yr	0.29	0.29	0.29	0.29
Debris (flushing), $ per meter/yr	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, Ce, $	30 % of initial cost	20 % of initial cost	15 % of initial cost	35 % of initial cost

3.3 Traditional lifecycle approach

In this study, AHP was used as a decision-making tool to assess and aggregate relative weights of various impacts in a traditional lifecycle approach. Integration of AHP and LCA provides a framework for decision making that is consistent with sustainable construction practices. The burdens and impacts listed in inventory were characterized and classified as general categories, and (sub) criteria hierarchically structured and developed. Figure 3-4 provided three levels of the proposed hierarchical model.

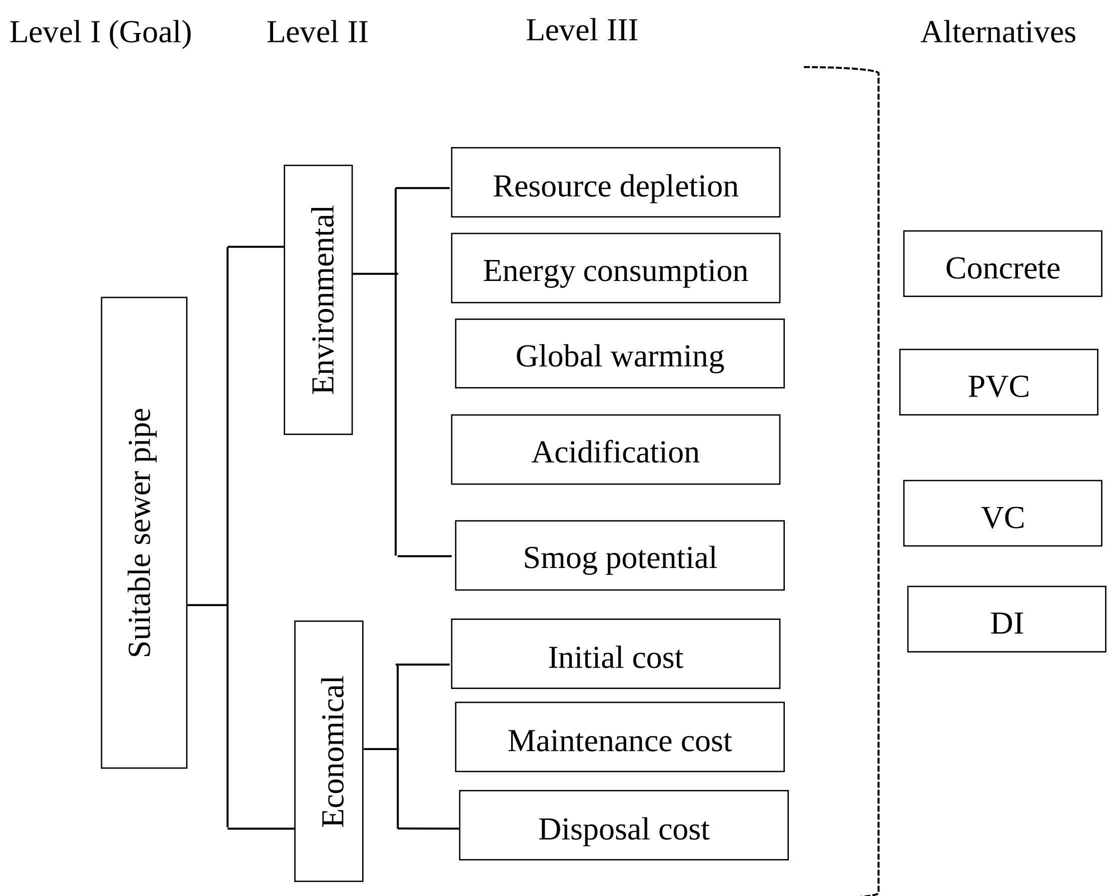

Figure 3-4: AHP model for traditional lifecycle approach

The goal of the study is defined at the first level. In the second level, sustainability criteria, environmental and economic factors are considered. Each of these main criteria is subdivided into numerous sub-criteria which are achieved from inventory analysis phase. After constructing the hierarchy, pair-wise comparisons are performed systematically to include all the combinations of criteria and sub-criteria relationships. The criteria and sub-criteria are compared according to their relative importance with respect to the parent element in the adjacent upper level. Applying AHP and pair-wise comparison matrices, the relative importance weight is assigned to each (sub) criterion.

In this research, equal weights are assumed for the main criteria (environmental and economic). According to LCA results, it can be observed that different sewer alternatives have varying levels of impacts with respect to different (sub) criteria. For those sub-criteria (e.g., energy consumption, global warming), preference weight has been assigned by normalizing the impact values (the smaller the impact the bigger the weight has been assigned). Table 3-9 represents the principal matrix of comparison, which contains the comparison between sub criteria in relation to the overall objective of the problem (i.e., the selection of a sustainable sewer material). From the Table, it is possible to observe that criterion energy consumption is 3 times more important that criterion resource use. As a logical consequence, criterion resource use is 5 times less important than criterion energy consumption. It is also possible to observe that the elements in the principal diagonal are always equal to 1, because w_{ij}=1 when $i=j$. In other words, the weight of a criterion in relation to itself, obviously, is always 1.

Table 3-9: Pairwise matrix and priorities for environmental sub criteria

Sub criteria	Resource use	Energy consumption	Global warming potential	Smog potential	Acidification
Resource use	1	1/3	1/4	3	3
Energy consumption	3	1	1/2	4	5
Global warming potential	4	3	1	5	7
Smog potential	1/3	1/4	1/5	1	3
Acidification	1/3	1/5	1/7	1/3	1

A local priority vector can be generated for the matrix of judgements in Table 3-9 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). Based on the above calculation, the relative priorities of criteria in the final selection of sustainable sewer materials are shown on Table 3-10.

Table 3-10: Relative priority of environmental sub criteria

Criteria	**Relative priority**
Resource Depletion	0.13
Fossil fuel	0.28
Global warming potential	0.47
Smog potential	0.08
Acidification	0.04

Thus, in order to measure the consistency of this first matrix of comparison, the consistency index (CI) is calculated. Imputing the values in equation 4, the CI for this first matrix is then calculated as:

$$0.13\left|\begin{array}{c}1.00\\3.00\\4.00\\0.33\\0.33\end{array}\right| +0.28\left|\begin{array}{c}0.33\\1.00\\3.00\\0.25\\0.20\end{array}\right| +0.47\left|\begin{array}{c}0.25\\0.50\\1.00\\0.20\\0.14\end{array}\right| +0.08\left|\begin{array}{c}3.00\\4.00\\5.00\\1.00\\0.33\end{array}\right| +0.04\left|\begin{array}{c}3.00\\5.00\\7.00\\3.00\\1.00\end{array}\right| = \begin{array}{c}0.71\\1.43\\2.52\\0.42\\0.22\end{array}$$

$$\frac{0.71}{0.13} = 5.33 \qquad \frac{1.43}{0.28} = 5.2 \qquad \frac{2.52}{0.47} = 5.42 \qquad \frac{0.42}{0.08} = 5.33 \qquad \frac{0.22}{0.04} = 5.38$$

$$\lambda max = \frac{5.33 + 5.2 + 5.42 + 5.33 + 5.38}{5} = 5.33$$

$$CI = \frac{\lambda max - n}{n - 1} = \frac{5.33 - 5}{5 - 1} = 0.083$$

Another index that needs to be calculated is the random index (RI). According to Saaty (2008), for the matrix of order 5, the RI is 1.12. Finally with these two values in hand, the CR can be calculated as:

$$CR = \frac{CI}{RI} = \frac{0.083}{1.12} = 0.0742$$

According to the AHP model, a matrix is considered consistent when the CR is less than 10%. So, for this case, the matrix is considered consistent and the same procedure is then carried out for the other comparison matrices. The final step in the pair-wise comparison involves comparing each pair of alternatives with respect to each sub-criterion.

3.4 Emergy-based lifecycle approach

The general framework of emergy analysis (EMA) has been explained in the series of handbooks by Odum et al. (2000) and was further explained in a variety of other publications

(Bargigli & Raugei, 2004; Brown & Ulgiati, 2004). Figure 3-5 shows the energy system diagram for the sewer system. The system diagram consists of major flows contributing at different stages of sewer lifecycle, which are resource extraction, manufacturing of materials, construction, operation, and maintenance and demolition (cradle-to-cradle).

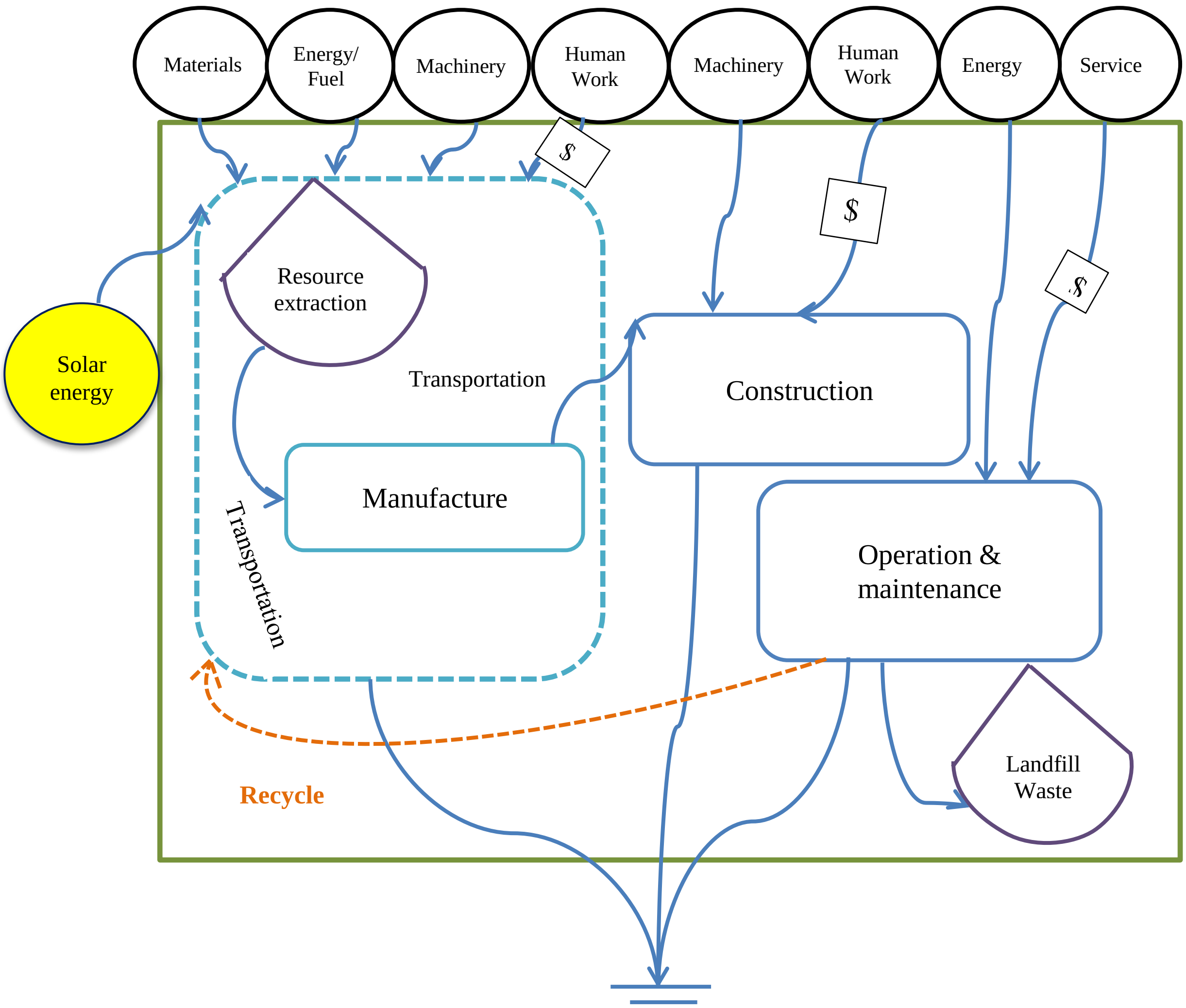

Figure 3-5: System diagram of a sewer lifecycle

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 lifecycle. Flows of money in the system are illustrated as dashed lines with a $ sign. The energy system diagram is drawn based on the symbols of the energy systems language given by H.T. Odum, (1996). As illustrated in Fig 3-5, the complete lifecycle of sewers from cradle-to-cradle is covered in this analysis. In emergy- based lifecycle approach, fluxes in each stage of a sewer lifecycle are transformed into their emergy equivalent. Here is a brief summary of major steps that are applied in the EM-LCA framework:

- **Defining system boundary**: Defining the system boundary is a primary requirement of emergy analysis. Particularly, to obtain a well-integrated result, the boundary of EMA should be set accordingly with the LCA scope (Figure 3-6). The boundary consists of major flows contributing at different stages of the sewer lifecycle, which are raw material extraction, manufacturing of materials, construction, operation, and maintenance and demolition (cradle-to-cradle). Tables of the actual flows of materials, labour 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 emergy.
- **Drawing a systems flow chart**: Relationships between components and pathways of resource flows are drawn in this step. Within the rectangular frame of the system, the sources, components, and flows are drawn with the emergy language symbols as shown in Figure 3-5. In this figure the lifecycle impacts (such as materials, energy and waste generation, etc.) associated with sewer material are shown as inflow and outflow pathways in the sewer system diagram.
- **Calculating emergy**: In this step, raw data and energy content of different sources and materials needed to complete the emergy analysis tables are extracted and summarized. The 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, Column 6: emergy.

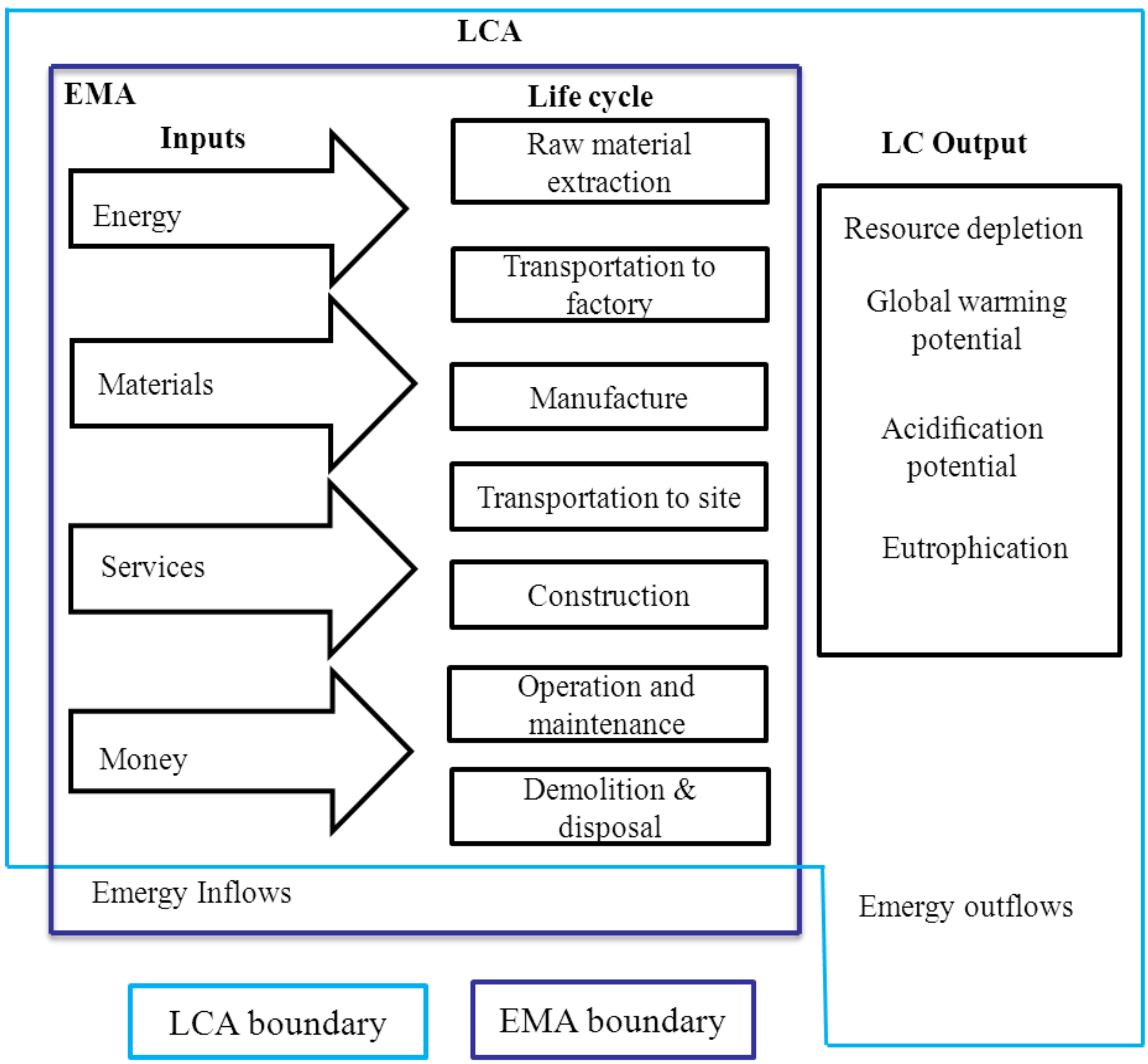

Figure 3-6: EM-LCA framework

Table 3-11 is an example of emergy evaluation table for concrete sewer's material inflow. This table demonstrates how items are transformed from raw units to solar emergy. Column 1 is the line item number, which is also the number of the footnote found below the table where raw data sources are cited and calculations are shown. Column 2 is the name of the item, which is shown on the systems diagram. Column 3 is the amount of raw data in joules, grams, dollars or other units. Column 4 is the transformity used for calculations, expressed in solar emergy joules per Joule or other appropriate units (sej/h; sej/g; sej/$). Transformity or specific emergy (the emergy per unit mass), are collected to convert raw data into emergy unit. Data on solar transformity are determined from emergy accounting studies which are available in the literature. The reference for each transformity value is shown in column 5. Column 6 is the solar emergy of a given flow, calculated as input times transformity (Column 3 and Column 4). For any commodity or resource, the lower the emergy-per-unit or transformity, the greater the efficiency of the production process.

Table 3-11: Emergy evaluation table for material inflow of concrete sewer pipe

Note	Item	Raw data (unit)	Transformity (sej/unit)	Reference	Solar emergy (sej)
1.1	Cement	1.32E+02 (kg)	3.04E+12	Pulselli et al. (2007)	4.01E+14
1.2	Sand	2.37E+02 (kg)	1.12E+12	Brown and Buranakarn (2003)	2.66E+14
1.3	Water	6.60E+01(kg)	1.95E+09	Odum (1996)	1.29E+11
1.4	Gravel	3.69E+02 (kg)	1.12E+12	Brown and Buranakarn (2003)	4.14E+14

4 RESULTS AND DISCUSSION

As mentioned in previous chapters, this research compares the results of traditional lifecycle approach and emergy-based lifecycle approach (EM-LCA) to select the most sustainable sewer network. The proposed lifecycle approach methodology, presented in the previous chapter, incorporates both the environmental (LCA) and economic impacts (LCC) which has been presented in the previous chapter. Multi-criteria decision-making is performed using AHP. Em-LCA uses results of traditional lifecycle approach but does not perform MCDM. It estimates the lifecycle impacts in emergy values.

4.1 Traditional lifecycle approach

In this study, four types of sewer materials, namely, concrete (CO), polyvinyl chloride (PVC), vitrified clay (VC) and ductile iron (DI) were analyzed based on the traditional lifecycle approach. The results obtained from the environmental (LCA) and economic (LCC) impacts are discussed in the next sections.

4.1.1 Lifecycle assessment (LCA)

Lifecycle assessment (LCA) method is mainly used for studying the total resources needed and the total emissions emitted in the production stage. However, by increasing the scope of LCA, the use phase of production can also be covered. In this study, environmental impacts were evaluated in each stage of the lifecycle. The results are shown in Table 4-1. LCA of sewer construction materials was conducted to find all types of material and energy inflows consumed for their production, manufacture, operation, maintenance and end of life stage.

Table 4-1: LCA for concrete sewer

Assessment criteria	Production	Construction	Operation & maintenance	End of Life
Cement	6.59E+01(kg)	-	6.59E+01(kg)	-
Sand	1.19E+02(kg)	-	1.19E+02(kg)	-
Water	3.30E+01(kg)	-	3.30E+01(kg)	-
Gravel	1.85E+02(kg)	-	1.85E+02(kg)	-
Concrete mixer fuel use				
Diesel	2.64E+08(J)	-	-	-
Electricity	1.13E+08(J)	-	-	-
Pipe manufacture fuel use				
Electricity	6.52E+08(J)	-	-	-
Excavator fuel use	-	1.69E+08(J)	1.69E+08(J)	-
Compactor fuel use	-	1.24E+08(J)	1.24E+08(J)	-
Truck (dump) fuel use	2.11E+08(J)	1.06E+08(J)	5.29E+07(J)	2.11E+07(J)
Machinery				
Concrete mixer	1.81E+04(kg)	-	-	-
Vibrator	3.00E+03(kg)	-	-	-
Excavator	-	6.32E+02(kg)	6.32E+02(kg)	-
Compactor	-	2.10E+01(kg)	2.10E+01(kg)	-
Truck	2.72E+03(kg)	2.72E+03(kg)	2.72E+03(kg)	2.72E+03(kg)
Landfilling	-	-	-	4.02E+02(kg)
CO_2 emission	3.90E+01(kg)	7.98E+00(kg)	5.87E+00(kg)	4.91E+00(kg)
NOx emission impact	2.71E-01(kg)	5.54E-02(kg)	4.07E-02(kg)	3.41E-02(kg)
SOx emission impact	9.81E-01(kg)	2.01E-01(kg)	1.48E-01(kg)	1.23E-01(kg)

Environmental impacts associated with sewer materials were determined through lifecycle inventory analysis. The impacts were calculated for every stage of lifecycle which are given below:

Resource use

Figure 4-1 illustrates the resources used for different sewer materials over different lifecycle stages. In this category, the main contributing phases are manufacturing and operational stage. Concrete pipe has the higher resource use rate which is about 25000 kg. Vitrified clay pipe consumed more resource than PVC and DI pipe.

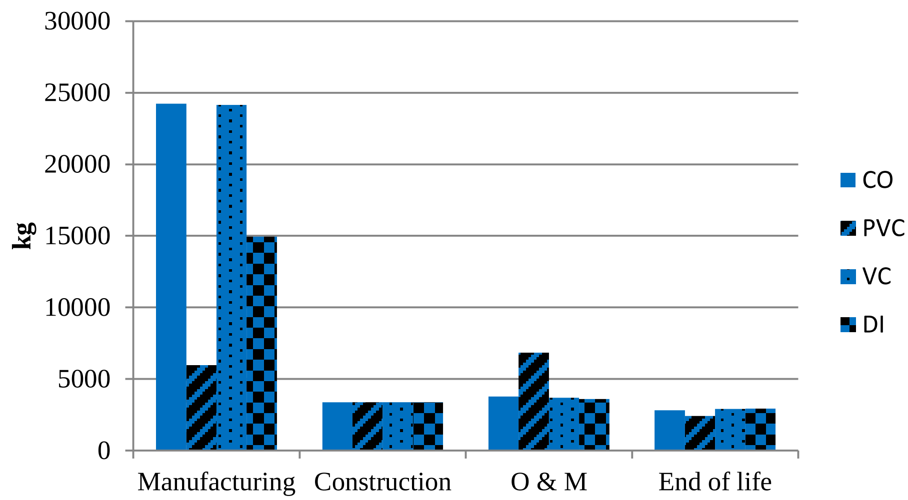

Figure 4-1: Resource use for different sewer pipes

Energy consumption

Energy consumption includes all energy, direct and indirect, used to transform or transport raw materials into products. Energy consumption is reported as Giga joules (GJ). Figure 4-2 shows the energy consumption over life cycle stages of the four selected types of sewer systems. As shown in the figure, most energy was consumed in the manufacturing stage. DI pipe has the highest energy consumption rate (10.52 GJ) than all other pipes as more energy is consumed to manufacture and recycle it. Concrete pipe consumed the lowest energy (2.01GJ) among all the pipes.

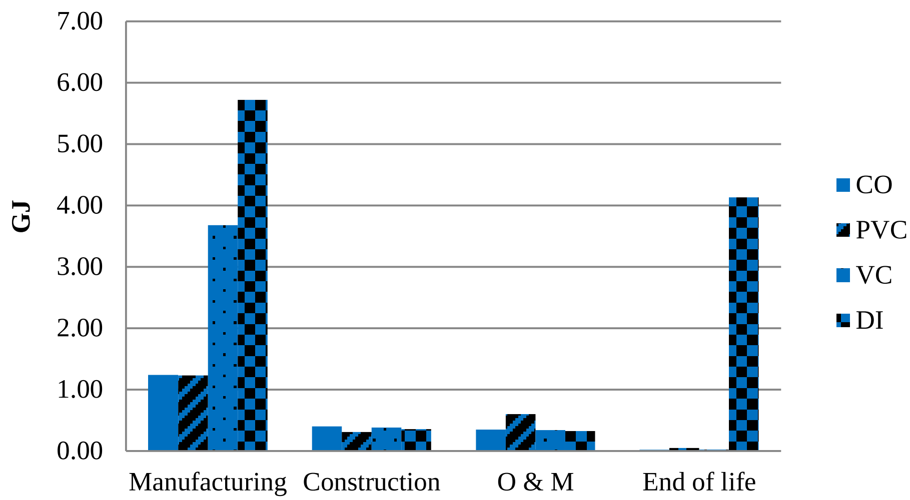

Figure 4-2: Energy consumption for different sewer pipes

Global warming potential

Global warming potential (GWP) can be expressed as an equivalent to carbon dioxide – in kg or tonnes CO_2 equivalent. Carbon dioxide is the reference standard for global warming or greenhouse gas effects. All other greenhouse gases are referred to as having a "CO_2 equivalence effect" which is simply a multiple of the greenhouse potential of carbon dioxide. It can be seen from the LCA that DI pipe emits more CO_2 in the manufacturing stage. The total emission of CO_2 of DI pipe is 241 kg CO_2 eq. For PVC, VC and CO pipe this number is 53, 195 and 57 kg CO_2 eq respectively.

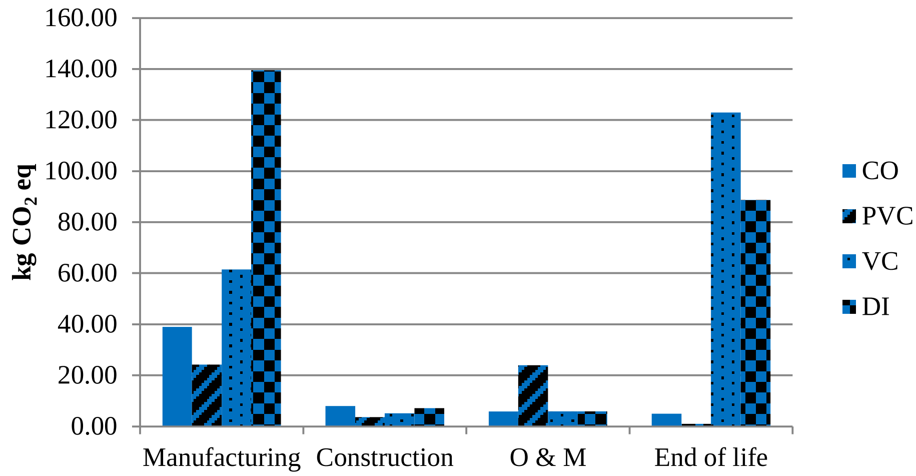

Figure 4-3: Global warming potential for different sewer pipes

Acidification

Acidification is more regional rather than global impact affecting human health when high concentrations of NOx and SOx are released. Acidification potential (AP) is represented by the group of substance mainly SOx. The functional unit can be taken as SO_2 emitted per unit construction product or process. However, it can be seen that the NOx and SOx emissions are negligible as compared to CO_2 emissions. Concrete pipe emits only about 1 kg of SOx where the emission of CO_2 is about 57 kg. However, major portion of SOx is emitted by DI pipe in its manufacturing stage. For the end of life stage, VC pipe emits more SOx than all other pipes. Figure 4-4 shows the acidification potential of different pipes.

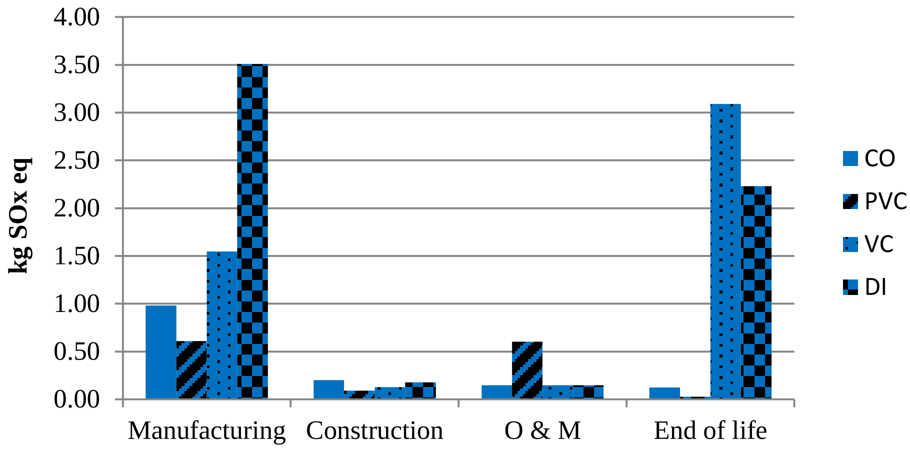

Figure 4-4: Acidification potential for different sewer pipes

Smog potential

Smog potential agents are generally very corrosive. The common functional unit is the amount of NOx emitted per unit of construction process. DI pipe emits more NOx than all other pipes. Most of the NOx is emitted in the manufacturing stage. PVC pipe emits more NOx in the operation and maintenance stage and VC pipe emits more NOx in the end of life stage.

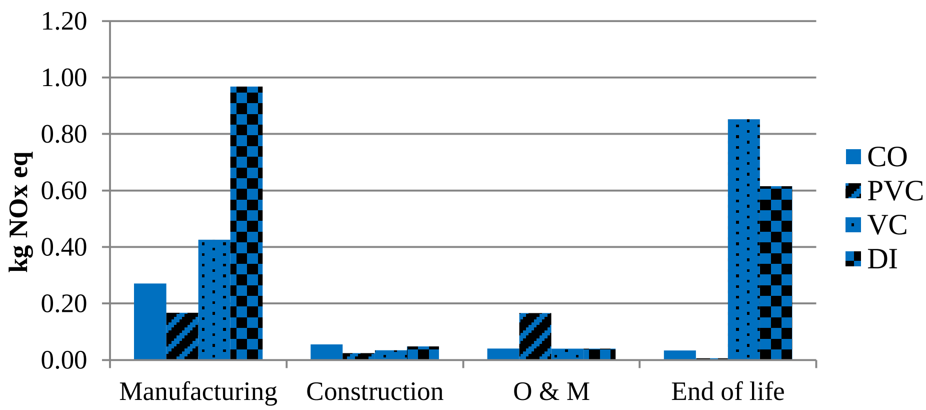

Figure 4-5: Smog potential for different sewer pipes

Table 4-2: Environmental impacts of sewer pipe

	Manufacturing					Construction					O & M					End of Life				
	Resource use , kg	Energy consumption, GJ	Global warming potential , kg CO2 eq	Acidification, kg SOx eq	Smog potential, kg NOx eq	Resource use, kg	Energy consumption, GJ	Global warming potential , kg CO2 eq	Acidification, kg SOx eq	Smog potential, kg NOx eq	Resource use, kg	Energy consumption, GJ	Global warming potential, kg CO2 eq	Acidification, kg SOx eq	Smog potential, kg NOx eq	Resource use, kg	Energy consumption, GJ	Global warming potential, kg CO2 eq	Acidification, kg SOx eq	Smog potential, kg NOx eq
CO	24224.3	1.24	39.02	0.98	0.27	3375	0.40	7.98	0.20	0.06	3777	0.35	5.87	0.15	0.04	2822	0.02	4.91	0.12	0.03
PVC	5966	1.23	24.19	0.61	0.17	3375	0.30	3.62	0.09	0.03	6838	0.60	23.92	0.60	0.17	2422	0.05	0.98	0.02	0.01
VC	24136	3.68	61.46	1.55	0.43	3375	0.38	5.04	0.13	0.03	3689	0.33	5.87	0.15	0.04	2904	0.02	122.94	3.09	0.85
DI	14949	5.72	139.50	3.51	0.97	3375	0.35	7.06	0.18	0.05	3602	0.32	5.87	0.15	0.04	2923	4.13	88.73	2.23	0.62

4.2 Lifecycle costing (LCC)

In a sewer lifecycle, there are several costs (initial, maintenance, repair, replacement and end of life cost, etc.) involved during the service period. These costs should be considered to calculate the expected lifecycle cost. LCC method converts all the costs to present values by discounting them to a common time, usually the base date. In this study, future costs for repair, maintenance, replacement and end of life cost are calculated based on the predicted service life of the different pipes (as shown in Figure 3-3). Present worth (PW) annuity method is used to calculate the lifecycle costing. Costs data are acquired from different sources and published literatures which are discussed earlier in chapter 3. Table 4-3 shows the calculation of LCC of DI pipe where future costs are presented in the present worth method and cost data are obtained from Table 3-9.

Table 4-3: LCC calculations for DI pipe

Description and calculation		**$**
Initial cost		1374.18
Maintenance cost		
Root (chemical treatment)		64.51
Sludge maintenance (rodding)	$PW = A \cdot \frac{(1+i)^n - 1}{i(1+i)^n}$	41.72
Grease (pressurized cleaning/jetting)		20.50
Debris (flushing)		21.11
Repair cost		137.42
Replacement cost	$PW = \frac{F}{(1+i)^n}$	46.28
End of Life cost	$PW = \frac{F}{(1+i)^n}$	8.09
Total cost (CAD)		1697.63

The total lifecycle cost was calculated by adding all the costs. The total costs of different pipes are summarized in Figure 4-6. DI pipe is found to be the most expensive pipe material considering the whole lifecycle. The total lifecycle cost of three meter ductile iron pipe is $1698, where the total cost of CO, PVC and VC pipes are $1129, $1551and $1513 respectively.

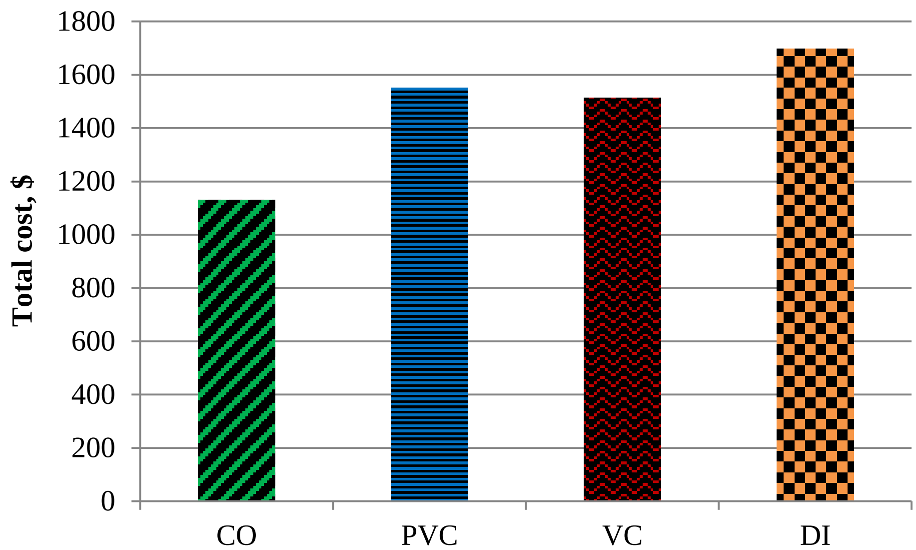

Figure 4-6: Total lifecycle costing for various pipes

4.3 Results from traditional lifecycle approach

In this study, analytical hierarchy process was used as a decision-making tool to assess and aggregate cumulative impacts of selected sewer pipes. The impacts that have been estimated in previous steps are classified as general categories, and (sub) criteria have been hierarchically structured and developed. The goal of the study is defined at the first level. In the second level, environmental and economic factors are considered. Each of these main criteria is subdivided into sub-criteria. Applying pair-wise comparison matrices, the relative importance weight can be assigned to each (sub) criterion. In this research equal weights have been assumed for main environmental and economic factors.

Different pipe alternatives have varying degrees of impacts with respect to different (sub) criteria. Therefore, the preference weight is assigned to each alternative with respect to the lowest level sub-criteria (as discussed in section 3.2). For those sub-criteria that related impacts have been quantified from LCA (e.g., global warming, energy consumption), preference weight has been assigned by normalizing absolute impact values (smaller the expected impact, bigger the weight will be assigned).

After computing the normalized priority weights for each pair-wise comparison of the AHP hierarchy, the next phase is to synthesize the rating for each criterion. The normalized priority weights of sub criteria are combined together in order to obtain the final weights of all the alternatives used in the third level of the AHP model. Table 4-4 shows the overall weights of the four sewer pipes. Finally, the ranking of alternatives is conducted and the impacts of various (sub) criteria are assessed and aggregated as a single measure.

Table 4-4: Overall weights of the four sewer pipes using AHP-based 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						**0.28**	**0.27**	**0.19**	**0.22**

As shown in Table 4-4, the sewer pipes are ranked according to their overall priorities. Concrete pipe turns out to be the most preferable material among the three materials, with an overall priority weight of 0.28. The weights of different pipes are shown in Figure 4-7.

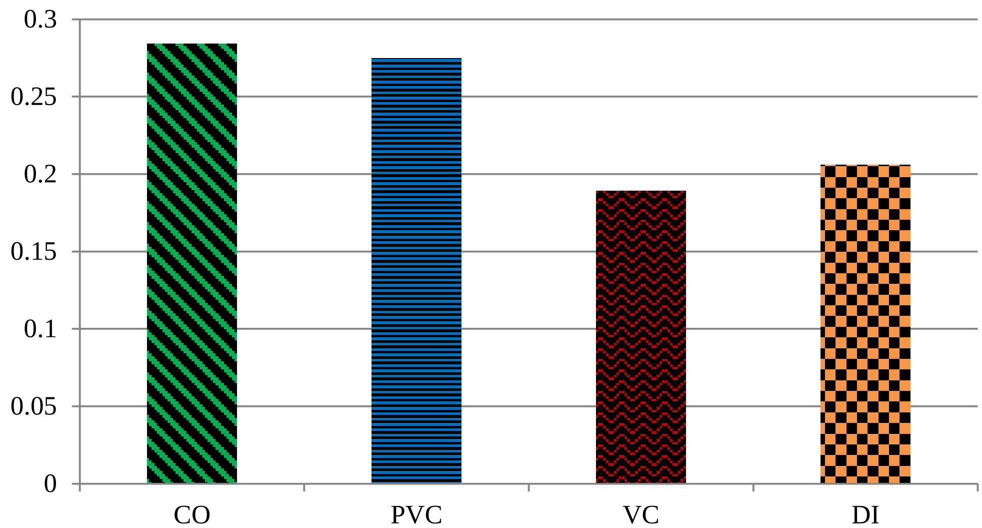

Figure 4-7: Relative weights based on environment and economic criteria

The assignment of relative importance involves human subjectivity. To counter this bias, a sensitivity analysis must be conducted, in which different weighting schemes can be applied to re-evaluate each alternative. In this research, the analysis is repeated further in two trials. In the first trial, environmental impact is given priority and the weight is assumed as 1. In the second trial, economic impact was assumed most important than the other criteria and the weight is assumed as 1. The weighting schemes for the three trials for each alternative has been summarized in Table 4-5 and graphically indicated in Figure 4-8.

Table 4-5: Different trials for sewer alternatives

	First trial		Second trial		Third trial	
	Env	Eco	Env	Eco	Env	Eco
Weights	0.5	0.5	1.0	0	0	1.0
CO	0.28		0.35		0.18	
PVC	0.27		0.39		0.15	
VC	0.18		0.14		0.27	
DI	0.20		0.10		0.16	

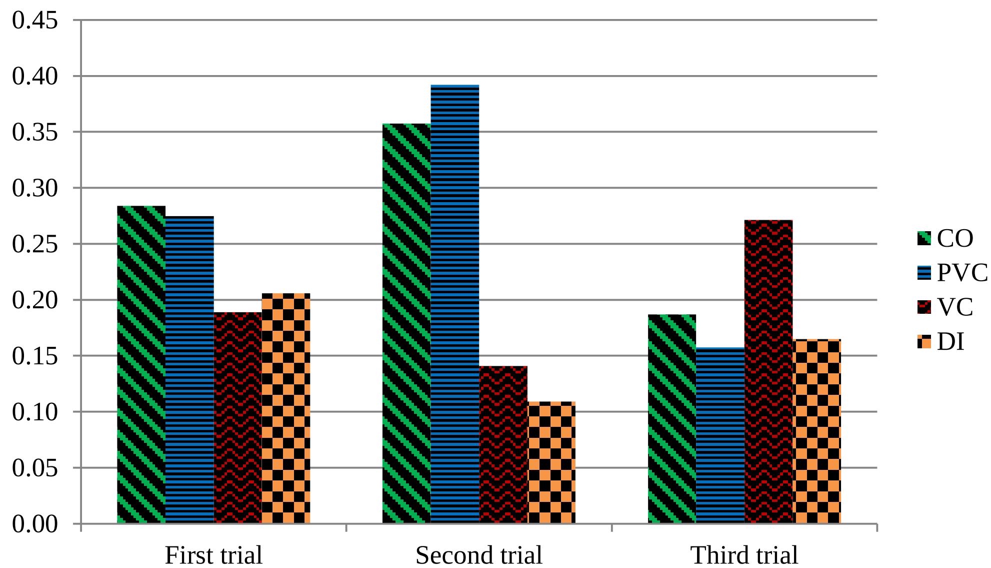

Figure 4-8: Relative weights of different sewer alternatives in different trials

The results show that CO pipe is most preferable in the first trial, while for the second and third trials, PVC and VC pipe show the best performance. In traditional lifecycle approach, comparison of different criteria built on human subjectivity which includes uncertainty. Making comparison between different criteria is the most controversial challenge in AHP analysis. There is no widely agreed method to determine the relative importance of different impacts. Therefore, the emergy accounting method has been proposed and explored to reduce the multi-criteria dilemma to a single criterion model, which gives more reliable results.

4.4 Emergy-based lifecycle approach

Emergy analysis was applied for assessing energy and material inflows to every stage of the lifecycle for selected sewer pipes. Materials and energy inflows were calculated from LCA inputs and emission were calculated from LCA outputs. The machinery and total costs were also calculated as emergy inflows. Specific emergy values for every pipe materials were calculated using emergy transformity values obtained from the literature. Results were divided into the following five sections:

(1) emergy for material use
(2) energy consumption
(3) machinery
(4) service or cost and
(5) emissions

The analysis was performed based on the sewer's life-span. Tables 4-6 to 4-9 show the sample emergy calculation for different pipe material.

Table 4-6: Emergy calculations for concrete sewer pipe

Item	Input	Unit	Specific Emergy (sej/unit)	Reference	Emergy (sej)
Material					
Cement	1.32E+02	kg	3.04E+12	Odum (1992)	4.01E+14
Sand	2.37E+02	kg	1.12E+12	Odum (1992)	2.66E+14
Water	6.60E+01	kg	1.95E+09	Odum (1996)	1.29E+11
Gravel	3.69E+02	kg	1.12E+12	Buranakarn (1998)	4.14E+14
Energy					
Concrete mixer fuel use	2.64E+08	J	1.13E+05	Ulgiati et al. (1994)	2.98E+13
Electricity	7.65E+08	J	2.00E+05	Odum (2000)	1.53E+14
Excavator fuel use	3.38E+08	J	1.13E+05	Ulgiati et al. (1994)	3.82E+13
Compactor fuel use	2.48E+08	J	1.13E+05	Ulgiati et al. (1994)	2.80E+13
Demolition fuel use	2.46E+08	J	1.13E+05	Ulgiati et al. (1994)	2.78E+13
Truck (dump) fuel use	3.91E+08	J	1.13E+05	Ulgiati et al. (1994)	4.42E+13
Machinery					
Concrete mixer	1.81E+03	kg	1.12E+13	Luchi and Ulgiat (2000)	2.03E+16
Vibrator	3.00E+03	kg	1.12E+13	Luchi and Ulgiat (2000)	3.36E+16
Excavator	1.26E+03	kg	1.12E+13	Luchi and Ulgiat (2000)	1.41E+16
Compactor	4.20E+01	kg	1.12E+13	Luchi and Ulgiat (2000)	4.70E+14
Truck	2.72E+03	kg	1.07E+13	Luchi and Ulgiat (2000)	2.91E+16
Service					
Initial cost	863.7	$	2.6E+12	Bastianoni et al. (2005)	2.25E+15
Maintenance cost	147.87	$	2.6E+12	Bastianoni et al. (2005)	2.26E+14
Repair cost	86.37	$	2.6E+12	Bastianoni et al. (2005)	2.25E+14
Replacement cost	32.88	$	2.6E+12	Bastianoni et al. (2005)	7.45E+12
Landfilling	4.02E+02	kg	1.97E+10	Pulselli et al. (2007)	7.92E+12
Climate change					
Global warming potential	5.52E+01	kg	2.52E+08	Pulselli et al. (2007)	1.39E+10
NOx emission	3.91E-01	kg	1.66E+12	Bakshi (2001)	6.49E+11
SOx emission	1.39E+00	kg	3.03E+11	Bakshi (2001)	4.21E+11

Table 4-7: Emergy calculations for PVC sewer pipe

Item	Input	Unit	Specific Emergy (sej/unit)	Reference	Emergy (sej)
Material					
Cement	1.32E+02	kg	3.04E+12	Odum (1992)	4.01E+14
Sand	2.37E+02	kg	1.12E+12	Odum (1992)	2.66E+14
Water	6.60E+01	kg	1.95E+09	Odum (1996)	1.29E+11
Gravel	3.69E+02	kg	1.12E+12	Buranakarn (1998)	4.14E+14
Energy					
Concrete mixer fuel use	2.64E+08	J	1.13E+05	Ulgiati et al. (1994)	2.98E+13
Electricity	7.65E+08	J	2.00E+05	Odum (2000)	1.53E+14
Excavator fuel use	3.38E+08	J	1.13E+05	Ulgiati et al. (1994)	3.82E+13
Compactor fuel use	2.48E+08	J	1.13E+05	Ulgiati et al. (1994)	2.80E+13
Demolition fuel use	2.46E+08	J	1.13E+05	Ulgiati et al. (1994)	2.78E+13
Truck (dump) fuel use	3.91E+08	J	1.13E+05	Ulgiati et al. (1994)	4.42E+13
Machinery					
Concrete mixer	1.81E+03	kg	1.12E+13	Luchi and Ulgiat (2000)	2.03E+16
Vibrator	3.00E+03	kg	1.12E+13	Luchi and Ulgiat (2000)	3.36E+16
Excavator	1.26E+03	kg	1.12E+13	Luchi and Ulgiat (2000)	1.41E+16
Compactor	4.20E+01	kg	1.12E+13	Luchi and Ulgiat (2000)	4.70E+14
Truck	2.72E+03	kg	1.07E+13	Luchi and Ulgiat (2000)	2.91E+16
Service					
Initial cost	1128.12	$	2.6E+12	Bastianoni et al. (2005)	2.25E+15
Maintenance cost	147.87	$	2.6E+12	Bastianoni et al. (2005)	2.26E+14
Repair cost	112.81	$	2.6E+12	Bastianoni et al. (2005)	2.25E+14
Replacement cost	179.45	$	2.6E+12	Bastianoni et al. (2005)	7.45E+12
Landfilling	4.02E+02	kg	1.97E+10	Pulselli et al. (2007)	7.92E+12
Climate change					
Global warming potential	5.52E+01	kg	2.52E+08	Pulselli et al. (2007)	1.39E+10
NOx emission	3.91E-01	kg	1.66E+12	Bakshi (2001)	6.49E+11
SOx emission	1.39E+00	kg	3.03E+11	Bakshi (2001)	4.21E+11

Table 4-8: Emergy calculations for VC sewer pipe

Item	Input	Unit	Specific Emergy (sej/unit)	Reference	Emergy (sej)
Material					
Clay	5.88E+02	kg	1.96E+12	Odum (1992)	1.15E+15
Barium	2.64E+01	kg	1.68E+12	Buranakarn (1998)	4.43E+13
Calcite	1.38E+01	kg	1.95E+09	Odum (1996)	2.70E+10
Energy					
Diesel	2.21E+09	J	1.13E+05	Ulgiati et al. (1994)	2.49E+14
Electricity	6.52E+08	J	2.00E+05	Ulgiati et al. (1994)	1.30E+14
Excavator fuel use	3.39E+08	J	1.13E+05	Odum (2000)	3.83E+13
Compactor fuel use	2.48E+08	J	1.13E+05	Ulgiati et al. (1994)	2.80E+13
Truck (dump) fuel use	3.06E+08	J	1.13E+05	Ulgiati et al. (1994)	3.45E+13
Recycling fuel (Electricity)	5.69E+09	J	2.00E+05	Ulgiati et al. (1994)	1.14E+15
Machinery					
Vibrator	3.00E+03	kg	1.12E+13	Luchi and Ulgiat (2000)	3.36E+16
Excavator	1.26E+03	kg	1.12E+13	Luchi and Ulgiat (2000)	1.41E+16
Compactor	4.20E+01	kg	1.12E+13	Luchi and Ulgiat (2000)	4.70E+14
Truck	2.72E+03	kg	1.12E+13	Luchi and Ulgiat (2000)	3.05E+16
Service					
Initial cost	1215.75	$	2.6E+12	Bastianoni et al. (2005)	3.16E+15
Maintenance cost	147.87	$	2.6E+12	Bastianoni et al. (2005)	2.26E+14
Repair cost	121.58	$	2.6E+12	Bastianoni et al. (2005)	3.16E+14
Replacement cost	26.12	$	2.6E+12	Bastianoni et al. (2005)	8.50E+12
Climate change					
Global warming potential	1.95E+02	kg	2.52E+08	Pulselli et al. (2007)	4.92E+10
NOx emission	1.36E+00	kg	1.66E+12	Bakshi (2001)	2.25E+12
SOx emission	4.91E+00	kg	3.03E+11	Bakshi (2001)	1.49E+12

Table 4-9: Emergy calculations for DI sewer pipe

Item	Input	Unit	Specific Emergy (sej/unit)	Reference	Emergy (sej)
Material					
Cast iron	4.25E+02	kg	4.15E+12	Odum (1992)	1.76E+15
Carbon	1.54E+01	kg	1.68E+12	Buranakarn (1998)	2.59E+13
Silicon	1.27E+01	kg	1.95E+12	Odum (1996)	2.47E+13
Energy					
Coal	5.03E+09	J	4.00E+04	Ulgiati et al. (1994)	2.01E+14
Electricity	5.74E+08	J	2.00E+05	Odum (2000)	1.15E+14
Excavator fuel use	3.38E+08	J	1.13E+05	Ulgiati et al. (1994)	3.82E+13
Compactor fuel use	2.48E+08	J	1.13E+05	Ulgiati et al. (1994)	2.80E+13
Truck (dump) fuel use	3.91E+08	J	1.13E+05	Ulgiati et al. (1994)	4.42E+13
Recycling fuel (Electricity)	3.98E+09		2.00E+05	Odum (2000)	7.96E+14
Disposal fuel (Diesel)	1.38E+08	J	1.13E+05	Ulgiati et al. (1994)	1.56E+13
Machinery					
Centrifugal casting machine	1.20E+04	kg	1.12E+13	Luchi and Ulgiat (2000)	1.34E+17
Excavator	1.26E+03	kg	1.12E+13	Luchi and Ulgiat (2000)	1.42E+16
Compactor	4.20E+01	kg	1.12E+13	Luchi and Ulgiat (2000)	4.70E+14
Truck	2.72E+03	kg	1.12E+13	Luchi and Ulgiat (2000)	3.05E+16
Service					
Initial cost	1374.18	$	2.6E+12	Bastianoni et al. (2005)	3.57E+15
Maintenance cost	147.84	$	2.6E+12	Bastianoni et al. (2005)	2.26E+14
Repair cost	137.42	$	2.6E+12	Bastianoni et al. (2005)	3.57E+14
Replacement cost	46.28	$	2.6E+12	Bastianoni et al. (2005)	5.15E+12
Landfilling	6.22E+00	kg	1.97E+10	Pulselli et al. (2007)	1.23E+11
Climate change					
Global warming potential	2.41E+02	kg	2.52E+08	Pulselli et al. (2007)	6.08E+10
NOx emission	1.67E+00	kg	1.66E+12	Bakshi (2001)	2.78E+12
SOx emission	6.06E+00	kg	3.03E+11	Bakshi (2001)	1.84E+12

Results of the analysis show that the specific emergy of three meter concrete pipe is 8.97E+16 sej. The specific emergy of polyvinyl chloride, vitrified clay and ductile iron pipe is 8.33E+16, 8.52E+16 and 9.07E+16 sej respectively. The lower value of emergy means lower energy was required to produce the product. Comparing specific emergy of these four pipe materials, PVC with specific emergy of 8.33E+16 sej is a sustainable option among all the sewer pipes. Production of PVC does not only require less material and energy, but it also has lower environmental emission than all other pipes. The specific emergy of ductile iron pipe is greater than all other pipes. This indicates overall greater energy and material is consumed by this pipe and therefore it has greater environmental impacts.

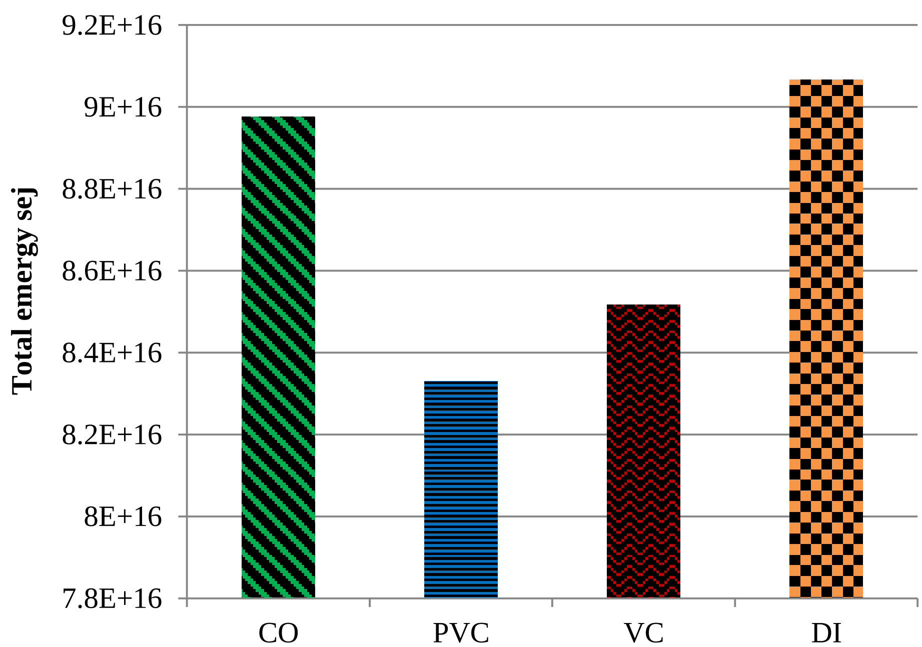

Figure 4-9: Total emergy of various pipes

4.5 Uncertainty analysis emergy accounting

A reliable uncertainty modeling is an integral part of any environmental accounting tools. Uncertainty is present at the inventory level and for the unit emergy values (transformity values) used to convert that data into emergy. Uncertainty modeling helps to perform realistic emergy analysis, achieves reliable output results and characterizes different sources of uncertainties. Different components of uncertainty in a model must be combined to estimate total uncertainty in the result. In multiple parameter models, such as emergy formula models, each parameter has its own characteristic uncertainty. These uncertainties may originate from uncertainty in model parameters, data parameters and scenario parameters.

Uncertainty data for both direct inputs and transformity values (existing and original) are included in the life cycle model. In this study, data uncertainties generated from the transformity values are analysed. The transformity values of different items of different sewer materials are generated from various literature sources which are given in Table 4-10. The data used for the transformity value has fuzziness and vagueness. To quantify the uncertainty, a fuzzy based approach is used. The most common transformity value is assumed as the most likely value in uncertainty modeling. In this study, the data parameter required for the uncertainty modeling can be grouped into three categories: resource use, energy consumption and emissions. The uncertainties in the transformity values of each data parameter are shown in Table 4-11.

Table 4-10: Sources of uncertainty in transformity values

Item	Input parameter	Unit	Transformity values	Sources
Cement	3.04E+12	kg	1.98E+12	Pulselli et al. (2007)
		kg	3.04E+12	Odum et al. (2000)
		kg	3.48E+12	Brown and Buranakarn (2003)
Sand	1.12E+12	kg	1.00E+12	Buranakarn (1998)
		kg	1.12E+12	Odum et al. (2000)
		kg	1.68E+12	Bastianoni et al. (2005)
Clay	1.96E+12	kg	1.68E+12	Odum (1996)
		kg	1.96E+12	Buranakarn (1998)
		kg	2.00E+12	Brown and Buranakarn (2003)
Plastic	5.87E+12	kg	5.76E+12	Buranakarn (1998)
		kg	5.87E+12	Odum et al. (2000)
		kg	9.83E+12	Brown and Buranakarn (2003)
Cast iron	4.15E+12	kg	1.32E+12	Odum, (1996, 2000)
		kg	4.15E+12	Buranakarn (1998)
		kg	4.75E+12	Brown and Buranakarn (2003)
Calcium carbonate	1.12E+12	kg	1.00E+12	Buranakarn (1998)
		kg	1.12E+12	Odum et al. (2000)
		kg	1.68E+12	Bastianoni et al. (2005)
Coal	4.00E+04	kg	3.92E+04	Brown and Buranakarn (2003)
		kg	4.00E+04	Odum (1996, 2000)
		kg	6.72E+04	Brown and Bardi (2001)
Water	1.95E+09	kg	1.25E+09	Brandt-Williams (2002)
		kg	1.95E+09	Tiezzi (2001)
		kg	2.03E+09	Almeida et al. (2010)
Gravel	1.12E+12	kg	1.00E+12	Buranakarn (1998)
		kg	1.12E+12	Odum (1996, 2000)
		kg	1.68E+12	Nelson et al. (2001)
Electricity	2.00E+05	J	1.74E+05	Odum (1996, 2000)
		J	2.00E+05	Brandt-Williams (2002)
		J	2.69E+05	Nelson et al. (2001)
Truck	1.07E+13	kg	1.00E+13	Buranakarn (1998)
		kg	1.07E+13	Brandt-Williams (2002)
		kg	1.12E+13	Zhou et al. (2007)
Global warming	2.52E+08	kg	1.44E+08	Bakshi (2001)
		kg	2.52E+08	Tiezzi (2001)
		kg	6.44E+08	Nelson et al. (2001)
NOx Emission	1.66E+12	kg	1.38E+12	Tiezzi (2001)
		kg	1.66E+12	Bakshi (2001)
		kg	1.94E+12	Nelson et al. (2001)

Table 4-11: Input parameters for concrete sewer

Item	Input	Transformity(sej/unit)		
		L	M	H
Cement	1.32E+02	1.98E+12	3.04E+12	3.48E+12
Sand	2.37E+02	1.00E+12	1.12E+12	1.68E+12
Water	6.60E+01	1.25E+09	1.95E+09	2.03E+09
Gravel	3.69E+02	1E+12	1.12E+12	1.68E+12
Concrete mixer fuel use	2.64E+08	1.13E+05	1.13E+05	1.13E+05
Excavator fuel use	3.38E+08	1.13E+05	1.13E+05	1.13E+05
Compactor fuel use	2.48E+08	1.13E+05	1.13E+05	1.13E+05
Demolition fuel use	2.46E+08	1.13E+05	1.13E+05	1.13E+05
Electricity	7.65E+08	1.74E+05	2.00E+05	2.69E+05
Concrete mixer	1.81E+03	1.12E+13	1.12E+13	1.12E+13
Vibrator	3.00E+03	1.12E+13	1.12E+13	1.12E+13
Excavator	1.26E+03	1.12E+13	1.12E+13	1.12E+13
Compactor	4.20E+01	1.12E+13	1.12E+13	1.12E+13
Truck	2.72E+03	1.00E+13	1.07E+13	1.12E+13
Total Cost	1.13E+03	2.60E+12	2.60E+12	2.60E+12
Global warming potential	5.52E+01	1.44E+08	2.52E+08	6.44E+08
NOx Emission	3.91E-01	1.38E+12	1.66E+12	1.94E+12
SOx Emission	1.39E+00	3.03E+11	3.03E+11	3.03E+11

To fully characterize uncertainty for transformity or unit emergy values, the sources of uncertainty need to be identified and quantified. In practice, describing the uncertainty in parameters, scenarios and models requires significant effort and must draw from previous applications of various models and across various scenarios. In this study, the data sufficient to characterize scenarios and models of uncertainty for each transformity value was not readily available and as a result only data uncertainty in sources of transformity values were analysed (as shown in Figure 4-10).

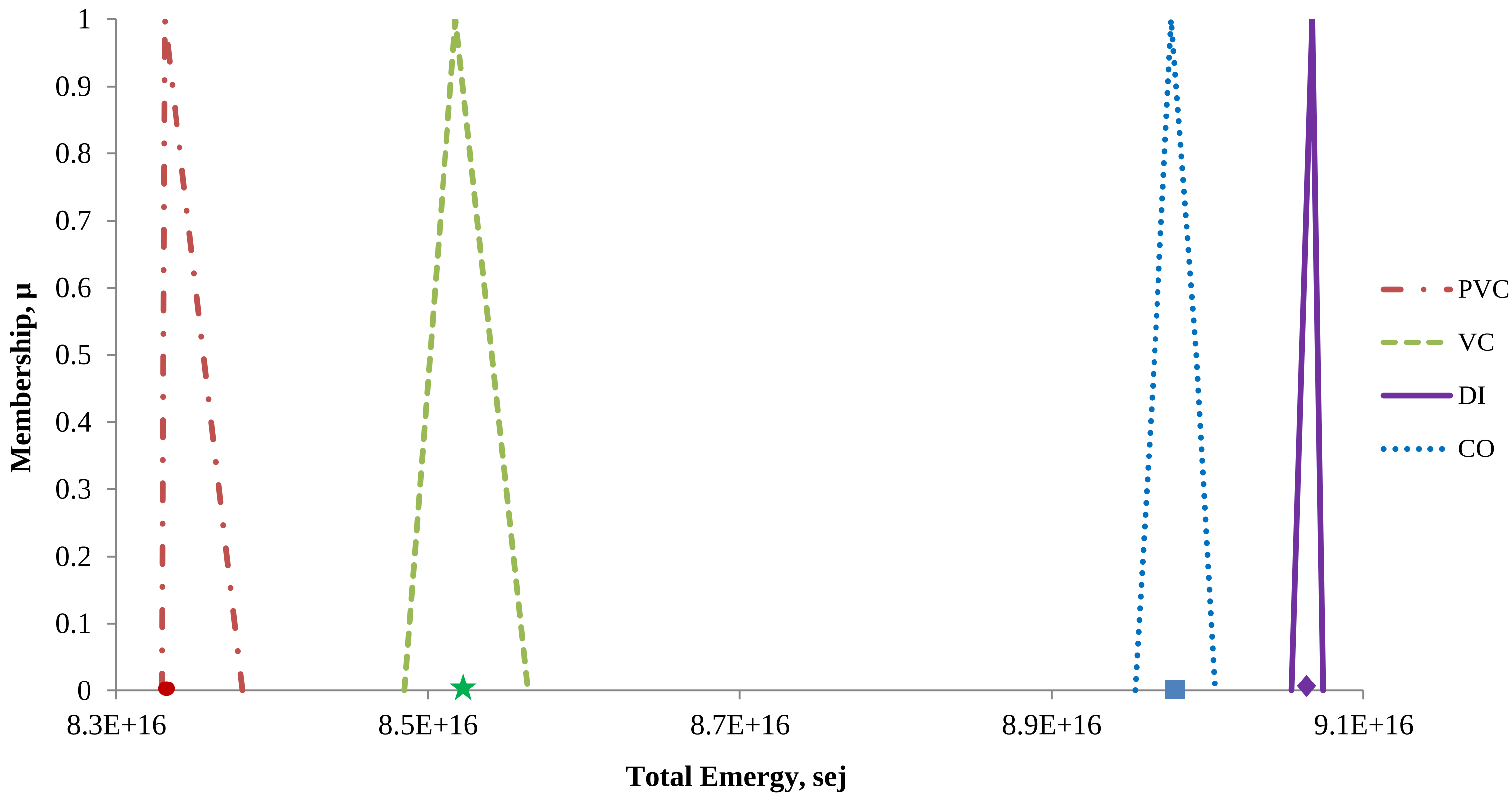

Figure 4-10: Membership function of total emergy of various pipes

■ Most likely value of CO

● Most likely value of PVC

★ Most likely value of VC

◆ Most likely value of DI

The membership functions of total emergy of different pipe materials are presented in Figure 4-10. The supports (i.e., membership at zero) of a fuzzy number show the possible ranges of total emrgy. The total emergy at membership equal to one (i.e., the full membership) shows the most likely values of total emergy. For α-cut 0, the lower and upper bound range of total emergy of CO, PVC, VC and DI sewer is [8.95E+16, 9.0E+16], [8.33E+16, 8.35E+16], [8.48E+16, 8.56E+16], and [9.05E+16, 9.07E+16], respectively. The lower and upper bounds of α-cut 0 provide a probability level of total emergy value occurs. The values outside of this range are not a member of fuzzy number. The most likely values of total emergy of CO, PVC, VC and DI pipes are 8.97E+16, 8.33E+16, 8.52E+16 and 9.07E+16 sej respectively which are also the deterministic results of these pipes. The support of a fuzzy number provides a range of uncertainty. In Figures 4-10, the supports of membership (i.e., uncertainty band) increase as the emergy level increase from PVC to DI pipe. The result shows that the deterministic result of total emergy of various sewer systems lies between the higher and lower value of total emergy. This result proves that the deterministic result of total energy is reliable considering the uncertainties. At α-cut 0, α-cut 0.5 and α-cut 1, the most likely value is the same for all the sewer pipes. Therefore, in all cases, the preference of sewer pipe is PVC, VC, CO and DI respectively.

4.6 Comparison of traditional lifecycle and EM-LCA approaches

In traditional lifecycle approach, multi criteria decision making technique (AHP) is widely used to aggregate the various lifecycle impacts. AHP-based lifecycle approach assists decision-makers to find suitable alternatives among available options and promises a more sustainable product or process. However, there are some limitations to develop the AHP-based LCA model. In some cases, decision making based on AHP technique can cause confusion and does not deal effectively with redundancy of selected criteria. The comparison of different criteria is built based on human subjectivity which includes uncertainty. As a result, alternatives show different results in different weighting schemes. It is a great challenge to make comparisons in AHP based LCA model. There is no widely agreed method to determine the relative importance of different impacts.

Analysis of emergy-based lifecycle approach method shows that, PVC pipe is the most suitable sewer material considering all the lifecycle impacts. However, in traditional lifecycle approach, different pipe materials show better performance in different sensitivity trials as it is biased with relative importance. Em–LCA accounts for all the lifecycle inflows and outflows through a single emergy unit. As a result, the comparison of all the alternatives is measured in a common unit, which overcomes the multi-criteria dilemma.

From emergy-based lifecycle approach results, it can be seen that almost 90% flows come from material use, energy consumption and emissions. This result proves that environmental impacts have 90% contribution towards total sustainability impacts, whereas economic flows make only around 10% of the total impacts. There are many socio-economic impacts such as (traffic disruption, loss of environment due to noise, vibration, air pollution) which were not considered in the study. Otherwise, considering this cost, the total economic cost would have a great impact in the lifecycle results.

In AHP-based lifecycle approach, relative importance of different sustainability criteria were assigned qualitatively as discussed in earlier section. However, weights can be derived based on emergy results. Emergy-based lifecycle approach traces energy inputs back further into the lifecycle and provide a much wider range of directly usable information. Therefore the EM-LCA provides comparatively more reliable results and helps to directly compare economic and environmental flows which can also be used in assigning weights for AHP-based method.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and conclusions

Sewer systems are an integral part of the buried infrastructure. The main purpose of sewer networks is to convey waste and stormwater from houses, roads and other sources, to wastewater treatment plants and points of disposal. Sewer systems ensure better public health, protect natural water bodies from pollution, and provide protection against flooding. Apart from their important role in the well-being of cities and other urban centers, sewer networks are also highly capital intensive. Moreover, many sewer networks in Canada are very old and undergoing aging and deterioration. The process of deterioration undermines the structural integrity of the sewer pipes, which results in failure and collapse of the system, requiring costly emergency repair works. Quantitative assessment of sustainability for infrastructure systems is of great importance. This research explored emergy-based lifecycle approach for investigating various design alternatives of sewer network systems in order to find more sustainable and reliable sewer pipe.

A comprehensive literature review has been performed on various aspects of this interdisciplinary research, which included lifecycle assessment, (LCA) (e.g., resource use, energy consumption,), lifecycle costing (LCC), multi-criteria decision making (e.g., AHP-based method) and emergy accounting method. In this research, lifecycle of common sewer materials in Canada were studied and their specific emergies were calculated using transformity functions. Analytical hierarchy process was also used to calculate the environmental and economic impacts of different pipe materials and results were compared. The results indicated that the emergy-based lifecycle approach proves to be very useful, and has provided a much wider range of directly usable information when compared to traditional lifecycle approach.

The analysis was performed in four steps. In the first step, environmental loads and economic factors on various sewer pipes were estimated considering the whole lifecycle. Lifecycle analysis (LCA) and lifecycle costing (LCC) methods were used for this purpose. In the second step, AHP-based method was used to aggregate the lifecycle impacts. The third step estimated the total emergy of the sewer materials using lifecycle inputs and outputs. Finally, the results of emergy-based lifecycle approach and traditional lifecycle approach were compared in the fourth step. The major outcomes of this research are as follows:

- This research used a cradle-to-cradle lifecycle approach for sewer pipes in the quantitative assessment of sustainability.
- In traditional lifecycle approach, CO pipe was found to be a more sustainable sewer pipe when the weights of the main sustainability criteria (environmental and economic) were assigned as equal. PVC and VC pipes showed best performance if the weights of the criteria differed.
- PVC pipe posed less lifecycle environmental impacts due to resource use, global warming, acidification, and smog potential. Based on emergy-based lifecycle approach, PVC pipe was found to be more sustainable sewer pipe, followed by VC, CO and DI pipe shows better performance respectively.
- Proposed emergy-based lifecycle approach has the potential to guide environmental policy decisions such as resource allocation and capital investment for effective management plans and sewers asset management.

5.2 Limitation and recommendations

This research has the following limitations:

- The main focus was on environmental and economic impacts of a sewer over its lifecycle. More socio-economic indicators need to be considered to improve the interpretation of the results.
- In this study, factors related to geographical location and hydraulics within sewer pipes were not considered which can affect the results greatly.
- Assumptions regarding transportation distance (from material extraction to production, production to installation site, and installation site to disposal site) are one of the limitations. More data needs to be collected for better decision-making.
- In this research, deterioration models for various pipes were taken from literature. However, condition data for various pipes can be collected to get more realistic deterioration curves.

Based on this research, we recommend the following for future research:

- This study is limited to sanitary sewer pipes, and therefore, it is recommended to extend the work to stormwater pipes, which are increasingly used in buried infrastructure facilities.
- This research can be expanded by considering and evaluating more socio-economic indicators (such as environmental damage associated with air pollution, noise, vibration, loss of amenity and disruption to traffic) over their lifecycle of sewer pipes.
- A detailed cost-benefit analysis for the selected sewer pipes is recommended.

- Emergy results can be integrated with AHP-based method for the better justification of relative importance of different sustainability criteria.
- Emergy-based lifecycle method should be applied for a case study that has long-term data available to evaluate the performance.

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APPENDIX A

Lifecycle Inventory of different pipes

Table A-1: Lifecycle inventory of PVC pipe

Assessment criteria	Production	Construction	Rehabilitation	End of Life
PVC resin	4.06E+01	-	40.5588	-
Calcium Carbonate	1.93E+00	-	1.9272	-
Stabiliser	1.31E+00	-	1.314	-
Energy and fuel use				
Pipe material production fuel (Diesel)	1.13E+09	-	-	-
Pipe manufacture fuel use				
Electricity	7.10E+07	-	-	-
Excavator fuel use	-	1.69E+08	3.39E+08	-
Compactor fuel use	-	1.24E+08	2.48E+08	-
Recycling fuel use	-			3.82E+07
Disposal fuel use	-			5.34E+06
Truck (dump) fuel use	2.30E+07	1.15E+07	1.15E+07	2.30E+06
Machinery				
PVC extruder	3.20E+03	-	-	-
Excavator	-	6.32E+02	1.26E+03	-
Compactor	-	2.10E+01	4.20E+01	-
Truck	2.72E+03	2.72E+03	5.44E+03	2.72E+03
Landfilling	-	-	-	2.63E+00
CO_2 emission	2.42E+01	3.62E+00	2.39E+01	9.77E-01
NOx emission impact	1.68E-01	0.025105666	1.66E-01	6.78E-03
SOx emission impact	6.08E-01	0.090959426	6.02E-01	2.46E-02

Table A-2: Lifecycle inventory of VC pipe

Assessment criteria	Production	Construction	Rehabilitation	End of Life
Material use:				
Clay	2.94E+02	-	2.94E+02	-
Barium	1.32E+01	-	1.32E+01	-
Calcite	6.91E+00	-	6.91E+00	-
Energy and fuel use				
Concrete mixer fuel use				
Diesel	2.21E+09	-	-	-
Electricity	6.52E+08	-	-	-
Pipe manufacture fuel use				
Electricity	6.52E+08	-	-	-
Excavator fuel use	-	1.69E+08	1.69E+08	-
Compactor fuel use	-	1.24E+08	1.24E+08	-
Truck (dump) fuel use	1.65E+08	8.26E+07	4.13E+07	1.65E+07
Machinery				
Concrete mixer	1.81E+04	-	-	-
Vibrator	3.00E+03	-	-	-
Excavator	-	6.32E+02	6.32E+02	-
Compactor	-	2.10E+01	2.10E+01	-
Truck	2.72E+03	2.72E+03	2.72E+03	2.72E+03
Landfilling	-	-	-	4.02E+02
CO_2 emission	6.15E+01	5.04E+00	5.87E+00	1.23E+02
NO_x emission impact	4.27E-01	3.50E-02	4.07E-02	8.53E-01
SO_x emission impact	1.55E+00	1.27E-01	1.48E-01	3.09E+00

Table A-3: Lifecycle inventory of DI pipe

Assessment criteria	Production	Construction	Rehabilitation	End of Life
Material use:				
Cast iron	2.12E+02	-	2.12E+02	-
Carbon	7.70E+00	-	7.70E+00	-
Silicon	6.34E+00	-	6.34E+00	-
Energy and fuel use				
Material production fuel use				
Coal	5.03E+09	-	-	-
Electricity	4.37E+08	-	-	-
Pipe manufacture fuel use				
Electricity	1.37E+08	-	-	-
Excavator fuel use	-	1.69E+08	1.69E+08	-
Compactor fuel use	-	1.24E+08	1.24E+08	-
Truck (dump) fuel use	1.19E+08	5.95E+07	2.98E+07	1.19E+07
Recycling fuel use	-	-	-	3.98E+09
Disposal fuel use	-	-	-	1.38E+08
Machinery				
centrifugal casting machine	1.20E+04	-	-	-
Excavator	-	6.32E+02	6.32E+02	-
Compactor	-	2.10E+01	2.10E+01	-
Truck	2.72E+03	2.72E+03	2.72E+03	2.72E+03
Landfilling				6.80E+00
CO_2 emission	1.40E+02	7.06E+00	6.46E+00	8.87E+01
NOx emission impact	9.68E-01	4.90E-02	4.48E-02	6.16E-01
SOx emission impact	3.51E+00	1.77E-01	1.62E-01	2.23E+00