AN INTEGRATED ASSET MANAGEMENT OF BURIED INFRASTRUCTURE : A BIM-BASED LIFE CYCLE THINKING FRAMEWORK

by

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Abstract

Water and sewer pipe networks are core public infrastructure critical for basic human services. These infrastructures should be sustainable as they consume natural resources and produce emissions into the environment during their life cycle. Water and sewer pipes should be sustainable based on their manufacturing and operation, which is typically evaluated using the established methods such as Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA). Additionally, a standard data management system that can interact with various built environments and collaborate with various databases improves the decision-making process. Building Information Modelling (BIM) can be used for this purpose, which has the capability of collaboration and interoperability, which are useful for infrastructure conflict resolution and stakeholder management. This research has proposed a BIM-based life cycle thinking framework for integrated asset management of buried infrastructure using a stochastic approach such as the Markov-chain model. A geo-referenced 3D model was developed in Civil 3D using GIS shapefiles obtained from open-source data of the City of Kelowna municipality. The life cycle impacts of five different pipe materials were evaluated using LCA and LCCA for the developed 3D model that includes four phases: production, installation, maintenance, and disposal. The results of life cycle environmental impacts with all the midpoint impact categories are aggregated into a sustainability score using a weighted sum method and compared with ReCiPe's single score. Furthermore, integrated maintenance is suggested as a possible alternative to conventional sequential maintenance, and a common trench is considered following the CSA, ASTM, ASCE, and AASHTO guidelines. The comparison of ReCiPe's single score to the estimated life cycle sustainability impact (LCSI) index gave contrasting results, mainly in the analysis of ductile iron and PVC pipe materials. Based on the LCSI index, the pipe materials are ranked, and the best pipe material is selected. The integrated maintenance approach was found to be cost-effective with a life cycle cost savings of 18%, but at a cost of 19% greater CO_2eq emissions. Nonetheless, when the LCSI index is considered, the integrated maintenance approach with a common trench has55% less life cycle environmental impacts than separate trenches. The proposed framework has demonstrated the potential for sustainable buried infrastructure through appropriate selection of pipe materials and integrated infrastructure management. Future research may expand the trench design with more green construction materials, that may further reduce

the CO_2eq emissions and conventional stochastic optimization techniques may be utilized for performance prediction models.

Lay Summary

The best outcome for community planning comes with aligned sustainability strategies and goals. The community sustainability fueled by global warming impacts has been intensified and remained the primary focus till today. As a result, city planners are challenged to achieve sustainability through collaboration and interoperability. The current study focuses on optimizing the renewal plans and developing a systematic methodology for sustainable procurement of various types of pipes used in buried infrastructure supporting the emission reduction strategies in communities. The methodology integrates BIM, life cycle thinking with multi-criteria decision-making techniques and develops a framework to evaluate the environmental and economic impacts of buried infrastructure. The results are expected to support sustainable community initiatives. The insights from this research will assist asset managers in achieving sustainability goals and the research outcome is expected to be the basis for BIM integration in municipalities paving way for digitalization of the urban water sector.

Preface

I, Venkata Uday Kiran Vadapalli, developed all the contents of this research under the direct supervision of Dr. Kasun Hewage. Dr. Rehan Sadiq who is co-supervisor, and Dr. Homayoun Najjaran and Dr. Ahmad Rteil who are supervisory committee members, reviewed and provided recommendations for the manuscript.

Journals from the Thesis

1. **Venkata U K Vadapalli**, Kasun Hewage, Gyan Chhipi-Shrestha, Rehan Sadiq (2021). Asset Management of Municipal Buried Infrastructure using Building Information Modeling (BIM): A Critical Review. *Submitted to Journal of Infrastructure Systems.*
2. **Venkata U K Vadapalli**, Kasun Hewage, Gyan Chhipi-Shrestha, Rehan Sadiq. BIM-based Life Cycle Thinking Framework for Integrated Asset Management of Buried Infrastructure: An Application to City of Kelowna (BC). *Journal under preparation.*

Book chapter published

1. Thais Ayres Rebello, Gyan Chhipi-Shrestha, **Venkata U. K. Vadapalli**, Emmi Matern, Rehan Sadiq, and Kasun Hewage (2021). A Fuzzy Approach to Analyze Data Uncertainty in The Life Cycle Assessment of an Drinking Water Systems: A Case Study of City of Penticton (CA): Submitted to John Wiley and Sons in April 2021.

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List of Abbreviations

Acronyms

ASCII	American Standard Code for Information Interchange
BIM	Building Information Modeling
CAD	Computer-aided design
GHG	Greenhouse gases
GIS	Geographic Information System
GWI	Global warming impact
ISO	The International Organization for Standardization
LCA	Life cycle assessment
LCCA	Life cycle cost analysis
MCDM	Multi-criteria decision making
US	United States
UTM	Universal Transverse Mercator
WSM	Weighted sum method

Abbreviations and units

kg	Kilogram
kg CO_2 eq	Kilograms of equivalent Carbon Dioxide
kg CFC11 eq	Kilograms of equivalent Trichlorofluoromethane
kg NOx eq	Kilograms of equivalent Oxides of Nitrogen
kg PM2.5 eq	Kilograms of equivalent particulate matter with a diameter of less than 2.5 μm
kg SO2 eq	Kilograms of equivalent Sulphur Dioxide
kg N eq	Kilograms of equivalent Nitrogen
km	kilometer
m^3	Cubic Meter
MJ	Mega Joules
p	process
tkm	tonne-kilometer

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Dedication

Dedicated to my beloved family, friends, and teachers,

Who loved me, protected me,

and made me a better person…

Chapter 1: Introduction

1.1 Background

The public civil infrastructure represents 3% of global GDP based on the current trend, with an estimated $94 trillion investment between 2016 and 2040 [1]. This includes electricity, rail, telecoms, airports, ports, and municipal infrastructures such as roads, bridges, water, and wastewater systems. Among all sectors, municipal infrastructure represents the majority of assets that need constant monitoring. For instance, in Canada, the municipal infrastructure alone represents 70% of the total civil infrastructure [2], with a recurring annual expenditure of $12 to $15 billion [3] being spent maintaining the assets. The municipal infrastructure state is at risk and requires significant attention in the coming decades. In particular, almost 30% of the Canadian linear assets (water and wastewater) are in *fair* or *worse* conditions and 45% have an unknown condition, which highlights the challenges in the asset management of buried infrastructure [4]. Municipalities have the responsibility to provide reliable water and wastewater services that meets appropriate quality standards. The quality of these services can be measured in terms of the level of service (LoS). LoS is a composite indicator, which is composed of functionality or asset condition (i.e., capacity, quality, reliability) cost, customer satisfaction, and environmental acceptability [5].

Most municipalities often either replace or ignore the buried infrastructure, specifically water, and wastewater systems, without detailed condition assessment and evaluation, mostly when the roads were reconstructed, putting the investments at risk [3]. Roads and buried infrastructure are inherently integrated and interdependent, which requires different renewal strategies for efficient asset management. Moreover, water and wastewater systems are critical components among the buried infrastructure, as they are capital intensive, having higher investments to returns than electricity, natural gas, and telecommunication services [6]. Aging assets, high level of service expectations, stringent legislations, rapid urbanization, limited financial resources, increased accountability, liability to provide minimum service standards, competition among service providers, and government initiatives have induced municipalities to maintain their assets efficiently and effectively [5], [7].

Sustainable development refers to the use of resources for development without depriving future generations of those resources according to the United Nations Brundtland

Commission Report. The 2030 sustainable city and community strategy, encompassing local and other waste management, aims to reduce per capita environmental impact of cities. [8]. Sustainability is a holistic concept, which can be measured quantitatively using the lifecycle thinking approach. Lifecycle assessment (LCA) and Lifecycle Costing Analysis (LCCA) are widely used tools to measure the lifecycle impacts, such as environmental and economic impacts, respectively. However, the established life cycle assessment methods are based on analysis of a functional unit that is assumed to represent the actual asset and this may not be appropriate for buried infrastructure where a comprehensive network analysis is preferred for better optimization strategies. The conventional approach for performing LCA requires quantification of assets for life cycle inventory (LCI), which is not only inefficient but also likely to err and an accurate asset inventory is essential for effective asset management.

Climate and environmental hazards are the top global concerns identified by the World Economic Forum 2020 as they are anticipated to have a financial impact on businesses. Thus environmental considerations are important in the decision-making process and asset management industry tend to combine several approaches to take a "values" approach that prioritize investors' principles over financial return. Therefore, asset management without effective environmental goals and technologies that drive the fourth industrial revolution may struggle in the long run to make climate-informed strategic decisions. Municipalities bear the burden of the economic impacts of global warming, from forest fires to ice storms to flooding. Climate change is the single most major challenge, and with municipalities accounting for roughly half of Canada's greenhouse gas emissions, scaling up local solutions is critical [9]. Commercial and residential economic sectors are responsible for 12% of GHG emissions, according to the US EPA, but these emissions are caused by fossil fuel combustion for heating and cooking, waste and wastewater management, refrigerant leaks, and other indirect emissions associated with the use of electricity. Other economic sectors that contribute significantly to US GHG emissions include transportation (28%), energy (27%), and industrial (22%). The urban water system alone accounts for around 2% of energy consumption in the United States, and community-level emissions are a combination of different economic sectors [10].

Effective asset management could be complicated when there are different data attributes associated with the asset from different stakeholders. To overcome these challenges, this study has implemented Building Information Modeling (BIM) approach to estimate the

Bill of Quantities (BOQ) and create a lifecycle database with asset inventory, condition, and maintenance data for future use. Literature such as Marzouk et al., 2018, Soust-Verdaguer 2017, W.Yang and S.S.Wang 2013, has discussed the implementation of Building Information Modeling for lifecycle analysis [11]–[13] but these studies never discussed the integration of BIM and relational databases. Municipal assets tend to deteriorate due to aging, usage, and other climatic effects requiring maintenance to ensure optimal service life. This requirement for maintenance highlights the importance of decision support tools. Municipal authorities also emphasize long-term asset management planning but limit themselves to life-cycle costing analysis. For instance, the Winnipeg municipality,Canada recommended the use of LCCA for all decisions related to studying the infrastructure alternatives [14]. The literature is also limited when it comes to integrated assessment of water and wastewater systems from a lifecycle thinking perspective, which was emphasized in this study. For instance, the pipe material plays a significant role in the structural integrity and performance of the buried infrastructure that may lead to pipe breakage if not properly taken care of [15]. Several studies such as G. Vladeanu and J. Matthews 2019, G Kabir et al., 2015, R Jafar et al., 2010, C. Fazal and Z. Tarek 2008, M. Najafi and G. Kulandaivel 2005, have discussed condition rating prediction models using statistical, multi-criteria decision analysis techniques for water and wastewater assets [7], [16]–[19] based on several spatial and temporal deterioration factors, including pipe material. While most of these studies have focused only on the structural and hydraulic aspects of the pipe, the looming environmental impacts make it necessary to give credit to lifecycle assessment in the decision-making process.

Environmental indicators such as carbon dioxide, average global surface temperature, water quality, deposition rates of atmospheric compounds are some of the common measures that describe the state of an environmental system. The environmental acceptability function represents the performance characteristics of the system and in this study, it is providing environmentally responsive pipe material. This material could be of plastic, cementitious or metallic pipe. For instance, the most common pipe materials in Canada were cast iron (48%) and ductile iron (19%) in early 1930s [15], concrete (58%) and vitrified clay (36%) [20] in 1994, concrete (41%), PVC (22%) and vitrified clay (16%) in 2002 [21], PVC (42%) followed by concrete (32%) in 2012 [22]. This indicates that over the years, the PVC plastic pipe turned out to be the best alternative over concrete and metallic pipes. This was supported by the research done by Alsadi 2019, Akhtar et al., 2014, Recio et al 2005 where their studies confirm that plastic pipes are the most sustainable option in terms of environmental and economic aspects for water and wastewater pipe materials [23]–[25].

On the contrary, studies that were done by Petit-Boix et al., 2014, Fei Du et al., 2013 illustrate concrete pipes with concrete and sand bedding perform better than plastic pipes [26], [27] and concluded that pipe trench has a significant role in lifecycle analysis. The trench may be common for water and wastewater pipelines which are expected to not only reduce the lifecycle and social costs but also improve the coordination issues with multiple utility stakeholders [28]. This study has analyzed the advantage of constructing a common trench by optimizing water and wastewater maintenance schedules. A technical assessment of plastic-related (such as PVC) materials credit for LEED by US Green Building Council indicates PVC is not the worst alternative in the cradle through use phase of the lifecycle but the end-of-life incineration and resulting dioxin production makes it the worst product [29]. The major inference here is that the LCA results are significantly altered due to the underlying assumptions, data uncertainty or data unavailability, or the definition of the system boundary. Apart from the environmental perspective, the structural health and integrity of plastic pipes (such as HDPE) are generally below the acceptable limits set by AASTHO standards [30]. The strength of plastic and concrete pipe is time-dependent where it decreases over time for plastic and increases over time for concrete under applied load. This is important for estimating the maximum service life of pipe, based on material.

Therefore, there is a need to develop a more comprehensive framework that assesses the sustainability of buried infrastructure asset management. A decision support framework is essential to determining the course of actions and a data management system improves the decision-making process. Municipalities with such advancements are more likely to have developed guidelines for post-disaster inspections [31]. Wang et al., 2019 found that inefficient utility management is attributable to the lack of a robust database digitized information model, lack of coherent representation of utility information, and ineffective assessment of condition and decision-making process [32]. Mahmoud 2008 mentioned that the process and data fragmentation created by independent asset maintenance programs caused many inefficiencies, which has persuaded industries to adopt an integrated approach to unify various utility information dimensions into one platform for effective asset management [33]. A standard integrated database is a crucial sophistication required for proactive asset management. The BIM can integrate the data from various built environment dimensions, such as 3D structure, cost, time, urban life and demography, traffic, air quality, noise, and floods [34]. Therefore, BIM has a business value in buried infrastructure asset management due to its technical complexity and intense operations. A fully integrated BIM database offers great advantages with improved collaboration and interoperability from performing the structural conditional assessments, hydraulic analysis, lifecycle assessments, energy analysis, information retrieval, space management, real-time data analysis through sensors directly on the geometry of the building model [35]. Wastiels L and Decuypere R 2019, has evaluated the BIM-LCA integration strategies and explained that most of the integration approaches are either a simple BOQ extraction from BIM-model and importing to LCA software or a real-time LCA calculation within the BIM environment using plug-in tools [36].

1.2 Research Gap

The research emerged due to lack of a comprehensive framework for sustainable asset management of buried infrastructure; and the fundamental conflict for cost-effective and environmentally responsive pipe material which were originated based on contradictory in the literature. A thorough literature review identified the following research gaps in the current body of knowledge.

A feasibility analysis for adapting integrated renewal strategy and a common trench for water and wastewater systems

Assets need maintenance and which comes at a cost. Municipalities are often challenged with aging assets and each infrastructure system has its priority and a renewal plan. In most Canadian municipalities, the road renewal plan drives the renewal planning of buried infrastructure. This is because of the assumption that buried infrastructure need to be replaced whenever the roads are constructed. On the contrary, some road works are completed without any condition assessment of buried infrastructure [3]. Both extremes result in a recurring annual expenditure that needs to be optimized and an integrated renewal strategy among the utilities could be a possible solution. The Commission of the European Communities states that urban densification is a sustainable way of urbanization and urban sprawling has to be limited [37]. As a potential solution, prior research addressed the construction of multi-purpose utility tunnels (MUT). However, while the MUTs are expected to not only reduce the lifecycle and social costs but also improve the coordination issues with multiple utility stakeholders but MUTs are highly expensive and difficult for construction [28]. A review of the literature revealed that instead of MUTs a common trench for water and wastewater could be explored for the core public buried infrastructure.

Ambiguous environmental impacts due to various system boundary definitions in the life cycle assessment of municipal buried infrastructure

Theoretically, a complete life cycle system commences from raw material extraction and ends with all materials back into the earth but not part of the system. The system boundary is dependent on the goal of the study and hence analysts often exclude certain stages. However, a system boundary analyzed differently from cradle to grave is a decision by the analyst who is believed to understand the possible consequences of such a decision is important for evaluating the trade-offs [38]. Most LCA studies analyzing the municipal buried infrastructure ignored certain stages depending on the life cycle inventory, specific goals, data uncertainty, or data unavailability. Results from different LCA studies have a difference of opinion on the best pipe material that has the lowest environmental impact. For instance, studies that were done by Alsadi 2019, Akhtar et al., 2014, Recio et al., 2005 confirm that plastic pipes are the most sustainable option in terms of environmental and economic aspects for water and wastewater pipe materials [23]–[25]. On the contrary, studies that were done by Petit-Boix et al., 2014, Fei Du et al., 2013 illustrate concrete pipes with concrete and sand bedding perform better than plastic pipes [26], [27] and concluded that pipe trench has a significant role in lifecycle analysis. A review of these studies revealed that the LCA results are significantly altered due to the underlying assumptions, data uncertainty or data unavailability, or the definition of the system boundary.

Lack of holistic environmental planning framework to understand community-level emissions for the selection of sustainable materials

Environmental planning emphasizes sustainability in communities which involves abatement of emissions, noise and air pollution, wetlands, habitat of endangered species, and other environmental impacts dealing with the relationship between natural and ecosystem. The US EPA indicated commercial and residential economic sector contributes around 12% of GHG emissions but these emissions come from fossil fuel combustion for heating and cooking needs, waste and wastewater management, refrigerant leaks, and other indirect emissions associated with the use of electricity. The community-level emissions are a mixture of transportation, electricity and industrial economic sectors and the Urban water system alone accounts for approximately 2% of energy consumption in the United States. Thus, a comprehensive set of decision support tools and guidelines are required to support the decision-makers for sustainable procurement focused on community-level emission mitigation strategies. Most planning frameworks address the environmental emissions independently and no framework or planning tool integrates these life cycle impacts with other conflicting objectives such as asset condition ratings. Most LCA studies have developed frameworks to rank and select sustainable material for low-carbon communities. Many third-party frameworks like Sustainability Tools for Assessing and Rating (STAR) ignore the condition of existing infrastructure and still receive higher points [39]. These third-party certifications like LEED, BREEAM, CEEQUAL, CASBEE, Green Star are typically point-haunting and consensus-based rating systems. Thus they are not suitable for sustainable buried infrastructure asset management, as they tend to make an objective assessment with some pre-established environmental, social, and economic criteria [40]. Therefore, developing a holistic environmental planning framework to understand the community-level emissions is much needed.

The feasibility of adapting the building information modeling process to a domain other than buildings

The debate on adapting BIM is accomplished now for the buildings sector and the infrastructure domain should have an inevitable cultural shift from traditional practices. Infrastructure projects being unique and of the public in nature cannot easily adapt to BIM-centric workflows. At the same time these emerging technologies i.e., BIM with the evolution of interaction with sustainability established that data management, simulation, quantity take-off, and visualization are the functionalities synonymous with sustainable practices [41]. To bridge the gap between BIM and sustainability, Olawumi & Chan 2018 suggested few strategies to establish metrics that measure qualitative benefits, policy formulation, and adopt green BIM [42]. The BIM applications like coordination of the works, design review process, and collaboration methodology are typical to buildings and infrastructure development projects from a Constructor's perspective. However, the buildings are more component-based than the infrastructure, where features like the clarity of information, clash detections, and visualization during the design phase are more beneficial. Moreover, the BIM usage in infrastructure projects raises important contractual issues during phase transition from construction to operations and includes the transfer of project risks, contractual guarantees, and copyright of documents. Most municipalities maintain the asset database in either 2D CAD files or GIS models, which may be efficient in spatial visualization and database query functions. These databases cannot analyze the objects by parameters that automatically determine the geometry of the real-world behavior in 3D. Such parametric modeling is the strength of BIM, and when integrated with GIS, it may analyze the data efficiently, both spatially and semantically.

Lack of knowledge on the capabilities of building information modeling beyond the 3-dimensional visualization for asset management of municipal buried infrastructure

Literature has been discussing the advantages of BIM adoption and implementation rather than providing a comprehensive review of BIM applications beyond its 3D modeling capabilities. A comprehensive review of BIM specifically from an infrastructure asset maintenance point of view is lacking. In addition to that, also there is a confusion between academy and industry in allocating the 6^{th} dimension to sustainability, as literature has used the 6^{th} dimension for health and safety, quality information, contract information, as-built representation (an extension to facility management) while the industry/practitioners (majority) using 6^{th} dimension for sustainability and 7^{th} dimension for facility management [43]. Although BIM is growing exponentially, it is limited more into design activities than O&M. Operational activities such as BIM integration with asset management, automated tracking of equipment, leveraging the BIM process for maintenance activities, linking the 3D model with analysis applications, integrating the 3D model with performance monitors, sensors, or smart devices are not so common every day but still, these activities have to be adopted [44].

In view of the aforesaid research gaps in existing knowledge, the following specific research questions were formed:

1) What is the adaptability of Building Information Modeling technology in municipal buried infrastructure?
2) Which sustainable pipe material can contribute to the abatement of environmental emissions?
3) How the pipeline renewal strategy can be optimized for both environmental and economic impacts?

1.3 Research Motivation

The urban water system thrives on the health and safety of people through healthy waterways and ecosystems. However, issues like rapid urbanization coupled with climate change have persuaded research to focus on developing more sustainable practices. Therefore, the selection of sustainable materials, the methodology is identified as one of the few ways of implementing sustainable practice in the design of buried infrastructure aimed at reducing the environmental and economic impacts. Often the selection of sustainable material is a conflicting decision taken by an analyst when there is a lack of knowledge on what is sustainable material. Vitrified clay pipe was a popular choice in the 1900s which has exceptional strength, abrasion, and corrosion resistance. According to the National Clay Pipe Institute, vitrified clay pipe is the most sustainable material which offers the longest service life available for water and wastewater systems. The major disadvantage with clay pipe is it is prone to root growth leading to leakage or blocking. Clay is expensive and challenging to transport because it is heavy and fragile. Cast iron pipes were equally popular during this time and according to the Cast Iron Soil Pipe Institute pipes have utilized green and sustainable resources but had a high risk of corrosion. Ductile iron came into existence in 1950 as an improvement to cast iron which has higher strength and corrosion resistance making it attractive for buried infrastructure. According to Ductile Iron Pipe Research Association, the ductile iron pipe has more tensile and impact strength which resists the hydrostatic burst pressure and the crushing load beyond that of PVC pipe material. Moreover, the strength of ductile iron pipe is not compromised by time, unlike PVC pipe material. The ductile iron pipe is prone to corrosion resulting in internal and external pitting and graphitization corrosion. Concrete pipes were also popular during this time and long lasted as a pipe material until plastic pipes came into the market in the 1960s. Today, plastic pipe is an increasingly popular pipe material, used for everything claiming the highest corrosion resistance and long-projected service life according to Plastics Pipe Institute. The American Concrete Pipe Association claims concrete pipes are the strongest and environmentally friendly pipe available. It has been recognized as the green material suitable for LEED projects and fits sustainable development.

The motivation of the research originated from the shrinking financial resources and need for sustainable pipe material and on the definition of what is a sustainable material. Understanding the complete lifecycle from cradle to grave is necessary and where most LCA studies have failed in contributing to the body of knowledge. An integrated comprehensive framework is necessary to assess the environmental and economic performance of the sustainable buried infrastructure, pipe material along with its history of condition compared to the traditional practice of assessing environmental, economic, and condition rating independently. It provides confidence to the stakeholders to make a sustainable decision. Moreover, the knowledge is useful for policy-makers to decide on this methodology and policies to reduce carbon footprint. The results of the research also support government climate action goals and global accords. This research seeks to generate the knowledge required to meet the goals mentioned above.

1.4 Research Objective

The main objective of this study is to develop a BIM-based life cycle thinking framework to improve the asset management process of buried municipal infrastructure. The framework focuses on drinking water, sanitary sewer, and storm sewer systems. The specific sub-objectives of the research are as follows:

1. Review the asset management process for municipal buried infrastructure and examine the feasibility of implementing BIM.
2. Develop a visual and geo-referenced 3D model that exchange life cycle data for asset management of buried infrastructure
3. Assess the life cycle sustainability of different pipes used in drinking water, wastewater and storm sewer systems.
4. Integrate BIM and develop an asset management framework using life cycle thinking approach for buried infrastructure.

1.4.1 Meta Language

The specific terms used to describe the above research objective are explained below.

Asset Management: Asset management is the combination of management, financial, economic, engineering, operational, and other practices applied to physical assets to the required Level of Service in the most cost-effective manner.

Sustainability: Sustainability is satisfying the present needs without disrupting the future to satisfy their own needs. Sustainability promotes the availability of opportunities to both current and future generations while addressing the environmental and social balance.

Building Information Modeling (BIM): Building Information Modeling is an integrated digital representation of a facility's physical and functional characteristics at various stages of the project life cycle in the form of a database.

Life cycle thinking: Life cycle thinking includes the economic and environmental consequences of a product or of a process that takes into account all phases of its life cycle. The life of a product or a process comprises the extraction, construction, operation and finishing processes of raw materials. This technique assesses the environmental impact of different pipe materials used in the buried infrastructure from raw material extraction, production, construction, maintenance, and disposal phase. Similarly, the life cycle economic impacts will examine the cost of production, installation, O&M, and the salvage value of the pipe material.

1.5 Thesis Organisation

There are 7 chapters in the thesis. The chapters mainly focusses on the literature review, methodology, findings, and conclusions.

Chapter 1: Chapter 1 gives an overview of the study, research gaps, motivation, objective such as the deliverables, and the organization of thesis.

Chapter 2: Chapter 2 gives information about the general research methodology and phases, followed by the study to meet the research objective.

Chapter 3: Chapter 3 reviews the research and assessment of the sustainability of the infrastructure undergoing the management of infrastructural assets, the elements of the Building Information Modeling and its integration with asset management.

The details of the achievement of the overarching objective of the study are provided by Chapters 4, 5 and 6. The chapters discuss the approaches utilised to achieve an objective, study findings and outcomes.

Chapter 4: Chapter 4 presented the development of a 3-Dimensional model from the open-source data obtained from the City of Kelowna, British Columbia. Additionally, the chapter discussed the creation of a lifecycle database that can store and exchange data with external databases such as a relational database management system.

Chapter 5: Chapter 5 presented the sustainability assessment of different pipe materials established through the life cycle environmental and life cycle cost impacts of different pipe materials from cradle to grave life cycle phases. The results from the chapter have been used for the case study developed in Chapter 6 assessing the life cycle impacts.

Chapter 6: Chapter 6 presents the condition assessment for water and wastewater systems using deterministic and stochastic approaches and determines deterioration curves for a required Level of Service. The deterioration curve has derived maintenance schedules for each asset system. From the developed 3D model in Chapter 4, and the life cycle environmental and cost assessment conducted in Chapter 5, a case study has been devised in Chapter 6 to analyze an integrated maintenance schedule using the life cycle impacts of a common trench.

Chapter 7: Chapter 7 summarizes the study findings, recommendations, study originality and future research. The interconnections between the chapters and the research sub-objectives accomplished in individual chapters are shown in Figure 1-1. Moreover, under the appropriate chapters the key actions, research results are indicated.

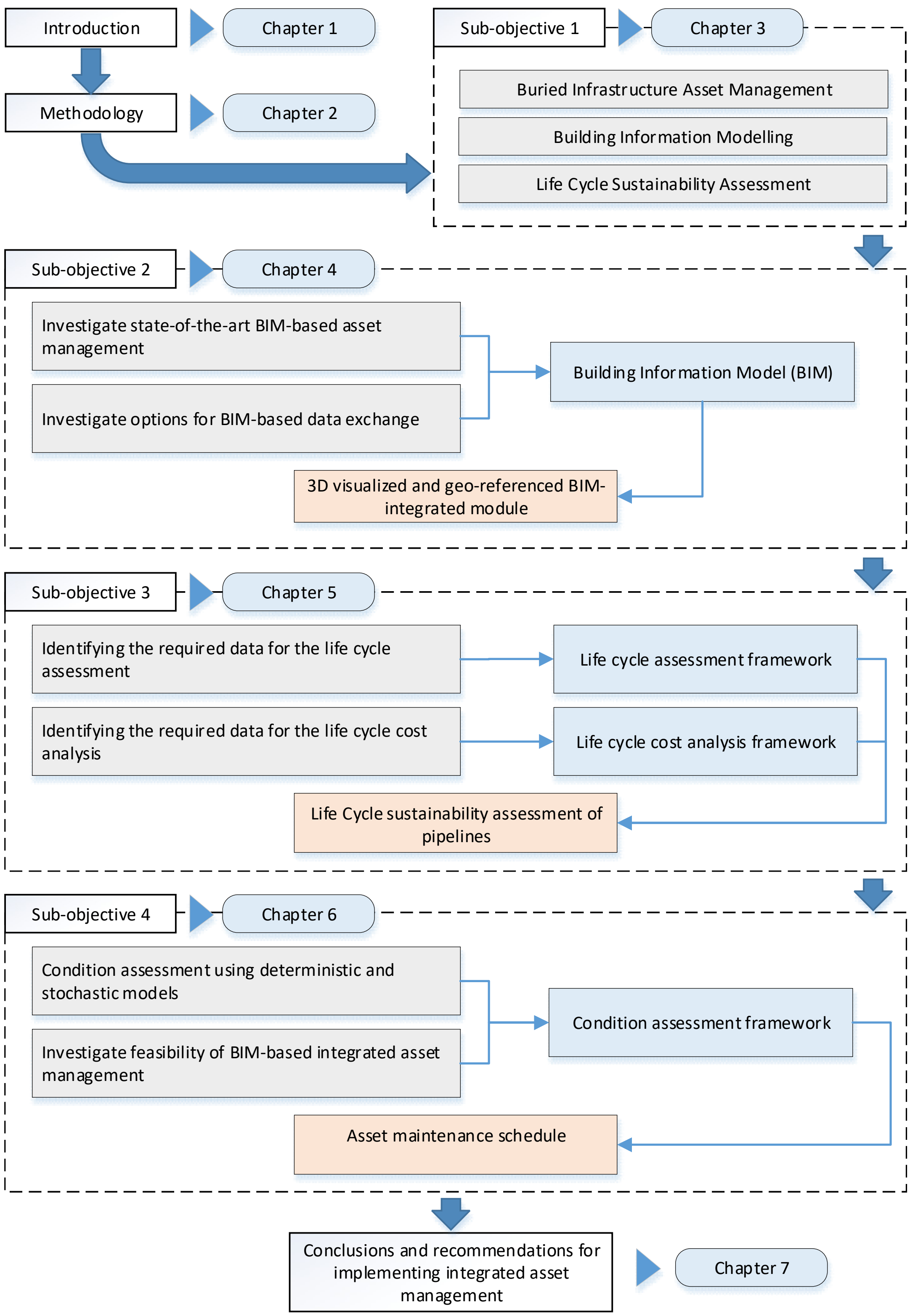

Figure 1-1: Integration of sub-objectives and thesis organization

Chapter 2: Methodology

This research focusses on evaluating the sustainability of municipal buried infrastructure which includes an integrated renewal plan of water and wastewater systems, life cycle impacts of different pipes. The LCA and LCCA methods encompass four main stages: pipe production, installation, maintenance, and disposal phases. The study objective was achieved in multiple phases and are integrated to develop a sustainable planning methodology at the community level. The research focused on the development of a BIM-based life cycle thinking framework using a multi-criteria decision-making approach and feasibility of BIM implementation to municipal buried infrastructure. The proposed methodology was demonstrated using a case study with data obtained from City of Kelowna municipality in the Okanagan Valley. This chapter illustrates the general approach employed in the study, whilst the corresponding chapters provide more extensive description of the methodologies employed in various phases.

- Phase 1: A literature review of buried infrastructure asset management
- Phase 2: Development of 3D model and BIM-based life cycle database
- Phase 3: Life cycle impacts of buried infrastructure
- Phase 4: Condition assessment and infrastructure management of buried infrastructure

The overview of the approach and the link between research phases and methodology to the essential sub-objectives is shown in Figure 2-1. Outputs from each phase were taken as inputs to the next phase. From the literature review, asset management practices of municipal buried infrastructure were identified along with investigating emerging technologies like Building Information Modeling. Phase 2 of the research involves developing a 3-dimensional model and a life cycle database using the BIM process which is used in Phase 3&4 to assess the life cycle impacts and pipe condition.

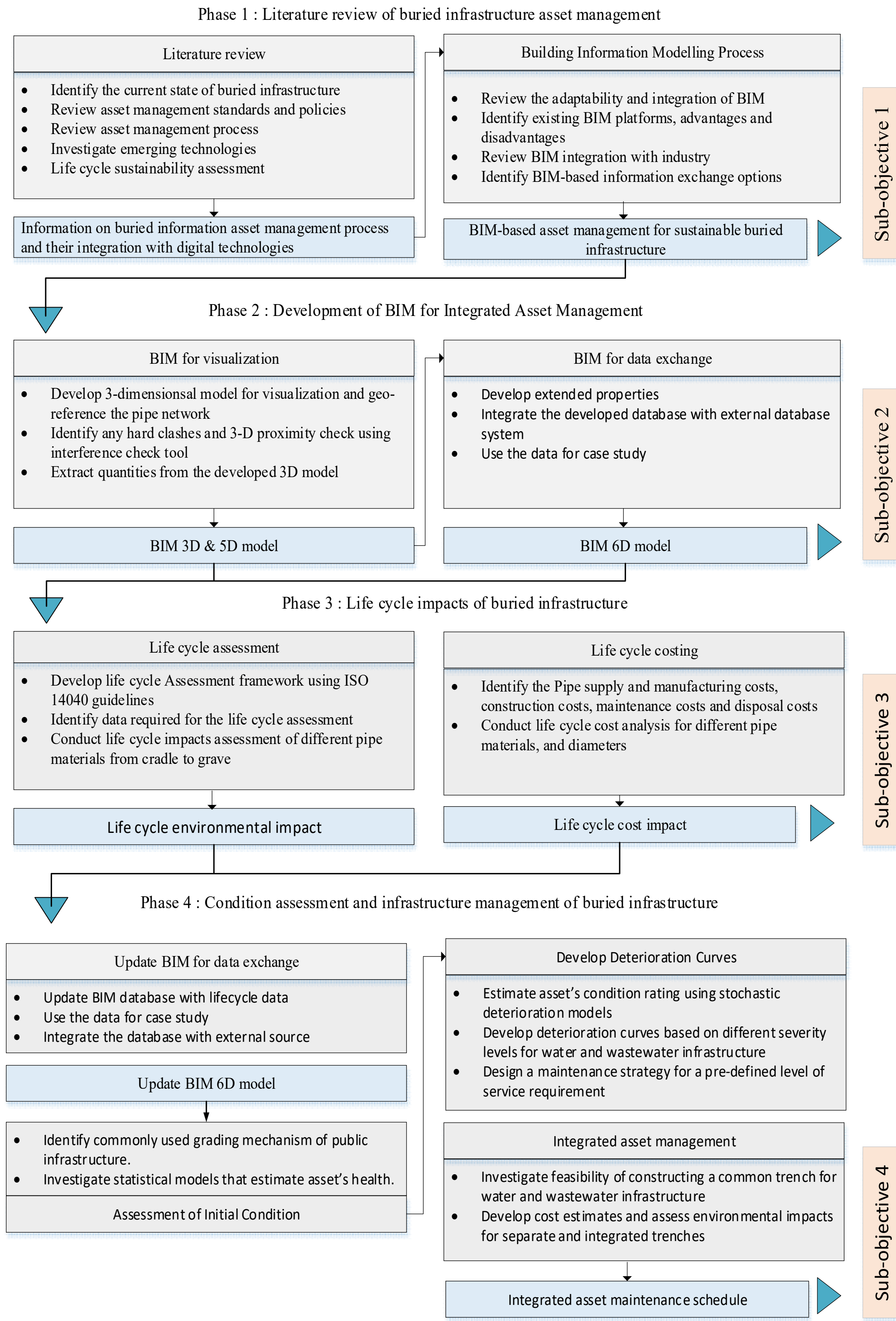

Figure 2-1: Methodology flow

2.1 Phase 1: Literature Review of Buried Infrastructure Asset Management Process and Investigation of Emerging Technologies

A systematic literature review of asset management process with an introduction of the BIM concept to buried infrastructure and its integration with asset management was conducted. Peer-reviewed literature was analyzed to explore existing BIM asset management technology patterns and their integration with other BIM authoring tools. The prospects, opportunities, and limitations are evaluated from the O&M perspective to understand BIM utilization trends for asset management. Literature was retrieved and collected from the major online databases like Compendex, GEOBASE, GeoRef, Scopus, ASCE Library, and Google Scholar. Journals, conference articles, books, book chapters, industrial reports, government reports, and other published literature with open access are retrieved. "BIM" and "Asset Management" are the specific keywords used with the boolean expression "AND" to search the subject of literature, including title, abstract and complete paper with published language restricted to English. Keyword combinations such as "Building Information Modeling" “BIM-GIS integration” “BIM-LCA integration” BIM-LCC integration” “buried infrastructure” “asset management” “condition assessment” were used for the search. Articles published after the year 2000 were prioritized to obtain the most recent data. Journals with high impact factors are considered to provide high-quality information [45], [46]. Therefore, journals with impact factors of 3 or above were reviewed specifically. Referenced peer-reviewed journals with an impact factor above 3 are listed below:

- Automation in Construction
- International Journal of Geo-Information
- Tunneling and Underground Space Technology
- Journal of Building Engineering
- International Journal of Geographical Information Science
- Renewable and Sustainable Energy Reviews
- Sustainable Cities and Society
- Journal of Management Information Systems

Moreover, in addition to the above, the literature is not only limited to high-impact journals but also includes published governmental, non-governmental reports along with conference articles to gather the advanced information that is required to introduce the BIM concept in the buried infrastructure asset management process.

2.2 Phase 2: Development of 3DModel

This study considered Autodesk Civil 3D for the development of a 3D model and the life cycle database in Chapter 4. Additionally, the Chapter also discusses the interaction of a BIM database with an external relational database such as Microsoft Access and/or simply Microsoft Excel. There are many methods to create the objects in Civil 3D using imported data from survey points, polylines from GIS shape files, and 2D CAD files. This study used the GIS shape files available as open-source from the City of Kelowna municipality to obtain the data of water and wastewater pipeline networks [47]. This study has followed the guidelines from InfraGuide's Best Practices for Utility-Based Data Management which has outlined the storage of information mainly the physical, meteorological, and environmental data compiled in relational databases and linked to GIS [3], [48]. Nevertheless, this study has extended the data interaction to BIM using some simple techniques without using any programming codes.

BIM is typically considered as only a 3D model for visualization and the information management aspect is often ignored. The BIM-based asset management relates to data management, storage, sharing, and exchange of asset management tasks through the BIM authoring tools. Optimization of maintenance and operation of assets throughout the asset useful life at minimum cost is the main characteristic of asset management. The asset management process includes maintenance of asset inventory, condition assessment, maintenance strategies, prioritization, and investment decisions. These processes are related through a shared flow of pertinent data and efficient asset management is about how organized the data is stored, analyzed, and utilized.

The requirements for BIM-ready asset management are having geometry in a precise location. When geometry has attributes, it is smart and has dynamic behavior. The attributes can be exchanged across the BIM portfolio when complied with Industry Foundation Class (IFC) and Construction Operations Building information exchange (COBie) standards. This study explains the development of asset databases using the "property sets" feature in Civil 3D software which can integrate with relational databases such as Microsoft Access realizing the value of the Civil infrastructure model. The attributes attached to the 3D objects are usually determined by the property set definition which is a group of related properties of the objects and object styles. The properties of these object data are of two types: automatic and manual. The automatic properties are built-in when they are created. Examples include length, diameter, thickness, and data retrieved from other sources. The manual properties are those that are explicitly entered such as condition rating, sustainability rating, manufacturer, owner, etc. Therefore, the BIM database has stored the following information for its future analysis, which includes:

1.Inventory data: the asset (pipe) object ID, installation year, and geometry

2.Condition data: the asset performance data such as condition rating

3.Maintenance data: deterioration environment, lifecycle costs, maintenance action

Further, the BIM and LCA integration strategies are achieved either with a simple BOQ extraction from the BIM and importing to LCA software using conventional spreadsheets or a real-time LCA calculation within the BIM environment using plug-in tools such as One Click LCA [27], [28]. The current research has adopted the conventional approach of extracting BOQ from the developed model and used it for lifecycle analysis. However, in the current research the BIM-LCA integration, is broadly referred as an integration of approaches and not simply software integration.

2.3 Phase 3: Life Cycle Impacts of Buried Infrastructure

Five pipes of different materials, asbestos cement (AC), concrete (CONC), ductile iron (DI), poly vinyl chloride (PVC), and vitrified clay (VIT), were selected for analyzing their sustainability and whenever a pipe has to be replaced completely a sustainable pipe material was chosen from the analysis. The analysis of life cycle impacts for pipe material has also established asscoaited trench, maintenance strategy and waste scenario. For example, the trench design is different for rigid pipes i.e., AC, Conc, VIT, DI and flexible pipes i.e., PVC. Similarly, the maintenance (CIPP) cycle times differ with pipe materials i.e., 7 times (AC, Conc, VIT) and 6 times for (DI and PVC) based on the service life in the 100 yr analysis period. The waste scenario is also dependent on the pipe material which has been included in the analysis. In case of conflict of interest among the alternative pipe material for choosing the lowest lifecycle cost criteria or low environmental impacts, a multi-criteria analysis was used. Additionally, the maintenance strategies such as repair, rehabilitate, or replacement whether in an integrated or separate pipe system was assessed based on the lifecycle cost analysis and the environmental impacts of the pipe network.

2.4 Phase 4: Condition Assessment of Buried Infrastructure

Core public infrastructure such as pipelines is the most critical component for municipalities as the failures are mostly catastrophic. Water and wastewater networks are aged in North America and most expensive to maintain when compared to the returns on investments made for other private utilities such as gas, electricity, and telecom. In this study, water and wastewater pipelines are considered as proof of methodology application of the proposed framework; nevertheless, the same methodology can be extended to other utilities in the future. City of Kelowna (CoK) municipality has been chosen for the application of the proposed framework and the data required are obtained from the opensource data of CoK for evaluating the pipeline condition, lifecycle costs, and environmental impacts [58].

This phase was initiated by performing asset condition assessment developing deterioration curves for water and wastewater systems. The condition assessment was described by condition rating typically calculated as a function of age. The fundamental assumption in establishing the condition rating is that the pipe network is in an undamaged initial condition and there is no history of condition assessment. The calculated condition rating was evaluated using Markov's transition probability matrices to account for the time dependency and uncertainty of the deterioration process, maintenance operations, and initial condition.

The methods adopted in Phases 1, 2, 3, and 4 show the BIM-based life cycle thinking asset management framework for buried infrastructure, which is depicted in Figure 2-2.

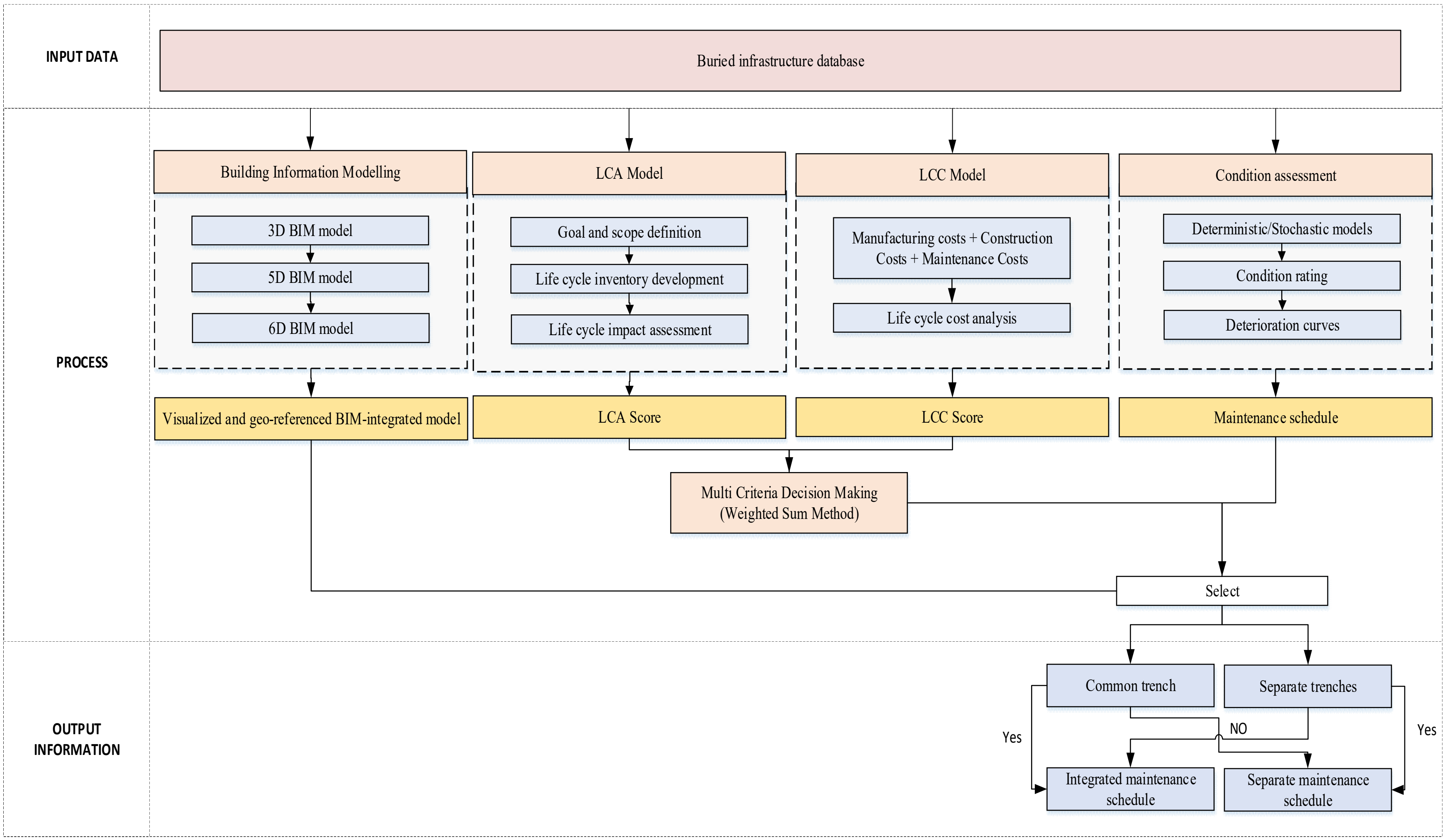

Figure 2-2: BIM-based life cycle thinking framework for integrated asset management

Chapter 3: Literature Review

The literature review was carried out to understand the available asset management practices, standards, and policies identifying the emerging technologies like Building Information Modeling, GIS, and Digital Twinning, which can co-function with asset management based on technological and operational requirements. Furthermore, earlier studies relevant to the adaptation of Building Information Modeling for asset management were reviewed to understand the level of technology required for implementing BIM at the municipal level. The results of the literature review are shown in the following sections.

3.1 Overview of Buried Infrastructure Asset Management

The UN Statistical Commission has endorsed urban areas (or municipalities) classification by population size worldwide. The size can be as small as 200 in Denmark and as high as 10,000 in China, where the municipalities are challenged to have a higher level of service and allocation of fiscal budgets regardless of the size. Other significant challenges include post-disaster management due to natural calamities, such as floods, hurricanes, and earthquakes. The city of Christchurch, in New Zealand, was able to use before and after data of an earthquake from a smart system to locate pipe breaks and prioritizing repairs based on the level of damage [44]. Countries like the United States and Canada with vast landmass are typically susceptible to extreme weather and soil conditions besides other asset deterioration contributors. An observation from Michigan Asset Management Plan has estimated a cost saving of 12-18% if preventive mechanisms are implemented rather than spending on reactive maintenance. Such preventive mechanisms would include applying GIS/CMMS and further these preventive mechanisms are enhanced with artificial intelligence (AI), an additional saving of 20 – 30% cost is foreseen [49]. Such integration of multiple platforms is supported by the BIM process and the BIM authoring tools use machine learning algorithms to identify the failure patterns. Thus, proper asset management is necessary, and municipalities with good asset management practices gain better resilience and sustainability planning. Typically, a municipal asset management system consists of an asset database and decision support systems [50].

3.1.1 Standards and Policies

Several asset management standards are available at the national and international level, guiding the industry with best practices. In addition to describing criteria for an asset management scheme, ISO 55000, ISO 55001, ISO 53010, and ISO 55011 offer an overview and conceptualization of asset management and the description and application of the systems. The International Infrastructure Management Manual (IIMM) provides the best practice for asset management through case studies in Australia and New Zealand. The supplement introduced by IIMM provides guidelines for executing ISO 55000 standards. PAS 55 is a British standard for an optimized framework for life-cycle management, enabling operational strategy enhancement. PAS 55 was the basis for the new ISO 55000 series. PAS 181 provides a roadmap for growth, adoption, and implementation of smart city strategy that includes business decision-making guidance, managing the smart city benefits, managing risks by monitoring smart city strategy's success. While ISO 55000 remains the standard for asset management practice in Canada, Public Sector Accounting Board of Canada introduced the PSAB 3150 standard, mandated for financial reporting of all Canadian municipalities' Tangible Capital Assets (TCAs) into their financial statements. This provided a solid base for budget planning and setting tax rates in Canadian Municipalities and encouraged Statistics Canada to collect the Canadian Infrastructure Report Card (CIRC), expanding to Canada's Core Public Infrastructure (CCPI) survey.

3.1.2 Asset Inventory

Maintaining an accurate asset inventory is the foundation for effective asset management as multiple participants deploy different data attributes and sometimes overlapping. Asset inventory and database are often interchanged but have different meanings and purposes. Asset inventory is a record of asset information, whereas the database is an organized collection of related data usually stored in a structured and logical way. The asset information includes asset attributes, asset condition, asset construction, rehabilitation or reconstruction, asset performance, O&M, financial, environmental, meteorological, and customer information. Data that is reliable, current, easy to understand, and easy to acquire is the key to effective asset management. Halfawy et al., 2006 classified data management systems as general-purpose, asset-specific, and other need-based (municipalities with developed in-house) systems [50]. All the systems are designed on a platform known as Relational Database Management System (RDBMS) and customized to specific systems/assets/needs with add-on modules supporting a wide range of applications like measuring performance and condition levels of the assets. BIM supports such integration of relational databases to 3D models, which helps asset managers to have all the asset information monitored visually. In addition to RDBMS, other studies have proved the BIM's capability integrating and advancing with other popular and widely used databases such as hierarchical model (IBM's IMS DBMS) [51], object-oriented model (Objectstore and Versant) [52], network model (IDS and IDMS) [53], object-relational model (Informix, ObjectStore, Oracle, Versant) [54], graph databases [55], and document databases.

3.1.3 Asset Inspection

When defining a maintenance strategy, asset managers must make a decision that takes into account all interdependent assets and design factors. It is challenging to integrate all the information on a common platform where the asset manager can make an informed decision. The BIM process can maintain such a common integrated database where different assets and data sources can come together. This sub-section provides a snapshot of asset inspection methods and the complexity of the associated data.

Broadly asset inspection methods are of two types: direct and indirect methods [56]–[58]. Direct methods include all the non-destructive techniques (NDT) and visual inspections indicating the distress indicators, whereas indirect methods include assessing inferential indicators or correlations from laboratory tests. Visual techniques like closed-circuit television (CCTV), sewer scanner, and evaluation technology (SSET), are widely used to assess the distress indicators like tuberculation, lining, and blockages in pipes. The non-destructive evaluation (NDE) includes inspection techniques like electromagnetic and radiofrequency techniques, acoustic and vibration techniques, radio frequency identification technique, and laser surveys aimed to assess the corrosion pits, wire breaks, pitting, cracks, leakage in pipes [56]–[59]. In roads, the NDT techniques include GPR, falling weight deflectometer (FWD), and international roughness indicator (IRI) [60], dynamic cone penetrometer (DCP), and laboratory testing include California bearing ratio (CBR), repeated load triaxial (RLT) [61] test to assess the subgrade strength and soil resistance. It is essential to determine the asset condition before it becomes vulnerable, highly dependent on observed distress indicators (physical index of the age), relying on the inspection methods' reliability and data.

Maintenance operators deploy different inspection techniques for each asset, i.e., road, water, sewer, and design parameter. For instance, in road condition assessment alone, inspection techniques like CBR (widely used to determine load-bearing capacity), Benkelman Beam (for surface deflections), RLT test (for rutting), and DCP (for strength and soil resistance) [59], [62]–[65] may be deployed by the operator to assess the condition of the road. Nevertheless, all these techniques have different information, and the databases will be independent of one technique to another.

3.1.4 Condition Assessment

After asset inspection, Condition assessment is the essential component in the asset management process which evaluates the asset's health. Sensors are utilized to capture the distress indicators during the asset inspection [66], [67], and several studies discussed visualizing the data on the 3D model through the BIM-sensor integration [68]–[72]. The data is translated into condition rating, which is subjective and fuzzy. Hua et al., 2007, Rajani et al., 2006 explained this translation of distress indicators into condition rating using the fuzzy synthetic evaluation technique and Dempster - Shafer (DS) theory [66], [67] Typically, the distress indicators include spalling, cracks, coloration, graphitization, wire breaks, delamination, tuberculation, roundness, change in alignment, joint displacement, joint diaper crack size, in case of pipes [66], [67] and raveling and weathering, rutting and shoving, bleeding, cracks, and patching for roads [73]. However, these indicators are from a structural or physical integrity perspective, and Sadiq et al. 2010, argued that the condition assessment should also consider the functional performance derived from Key Performance Indicators (KPI) [74]. The KPI includes system integrity, hydraulics of flow, water quality in water mains [75] and functional adequacy, groundwater infiltration, spare capacity in sewers [76], and driver safety, comfort, and travel time inroads.

Further, KPIs are quantitatively assessed to establish a performance benchmark defined as LoS. In the condition assessment process, the assets are compared to this performance benchmark or target LoS. The shortfall in the required LoS is addressed by a corrective maintenance action like do-nothing, repair, and replacement [77], [78]. Asset management is about managing the potential to fail. When the current condition is established, asset managers usually search for an answer to the remaining useful life of the asset and what to repair first. Typically the asset's remaining useful life is estimated using the deterioration models which helps to assess the life cycle costs to define different maintenance strategies [79].

3.2 Building Information Modeling

BIM is an effective process in the Architecture, Engineering, and Construction (AEC) industry, providing 3D representation of buildings, and infrastructure. National Building Information Model Standard (NBIMS) defined "BIM is an integrated digital representation of a facility's physical and functional characteristics at various stages of the project life cycle in the form of a database" [80]. BIM is efficient in the interoperability across disciplines [81], which is standardized by Industry Foundation Class (IFC), an object-oriented format developed by buildingSMART International (formerly the International Alliance for Interoperability (IAI)). Four levels of development define BIM maturity: Level 0 to 3, see Figure 3-1, where the conventional project and paper-centric processes (Level 0) is replaced with an integrated and interoperable workflow (Level 3) [82].

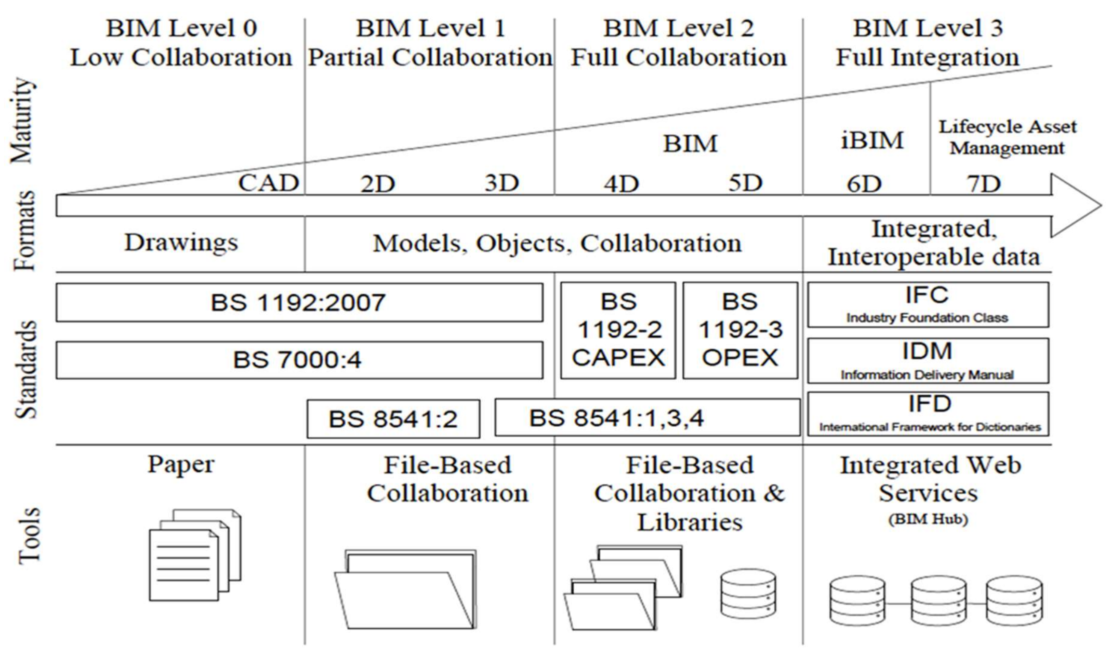

Figure 3-1: BIM maturity model based on PAS 1192

3D model shared across the project phases, reducing design conflicts and linking planned installation timing data using 4D CAD technique. This feature enables decision-makers to visualize construction sequences and inter-dependencies between trades. BIM process allows estimators to calculate quantities and cost to support the estimating process using the 5D analysis technique cutting the wait time till the detailed designs are made available.

Public organizations in Europe (Norway, Denmark, Finland, Italy, Spain, France, Germany, and United Kingdom), the United States, Middle East (Dubai, Israel), and Asia (China, Singapore, South Korea) have mandated the use of BIM process (varying levels) for publicly funded projects. Barlish & Sullivan 2012, assessed the BIM benefits from the owner's perspective and suggested a promising basis for BIM benefits to be achieved [83]. Cheng & Deng 2015, using BIM, successfully resolved the clashes virtually between the existing utility networks and the newly designed pipelines ahead of construction [84]. Lee et al., 2018, integrating BIM and GIS, indicated improved utility tunnel maintenance management [85]. Wang et al., (2019) developed a unified building model with BIM and GIS integrated for underground utilities, showing an integrated utility management framework [32].

3.2.1 Collaboration and Interoperability

Interoperability (semantic, schematic, and syntactic) is the capacity of information systems to share databases and [86], [87]. Interoperability supports collaboration with other BIM design tools, which have a relatively easy-to-understand interface. The import and export features of BIM design tools with open data exchange standards are the greatest strength of BIM as a process. BIM design tools with modular structure functionality provide a platform for scripting, automating low-level tasks. BIM design tools allow multiple users to work on the same project files by managing user access to different information parts. The object properties differ by application and form an essential part of the data required for most modeling tools. BIM supports an experimental setup of the properties and interacts with the associated objects it defines [82].

3.2.2 Parametric Modeling

Parametric modeling represents objects by parameters and geometry of their real-world behaviors and attributes, unlike the traditional 3D objects. It takes advantage of incorporating constructive solid geometry for editing and boundary representation for visualizing (rendering), clash detection, editing, and non-editing uses. As parametric modeling runs by rules, its capacity to manage various hierarchical rules is limited for specific BIM platforms. Cloud computing could be a solution to reduce performance issues due to limitations in memory and processing issues [82].

3.2.3 Sustainability Evaluation and Improvement

The United Nations Brundtland Commission Report in 1987 defined sustainability as satisfying the present needs without disrupting the future to satisfy their own needs. Sustainability indicators for buildings and infrastructure are mainly focused on energy analysis and operational productivity since it has significant cost implications during operation and maintenance. However, sustainability should be a balance between the social, economic, and environmental aspects. The sustainability of buildings is often shown by third-party certifications like LEED, BREEAM, CEEQUAL, CASBEE, Green Star, and others. These certifications are typically point haunting and consensus-based rating systems. These existing third-party frameworks are not suitable for asset management as they tend to make an objective assessment with some pre-established environmental, social, and economic criteria [40]. Life Cycle Assessments (LCA), risk assessment, benefit-cost analysis methods evaluate the payoff and return on investments. Al Hattab 2021 studied the evolution of the interaction between BIM and sustainability and established that data management, simulation, quantity take-off, and visualization are the BIM functionalities synonymous with sustainable practices [41]. To bridge the gap between BIM and sustainability, Olawumi & Chan, 2018 suggested few strategies to establish metrics that measure qualitative benefits, policy formulation, and adopt green BIM [42].

BIM helps to improve sustainability when it integrates mapping data sources like GIS for a broader context of the built environment [34]. Yung & Wang 2014 developed a 6D CAD model that can automatically assess building sustainability life cycle assessments overlaying the economic, social, and environmental impacts [88]. Charef et al., 2018 noticed that there is confusion between academy and industry in allocating the 6D to sustainability as literature has used the 6-dimension for health and safety, quality information, contract information, as-built representation (an extension to facility management) while the industry/practitioners (majority) using 6D for sustainability and 7D for facility management [43].

3.2.4 Facilities Management

Facility management (FM) ensures the built environment's functionality integrating resources with process and technology [35]. The National Institute of Standards and Technology (NIST) stated that the capital infrastructure industry had spent billions of dollars to retrieve data in the operations and maintenance (O&M) phase. FM teams spent time and effort in search of data related to historical asset management. The BIM and FM integration is said to improve performance allowing access to FM data, allowing integration with organizations' enterprise data systems like computer-aided facility management (CAFM), computerized maintenance management systems (CMMS), enterprise asset management (EAM), enterprise resource planning (ERP), and reducing costs by providing accurate and complete data to facility managers. The BIM integration with various asset database management systems is further elaborated in sub-section 3.3. The BIM 7D allows facility managers to visualize an accurate virtual model used to retrieve information when needed, analyze for space management, and produce real-time data analysis as obtained from the sensors directly on the geometry of the building model [35]. In addition to FM, these smart infrastructure systems using information technology (e.g., sensors) can also assist disaster management. Sensors installed in a water or wastewater network can gather real-time information such as flow rate, water levels, and pressures, integrating with 3D models having all the asset information. Such models can quickly identify the irregularities that require attention and define the performance levels in real-time [44]. Jianli Chen (2014) introduced an approach connecting sensor data from the geothermal bridge deck deicing system to the BIM 3D model to assess the bridge condition under different temperatures using an application programming interface (API) as a plug-in into Revit [89]. Cheng et al., (2016) explained the applications of sensor technology for performing tasks like condition monitoring in buildings are specific monitoring aspects like power usage, temperature, and humidity, water flow, airflow, leak detection, air pressure [90].

3.2.5 Existing BIM Platforms

BIM is often confused with the software (tool) that produces the 3D model. But the term BIM can be inferred for both technology and process. Models containing only 3D data without the properties of objects, models that cannot present a holistic view without referring to multiple CAD files, models that are not changed dynamically from one view to another do not constitute BIM platform. Therefore, it is essential to define the platforms, as shown in Table 3 - 1, to assess different software based on functional capabilities like synchronization, external parameter management, linking ability to external catalog files, and parametric model data exchanges. The availability of product libraries and object libraries is also crucial while selecting a suitable tool [82]. All commonly used software listed here are parametric-based modeling packages, and different marketing strategies have led to varying collections of functionalities. Some software like ArchiCAD, Bentley Systems, and Vector Works support custom parametric objects using a scripting language. In contrast, some other software like DESTINI Profiler, Digital Project are tailor-made to perform specific tasks. Among all, Autodesk-Revit seems to have an easy-to-use interface and thus a well-known and popular BIM platform. Sacks et al., 2018, has evaluated the tools listed in Table-1, based on the user interface, drawing generation, ease of developing custom parametric objects, complex curved surface modeling, object libraries, extensibility, interoperability, multiuser interface, effective support for managing properties, clash detection, quantity takeoffs, issue tracking, and incorporation of product and construction specifications. Among all, Autodesk Revit is a well-known and widely used BIM platform because it has a user-friendly interface with drag-and-drop hints and well-organized menus, allowing bi-directional editing from model to drawing and vice versa [82].

Table 3-1: BIM tools based on functional capabilities

Software	**Description**	**Advantages**	**Disadvantages**
Allplan	Parametric	Handles complex geometry, quantity take-offs, and schedules with less customization. Model integrity is the key feature when viewed in different views.	Have a complex interface and manual setup is needed
ArchiCAD	Parametric and supports Geometric Description Language (GDL).	GDL supports interoperability with -Structural engineering, -Mechanical engineering, -Energy efficiency and environmental impacts, -Rendering and Visualizations -Facility management	Do not support algebraic expressions and conditionals.
Bentley Systems	Parametric, building modeling and	Supports -complex curved surfaces, -importing external objects,	Integration with applications is time taking

Software	Description	Advantages	Disadvantages
	drawing production	-clash detection, -4D scheduling simulations, -rendering and animations.	
DESTINI Profiler	Parametric	A platform for conceptual designs with cost estimations	It must interface with other tools (Revit) for further model development
Digital Project	Parametric, in-built Workbench tool modules	Handles large complex assemblies with ease, supports MEP layouts, curved surface modeling, Interfaces with -Ecotect: energy studies, -3D Via composer: documentation, -MSP, Primavera: Scheduling, -ENOVIA: life cycle management, -3DXML: lightweight viewing	An expensive, complex user interface, limited predefined building objects, limited architectural capabilities
Revit	Parametric	Easy interface, organized menus, bidirectional editing, easier editing of predefined objects, -Supports trigonometric functions and hierarchical parameter relations, Collaborates with: -AutoCAD Civil 3D, -Autodesk Inventor, -LANDCADD, -US Cost, Cost OS, Sage Timberline, and Tocoman iLink: cost estimation,	Slows down significantly if the project files are larger for given memory space, generating complex curved surfaces have limitations

Software	Description	Advantages	Disadvantages
		-Innovaya: cost and links Primavera, MSP, -Autodesk Naviswork: clash detection, -Vico office: scheduling and quantity take-offs, -BSD Linkman mapping tool: specifications, -Revit can import DXF files	
Tekla Structures	Parametric, file-based	-scaling is good -provides an open-source application programming interface. - multiple access possible to projects on the same server - able to model structures with a variety of materials,	-complex to learn and utilize for full functionality. -parametric components require dedicated operators with a high level of skills -can import objects with complex multi-curved surfaces but cannot be edited.
Vectorworks	Parasolid geometry engine	Various Vectorworks tools include Architect, Landmark, Spotlight, and Fundamentals. Each tool has specific application such as architectural modeling, landscaping, lighting analysis, integrated rendering, and others	

3.3 BIM-based Asset Management

The applications of BIM for infrastructure asset management are less explored in literature than asset management of Buildings. The traditional approach to O&M involves the transfer of documents from owner to operator. The information is then entered into asset management systems like CMMS, CAFM, ERP, and EAM, which could be time-consuming and error-prone, leading to expensive and reactive maintenance. BIM can be a better approach in exploiting the data and transmittal to O&M operators, but this can be effective only if the information is developed during design, construction, and commissioning with the involvement of respective parties from the early stages of the project [91]. Most municipalities maintain the asset database in either 2D CAD files or GIS models, which may be efficient in spatial visualization and database query functions. Still, these databases cannot analyze the objects by parameters that automatically determine the geometry of the real-world behavior in 3D. Such parametric modeling is the strength of BIM, and when integrated with GIS, it may analyze the data efficiently, both spatially and semantically. Al-Kasasbeh et al., 2021 addressed few alternatives for the convergence of BIM and asset management data by using proprietary links, IFC, and APIs [92].

The United States General Services Administration (GSA) provided guidelines on how to link BIM to facility management, including the use of the Construction Operations Building information exchange (COBie). COBie is an open standard approach developed by the Army Corps of Engineers and NASA, including GSA, to handle the design and construction information exchange over facility management. The BIM data can be extracted into a COBie compliant file, which can be directly imported into the asset management systems to update and track facility asset data [91]. The Spreadsheet format of COBie information exchange is popular and widely accepted than the IFC. IFC XML versions are easy to understand and can be transmitted to commercial asset management software systems.

The BIM applications like coordination of the works, design review process, and collaboration methodology are typical to buildings and infrastructure development projects from a Constructor's perspective. However, the buildings are more component-based than the infrastructure, where features like the clarity of information, clash detections, and visualization during the design phase are more beneficial. BIM usage raises important contractual issues during phase transition from construction to facilities management and includes the transfer of project risks, contractual guarantees, and copyright of documents [93]. One of the main issues that municipal customers, consultants, and others have about using BIM is the perception that the legal framework is too vague [82]. Apart from the contractual issues, interoperability between BIM and enterprise data systems challenges BIM and asset management integration. Nevertheless, BIM for infrastructure can have the full potential when it is integrated with information and mapping databases like GIS [94] and with relational and object-oriented database management systems like CMMS, CAFM, APM (Asset Performance Management) to visualize the FM data providing a user-friendly interface for O&M. Thus, BIM should be able to manage the asset inventory, asset condition data, topographic data of the assets, asset bill of quantities, asset LoS, failure history, life expectancy data of equipment and materials, potential maintenance interventions and associated costs.

3.3.1 Industry Applications

Dodge Data & Analytics studied the advancement of BIM usage in the North American industries and the report. Business Value of BIM for Water Projects highlighted that the BIM has exponentially matured in the water sector and more into design activities than operational construction activities. According to the report, the most frequently used BIM activities by the Engineers, Contractors, and Owners are creating bid/construction drawings, clash detection, avoidance, quantities, and cost estimating integration. Operational activities such as BIM 3D model integration with asset management, automated tracking of equipment, leveraging for maintenance activities, linking the BIM 3D model with analysis applications, integrating the BIM 3D model with performance monitors, sensors, or smart devices are not so every day. Still, these activities are emerging to be adopted [44]. McKinsey & Company, a strategist and management consultant, analyzed that the upcoming insurance contracts will be digital, although the industry is slow in digital transformation [95].

3.3.2 Digital Twinning (DT)

BIM may not be comprehensive for asset management unless it is combined with the Digital Twin (DT). DT is the digital replication of physical assets and the dynamics of how an internet of things (IoT) device operates and works. DT integrates with IoT and AI to create a dynamic digital model [96], and BIM is the first evolutionary step towards digital transformation. In other words, the next generation DT allows systems (infrastructure) to model and visualize besides making predictions, taking actions in real-time, and data enhancing using technologies like artificial intelligence and machine learning. The DT can bridge the gap between the real world and digital systems, represent complex environments, and respond effectively to real-time situations and get a more accurate and interactive model of the real world. Digital twin for water and wastewater treatment facilities is uncommon but having such a model can efficiently deal with the process interconnections. As the utility information is maintained in a maintenance and management system, expert knowledge of plant assets can be easily lost, impacting operations' efficiency. The Fraunhofer Society, a German research organization, mentioned that the success of the 4th industrial revolution depends on creating digital twins and BIM with a structured database that may be key to generating such digital twins whose dynamic performance is studied using simulation tools different boundary conditions.

3.3.3 BIM Integrated GIS

BIM and GIS are both object-based applications sharing some similarities in terms of geometrics. The integration of BIM and GIS has been promising in resolving problems. Simultaneously, BIM allows capturing geometric and semantic information, and GIS has its advantages of geo-visualization-based decision making and geospatial modeling capabilities [97]. Nevertheless, either IFC or CityGML (City Geography Markup Language) cannot accomplish discreetly [98], which are the primary semantic standards, respectively, for BIM and GIS data exchange [99]. BIM provides a common platform to various stakeholders for data sharing [100], and GIS shows a dynamic function in data integration, visualization, and application [101]. Thus, the BIM-GIS integrated model is information-rich, having coherent 3D information by representing the building about its surroundings [102]. The important BIM and GIS integration applications are its efficiency in asset management, architectural heritage data management, site selection, and optimal layout plans, urban environmental analysis, location-based services, and navigation, 3D cadaster, and construction safety process [103] planning utility infrastructure for smart city concepts [104]. With the BIM integration with GIS, the critical points of the buried infrastructure are easily located and the estimation of service impact to customers is easily performed [44].

Cheng & Deng 2015 developed an integrated 3D framework with the asset information such as inspection records, the owner's data integrating BIM and GIS technologies to manage and analyze buried infrastructure [84]. The integrated model is aimed to analyze the clashes between the existing and the proposed pipelines to resolve virtually ahead of time. Lee et al., 2018 proposed to utilize the BIM-3DGIS integrated system for utility tunnel maintenance as the CMMS and building automation system (BAS) are unable to provide appropriate visualization and interoperability [85]. Deng et al., 2016a using BIM and 3D GIS, developed a framework to evaluate traffic noise to a greater detail, which is not possible with GIS or 3D GIS alone as the absorption coefficient and transmission loss data are not adequately extracted [105]. Barazzetti et al., 2020 through LiDAR technology, detected the road geometry automatically using BIM and GIS technologies [106]. Furthermore, GIS alone is not sufficient for clash detection such as soft clash.Soft clash is a geometric tolerance in the 3d proximity set for other objects that commonly require buffer space for safe and future maintenance works, which can be detected by combining GIS with BIM.

3.3.4 BIM Integrated Relational Database Management System

The problem of how to record information for future reference is not new. Codd 1983 defined relational structuring of data by organizing into data tables defined by rules for smooth retrieval of information irrespective of how it is stored [107]. The popular relational database management systems (RDBMS) are Microsoft SQL server, cloud-hosted Azure SQL database, Oracle, PostgreSQL, IBM's Db2, and MySQL. MySQL is popular for web-based database management systems. Microsoft Access and FileMaker are meant for smaller databases that can run on a local computer's desktop. Regardless of the application, all RDBMS needs to perform two distinct tasks, the first is to create and modify the structure of the data, and the second is to allow it to work with and manipulate data records. Relations, domains, and tuples are the core database components of RDBMS, commonly referred to as tables, columns, and records. Al-Kasasbeh et al., 2021 developed a life-cycle work breakdown structure integrating BIM and RDBMS for asset management decision support to address the interoperability between the life cycle phases of an education Building [92]. Le et al., 2020 developed a relational database module using Microsoft Access and a visual programming interface, dynamo, as BIM 6D to compute the life cycle costs. The process has automated the collection of required data from BIM 3D model elements, which otherwise would have to be fed manually for the life cycle cost analysis [108]. Althobaiti 2009 created an open database connectivity (ODBC) file with Microsoft Access to create a green building products database and integrate it with the BIM Revit tool [53].

3.4 Life Cycle Sustainability Assessment

Life cycle thinking is a conceptual framework, and Life Cycle Assessment (LCA), Life Cycle Management (LCM), Life Cycle Costing (LCC) are some of the commonly used methods for analyzing the life cycle induced impacts. Government regulatory requirements and customer demands typically influence investment needs and the budgetary decisions to maintain municipal infrastructure. Implementing 5D BIM not only assists asset managers in Quantity Take Off (QTO) but also leveraged to perform "what if" analysis with various options of alternative maintenance strategies from a life cycle cost perspective with low operating and maintenance costs [109]. Integrating the lifecycle thinking approach with structural and hydraulic condition assessment of pipe has the potential in reducing the carbon footprint for sustainable communities. Understanding the complete lifecycle from cradle to grave of different pipe materials may have a significant environmental and economic impact. Therefore, the buried infrastructure asset management cannot isolate the environmental impacts and economic cost and benefits along with the asset condition assessment for sustainable communities.

3.4.1 Life Cycle Assessment

The life cycle assessment consists of an evaluation of environmental impacts from raw material extraction, production, embodied energy required for the respective processes, construction activities, energy, and material consumption during usage of the facility, operations, and maintenance, recycle and or disposal/waste scenario. This is defined as the LCA of Cradle to Grave phase and the LCA studies do not necessarily have to contain all the phases according to ISO 14040 guidelines. For each phase in the LCA system boundaries, different material and energy flows should be evaluated to influence the overall life cycle performance of the facility. The approach for life cycle assessment (LCA) is often used to measure the performance of the entire process and to evaluate the entire system's holistic impact.

3.4.1.1 Framework

The LCA framework is methodological in estimating and assessing the environmental impacts attributable to the life cycle of a product. ISO 14040:2006, Environmental management – Life cycle assessment – Principles and framework, provides an overview of the practice, applications, and limitations aimed at a broader target audience. While the detailed technical requirements of each LCA phase are explained in ISO 14044:2006, Environmental management – Life cycle assessment – Requirements and guidelines as a core reference document for LCA practitioners. The LCA framework mainly consists of phases as depicted in Figure 3-2 and described below:

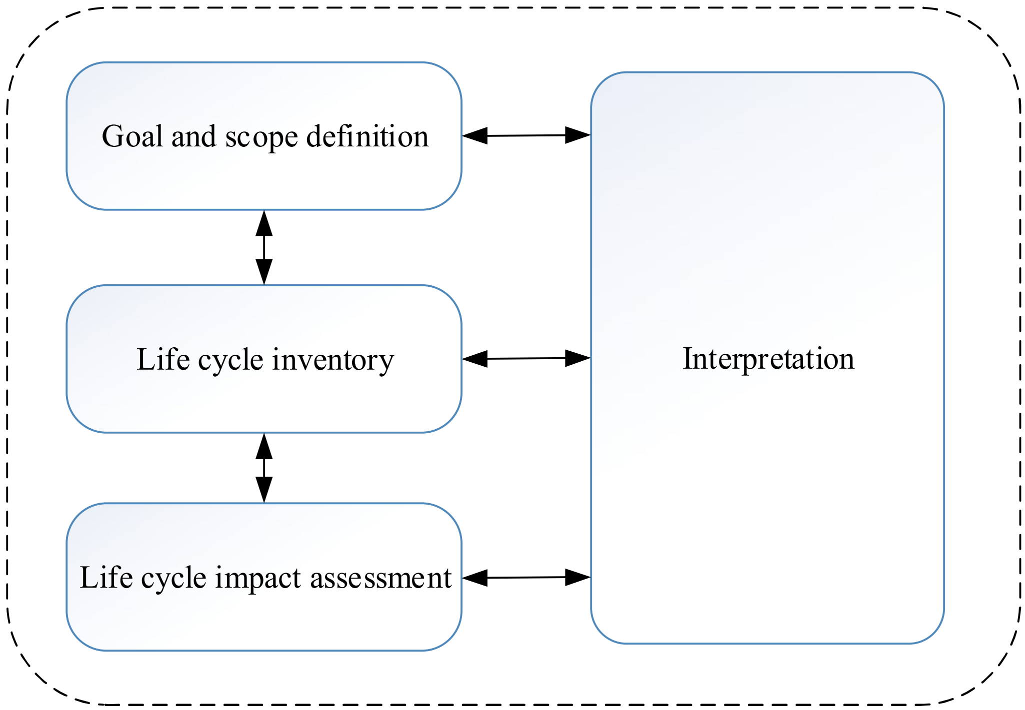

Figure 3-2: LCA framework, ISO 14040 2006

- **Goal and Scope Definition:** The objectives and parameters of the LCA study, such as functional unit, system boundary, life cycle inventory, and impact categories, in the goal and scope definition will guide the research's execution.
- **Inventory Analysis:** Inventory analysis involves identifying system inflows, such as resource and energy consumption, as well as system outflows, such as emissions to air, water, and soil, each functional unit inside the system boundary.
- **Impact Assessment:** Impact assessment categorizes the study's results in terms of their importance and potential environmental ramifications, such as ozone layer depletion or global warming. The output of the calculation is a numeric indicator, which is commonly expressed on an equivalency basis.
- **Interpretation:** Interpretation considers the goal and scope of the project, evaluates the impact assessment results, and offer findings and recommendations.

The above four phases are iterative and the collected data may lead to modification of the scope and revision of the goal. The scope is further defined by a system boundary with the included unit processes of the LCA study. A process is defined as the smallest element in the lifecycle analysis for which input and output data are quantified. The results of the LCA are reported in terms of a functional unit which is the calculation reference and defining the functional unit is the first step to commence the analysis. The inputs and outputs in the form of product, material, or energy for the processes in the system boundary are known as a flow and if it produces waste material or energy from the process it is known as waste flow. Typically flows can be called elementary flows if they enter or leave directly to the environment from the process under the system boundary. Product or Intermediary or Economic flows are the material or energy exchanged between the processes of the process under focus. The life cycle inventory mainly comprises materials and energy flow within the defined system boundary resulting in an inventory. LCA always does not use LCI and typically the impact assessment is done using the inventory alone. The selection of the LCIA method should be consistent with the goal and scope of the study. The classification can be described as the determination of inputs and outputs during the inventory process according to environmental impact categories. The characterization is defined as assigning relative weights or potencies to different types of emissions; energy use and materials used. The potencies reflect the degree to which the inventory flows contribute to relevant impact category indicators such as human health, ecosystems, and resource depletion. Figure 3-3 identifies the mandatory and optional elements for the LCIA modeling. The mandatory elements are a selection of impact categories, classification of the LCI results, and modeling an LCIA profile using the characterization factors to determine its contribution to each impact category. Nevertheless, normalization, grouping, and weighting are the optional elements in the LCIA process.

The normalization is performed to provide the reference value to the information from the spatial and temporal aspects. The grouping is generally conducted by ranking the LCIA results to meet the objectives defined in the goal and scope definition. To generate a single score, the impact results are multiplied with a weighting factor to create a weighted score of the LCIA results which is often subjective and derived with stakeholder involvement [99]. The CML – LCA method has laid the foundation in 1992 as the baseline method for characterization as the midpoint approach. This has been followed by the development of Eco-indicator 99 focused on the interpretation of results using the endpoint approach. The ReCiPe 2008 is the initial model framework and has a common methodology that includes both the midpoint and endpoint approaches.

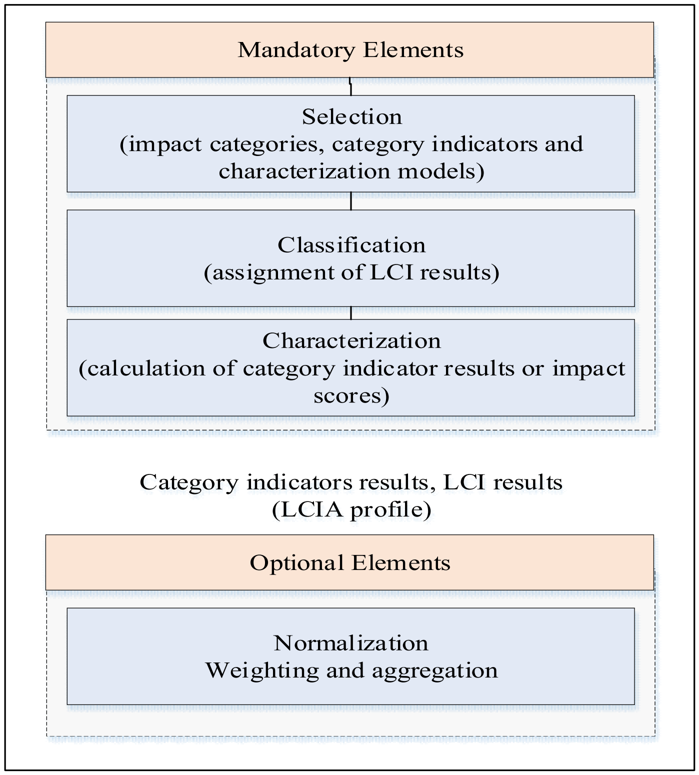

Figure 3-3: Life cycle impact assessment (ISO 14040:2006)

Further, the ISO 14040 explains that the following principles should be used as fundamental guidance for decisions on conducting and planning for LCA studies [110]:

- **Life cycle perspective**: LCA considers a product's entire life cycle, beginning with raw material extraction and acquisition and continuing through energy and material processing and manufacturing, use, end-of-life care, and final disposal. The shifting of a potential environmental burden between life cycle stages or individual processes can be defined and likely avoided using such a systematic overview and perspective.
- **Environmental focus**: LCA considers the environmental aspects and consequences of a product scheme. Economic and social issues and impacts are usually excluded from the framework of the LCA. Other methods can be used in conjunction with LCA to conduct more comprehensive evaluations.
- **Relative approach and functional unit:** LCA are a relative approach that revolves around a functional unit. What is being studied is described by this functional unit. All subsequent studies are then relative to that functional unit since all inputs and outputs in the LCI, and hence the LCIA profile, are connected to it.

- **Iterative approach:** LCA is an iterative process. The outcomes of the previous phases are used in the individual phases of an LCA. The iterative approach used within and between phases contributes to the study's comprehensiveness and accuracy, as well as the published findings.
- **Transparency:** Because of the inherent uncertainty of LCA, transparency is an essential guiding principle in carrying out LCAs to ensure proper analysis of the findings.
- **Comprehensiveness:** LCA takes into account all aspects of the natural environment, human health, and energy. Potential trade-offs can be defined and analyzed by examining all characteristics and factors of a single study from a cross-media perspective.
- **Priority of scientific approach:** Decisions in an LCA study should ideally be focused on natural science. If this is not feasible, other scientific approaches (for example, from social and economic sciences) or international conventions may be used. If no empirical rationale exists and no argument based on other scientific methods or international conventions is feasible, decisions may be based on value choices, as applicable.

3.4.1.2 Uncertainties in Life Cycle Characterization Models

The characterisation models used in life cycle assessments are obviously a source of uncertainty, and the interactions modelled reflect inadequate and imprecise knowledge of the environmental systems underlying climate change, acidification, and other issues. In the ReCiPe model framework, the uncertainty from different sources and different choices are grouped as perspectives or scenarios as follows [111]:

- Egalitarian (E)
- Individualist (I)
- Hierarchist (H)

However, these perspectives, on the other hand, do not claim to represent the epitome of human conduct; rather, they are utilised to bring together similar types of assumptions and decisions. For example:

- The Egalitarian Perspective (E) is most cautious given the longest term, the sorts of impacts not yet fully defined but with certain indicators, etc.

- In the short-run interest, uncontested impact types, technical optimism in human adaptation are built upon an individualistic view (I).
- The view of hierarchies (H) is based on the most frequent policies regarding time and other matters.

3.4.2 Life Cycle Cost Analysis

The economic analysis is the monetary evaluation of multiple alternatives that serve the same function. The overall ascertained costs are interpreted as the best option for the scenario having the lowest lifecycle costs. In most municipalities, the LCCA acts as a policy support mechanism where infrastructure management plans are motivated by the concept of optimizing the worth of the asset over its lifecycle. The concept of lifecycle cost analysis can be applied to all phases of a particular phase of the lifecycle. The life cycle cost is the total cost of an asset, in present value, including capital investments, maintenance, repair, and renewal fees, over the service life of the asset accounting for the time value of money. Life cycle cost analysis is often used as a decision support tool for managing municipal infrastructure assets while optimizing the investments and maximizing assets' value over their life cycle [112]. However, life cycle costs analysis must deal with uncertainties in future costs, interest rates, and even future risks and service life [112]. These uncertainties are addressed with deterministic or probabilistic methods and using techniques like NPV, Monte-Carlo Simulation, Dynamic programming, and Activity-based costing. In a deterministic method, the present value of the total life cycle cost is calculated with a discounted rate assuming each cost as a single absolute value, without any probability, statistical significance, or variability in the identified values. The probabilistic method deals with each element of the total life cycle costs with a probability distribution function, assuming uncertainty from one year to another. Apart from the two methods discussed, soft computing techniques like fuzzy methods, artificial neural networks deal with each cost element's uncertainty as these costs usually do not fit in the probability distribution functions [113]. Tesfamariam et al., (2018) indicated that most of the LCC models in the literature are based on average cost for any maintenance strategy [75]. In contrast, the repair and rehabilitation costs are highly dependent on the land use and topographical condition the infrastructure is located.

Government agencies like the US Federal Highway Administration (FHWA) and the US Department of Transportation recommended the LCCA as part of the toolbox [114].

FHWA's innovative finance primer states that most municipalities depend on tax revenues, provincial/federal grants, development fees, and user fees/service charges as common revenue sources. The current financing issues result from declining capital investments, inadequate funding due to rising population growth and urbanization, water services underpricing, government priorities, disconnect between water infrastructure planning's long-term existence, and the short-term priorities of elected government/municipal authorities. The budgetary decisions can be improved by expanding the current asset inventories, determining the current condition, and precisely estimating the assets' remaining service life providing better information for risk analyses and long-term investment plans.

3.4.3 Multicriteria Decision Analysis

The preceding information indicates how important it is for the sustainable use of buried infrastructure to address both the economic and the environmental consequences of life cycles. However, both economic and environmental repercussions must be taken into account combined in the performance evaluation, given that economic and environmental criteria in most situations have several conflicting goals [20]. A commonly-used strategy for sustainable research is to aggregate environmental and economic impacts with the multi-attribute decisions (MADM) [101]. It gives a more complete understanding of the sustainable consequences of the alternative.

The study of multi-criteria decision analysis can be classified as elementary, unique synthesizing criteria, and outranking methods [102]. Dominance, maximin and maximax are considered to be non-preference approaches among the basic MADM methods [102]. The decision maker's preference is not required for these procedures. When the performance ratings of alternatives surpass a threshold value for all criteria, the conjunctive and disjunctive procedures were utilised to screen them out. The weighted additive and weighted product procedures are both basic procedures that require the decision maker's preference [102]. The weighted sum approach is the most commonly used method in asset management for infrastructure systems decision-making [115].

The AHP and TOPSIS approaches are two different types of synthesising criteria. The methods are commonly utilised in energy system decision-making [116], [117]. AHP offers the unique ability to compute an inconsistency index, which is used to assess consistency in decision-making. When evaluating several levels in decision-making criteria, it is also extensively used. [118], [119]. When decision-makers seek to prevent risk while also maximising advantages, they utilise the TOPSIS (Technique of Order Preference Similarity to the Ideal Solution) method [120], [121]. ELECTRE and PROMETHEE can handle both quantitative and qualitative criteria whereas PROMETHEE is less difficult and is utilised without standardisation by scores [122].

3.4.4 Summary

The main purpose of this chapter is to present how municipalities thrive for efficient and effective maintenance of aging assets with a higher risk of non-performance. The current state, anticipated Level of Service, and asset vulnerability is critical for sustainable asset performance. This can be achieved through accurate and relevant data that supports rational decision-making on the optimal maintenance and capital development management plans, considering long-term financing. This chapter has explored how the conventional database management systems such as CMMS, CAFM, and APM are inefficient in the representation of FM data and discussed how BIM integrated asset management offers a user-friendly interface for O&M. In addition to that, it was also discussed how mapping databases such as GIS operates in isolation assembling the spatial and temporal data without capturing geometric and semantic data. Nevertheless, it was evident from the literature that BIM in collaboration with GIS provides the platform in the form of IFC for data enrichment. BIM provides an integrated environment with a structured framework for other databases. A comprehensive understanding of these interactions will have the actual ability of BIM in automating asset management of the municipal infrastructure as a whole asset system. BIM is widely acknowledged in buildings and is more beneficial during the design and construction stages, with functionality such as information transparency, clash detections, and visualization being a component-based structure compared to infrastructure. Thus, this chapter focused on presenting a systematic literature review on the role of BIM in asset management for municipal infrastructure with a discussion on the challenges and ways forward.

Chapter 4: BIM for Integrated Asset Management

The aim of this chapter is to develop a BIM 3D model that can also interact with non-BIM users having a life cycle database. This chapter is concentrated on the development of a 3-dimensional model and a platform for life cycle database which will be updated subsequently with results of Chapter 5 i.e., lifecycle impacts. The BIM database will be linked to an external source using the relational database management system (RDBMS) such as Microsoft Access.

4.1 Background

BIM is a digital representation of the physical and functional characteristics of a facility according to the National Building Information Standard. The better way to deliver civil infrastructure projects with more efficient design documentation and minimizing errors and omissions is how the BIM authoring software tools work. The traditional 2D CAD environment does not support design changes at an advanced stage without putting in good efforts, while the intelligent 3D models built in the BIM environment can update the changes automatically along with the annotation that's associated with the dynamic model. The intelligent 3D model enables to keep the documentation consistent throughout the design and able to carry forward during O&M. Chapter 3 has already discussed the literature on various possibilities of BIM usage for buried infrastructure asset management, including such as structural conditional assessments, hydraulic analysis, lifecycle assessments, energy analysis, information retrieval, space management, real-time data analysis through sensors directly linked to the geometry of the building model [32].

The comprehensive literature review in chapter 3, showed the incapability of 2D models in realizing the value of BIM limiting them to only for visualization. The BIM has the significant potential not only in modeling but also as a database that can be linked to external sources. Although many studies have considered BIM usage for building life cycle phases, no study had considered modeling buried infrastructure comprehensively for asset management. In addition, there is a lack of knowledge on how the BIM database can be linked to external relational database management systems without writing programming scripts. InfraGuide's *Best Practices For Utility-Based Data* has outlined data management focused on

1) *What information is required?*
2) *What are the initial considerations?*

Further, the key life cycle data groups identified for municipal utilities can be broadly categorized into system attributes, O&M data, performance data, meteorological data, customer data, financial data, and environmental data [48]. Ideally, such data repositories must be supported by a non-proprietary data model/data structure for integration in any utility application. Such integration is comprehensively achievable with BIM where the database is built-in "extended properties" of the model using the concept of "property sets" and is linked to an external database which was discussed in detail in the next section. Therefore, evaluating these processes will contribute to the body of knowledge and will help future researchers to build comprehensive as-built information.

4.2 Methods and Procedure

This section provides a structured procedure for creating a 3D model and implementing BIM execution for asset management by developing a database in extended properties. Autodesk Civil 3D ® civil engineering design software supports the BIM process with integrated features like drafting, design, and construction documentation. The development of a 3D model is initiated with point creation followed by a polyline and a 3D solid. The CoK municipality maintains utility information in GIS shapefiles, which are directly imported to Civil 3D to create polylines in this study. However, this section has also discussed the procedure for creating points for municipalities that do not maintain shapefiles. The following methods describe the point or polyline creation.

4.2.1 Creating Pipe Network

Civil 3D allows direct import of GIS shapefiles into the planning and analysis workspace using the map-import tool. The planning and analysis workspace is an easy-to-use interface that allows Civil 3D to interact with ESRI SHP files directly. Once Civil 3D has established the connection with the SHP file, polylines are created with object data properties that are linked to the SHP file. These polylines serve as a template for drawing 3D pipe solids directly in Civil 3D after choosing the pipe diameter and material. For creating a geo-referenced polyline with object data properties, the GIS coordinate system should be matched with the Civil 3D drawing file. The data object properties from the polylines are not automatically acquired by the 3D pipe solids, but they must be assigned manually. It is recommended to import only the area that is necessary for modeling as importing larger SHP files increases the 3D model file size and becomes difficult to operate.

4.2.2 Creating Survey Points

Civil 3D also allows direct import of survey data without the need for any third-party software. The survey database settings include the "equipment database", "figure prefix database" and "linework code sets" displaying the survey data organized within these databases. The equipment database helps to set up the survey equipment to apply the correction factor for the traverse analyses. The figure prefix database helps to translate the field descriptions to lines in CAD called figures. The linework code set database allows the crew to customize the field data collection. These settings remain in the survey database and are not drawing specific [123].

Configuring description keys for point import

Description key is the listing of field raw descriptions and parameters that automatically control the imported or created point in the drawing. The description key is defined by code property and format property. The code property is used when the code and raw description are matched whereas the format property translates the raw description into a full description.

4.2.3 Creating COGO Points

A COGO point can represent the existing feature such as a tree, topography, road geometry, or a pipeline in this research. Civil 3D points are intelligent objects that represent *x, y,* and *z* locations in space. The points created or imported using a delimited text file are called a COordinate GeOmetry program (COGO) point. The major difference between a survey point and a COGO point is subtle. A COGO point is graphically represented in the drawing itself and its definition can often modify by its own properties' palettes. In contrast, a survey point has its definition stored within a survey database and its graphical representation stored in the drawing [123].

The above methods of point creation for 3D modeling are very basic and municipalities that do not have the asset information either in 2D CAD or in GIS can follow these methods. However, the pipe network creation is not daunting with a 2D CAD or GIS shape file. The advantage of importing a GIS shape file over 2D CAD is the asset attributes associated with the SHP file, which gets directly into Civil 3D as a polyline.

Interference check

To make sure the pipes and structures are properly spaced Civil 3D allows a 360-degree rotating visual check for any clashing. Interference check identifies the hard clashes where two components, pipes, inadvertently collide. It also identifies the minimum safe distance between the pipe networks by using a 3D proximity check criterion. The safe distance crierion is used to avoid hard clashes. Multiple pipelines are allowed to be designed in a common trench, provided the design is taken care of interference with service connections, stability of the benched portion of the trench, conflict with manholes and appurtenances. Sewers (sanitary and storm) in a shared trench with a horizontal clearance of not less than one metre between the pipes are allowed under Schedule 4 of Bylaw 7900 of the City of Kelowna, BC design requirements [124]. However this Bylaw does not encourage having a common trench for water and sewer pipelines in a common trench. The design guidelines from Washington Suburban Sanitary Commission (WSSC) specifies common trench for water and sewer provided a vertical clearance of 0.5 meter is maintained. Therefore, the interference check with a safe distance of 0.5 meter to 1.5 meter is analysed to accomplish the potential benefit from developing the 3D model. The interference check is performed by choosing a part of the two different pipe networks for which clashes are to be detected and running an interference check tool on it. To find the 3D proximity minimum safe distance criterion, any distance as per local regulations is applied. This setting helps to create a buffer for fitting pipe parts that might interfere in the future.

O&M typically requires design/asset information for deciding on an appropriate maintenance strategy. The process of information exchange from the designs to O&M is daunting as the current practice requires some extent of manual integration of drawings and their corresponding asset information such as its inventory, condition, and maintenance data. Existing spatial systems such as GIS are helpful in geo-tagging the asset spatially but inefficient in collaborating with FM tools like CMMS and therefore the software interoperability remains a significant challenge. This can be overcome with the integration of BIM and FM tools to a certain extent by maintaining the required asset data in the model. This may be extremely helpful for municipalities with large asset information where the necessity of maintaining separate databases for design drawings and asset information can be eliminated.

4.2.4 Property Sets (PS)

This section describes how the different types of data can be stored using the Property sets feature in Civil 3D. A property set defines a custom-specific characteristic that can be associated with an object in Civil 3D. The PS is defined by using the style manager either manually or automatically. For instance, the physical characteristic such as the volume of a 3D pipe is an automatic property that can be obtained from setting up property sets. Using the properties palette, the extended or custom properties are assigned to the 3D object and the object becomes the container for the property data. The PS data is enriched with Fields, Lists, and predefined content which can enhance the documentation capabilities within the model. The Field values are automatically updated whenever there is a property change. Fields can be associated with hyperlinks or an external database.

- **Database Fields:** A single area of a query or table in a database is referred to as a database field. This allows data to be linked to other databases, and the database to be linked back to the model. Database Fields supports text, memo, data/time, integer, real, and Boolean only and ignores all other data types. The supported database providers are Microsoft Jet 4.0 OLE DB Provider (Access) and Microsoft OLE DB Provider for ODBC Drivers. These database providers allow linking the data to Microsoft Access database (MDB), Microsoft Excel file (XLS), and Microsoft Text file (TXT, CSV) data sources. The database field contains the following components:
  1. An optional reference to an existing Microsoft Data Link file (udl)
  2. A connection string
  3. The name of the table or query containing the selected field
  4. The name of the selected field
  5. The key access type: a primary key (1) or a row index (2)
  6. The SQL Select clause to retrieve the field from the specified record in the specified table or query
  7. Optional formatting options, depending upon the data type of the selected field

The field code retrieves the selected field value using the primary key value. Therefore, a primary key is important for each table to connect with which is the basis for relational databases.

- **Lists:** A list definition can be used to construct a list of objects, which are then added to a manual property definition. With a predefined list of valid objects, an item can be selected from the list for a manual property either in the property set description or on the Extended Data tab of the Properties palette. This decreases the redundancy of entering frequently used values.

4.2.5 Quantity Takeoff (QTO)

Civil 3D features QTO from the model to quantify and export the data to different formats. The 3D model is typically associated with three files mainly: pay item list, pay item categorization file, and the formula file. The pay item list is maintained externally in CSV (comma delimited), AASHTO TransXML, and Florida DOT file types. The pay item list provides information on the pay item number, description, and unit of measure as a minimum. The pay items are organized as pay categories (for example Division 200 for Earthwork) and the pay categorization file is used for this which is formatted as XML file type. Once these files are associated with the model, the model saves the path to these files stored in the computer and cannot be altered.

4.2.6 Developing 3-dimensional Model

The development of the 3D model in this research work has considered the open-source data of water and wastewater pipe network from the City of Kelowna (CoK) municipality, British Columbia [47]. The CoK maintains GIS files in their database and hence the 3D model for the pipe network in this study has been developed directly from the GIS SHP file. The 3-dimensional model was developed by the following four important steps:

Step: (1) SHP file preparation

Step: (2) Defining existing ground surface from contours

Step: (3) Drawing 3D pipes from polylines

Step: (4) Interference checks

Step: (1) SHP file preparation: The CoK municipality has a total of 1457 km of pipeline in total including water and wastewater (as available in the opensource dataset) within a city boundary of 262 square kilometers, s*ee* Figure 4-1. A small area in the CoK municipality near a lower mission area with 6.52 km of the pipeline (water and wastewater) was masked and extracted using a clipping algorithm in QGIS (Quantum-GIS), QGIS is a free and open-source Geographic Information System [125].

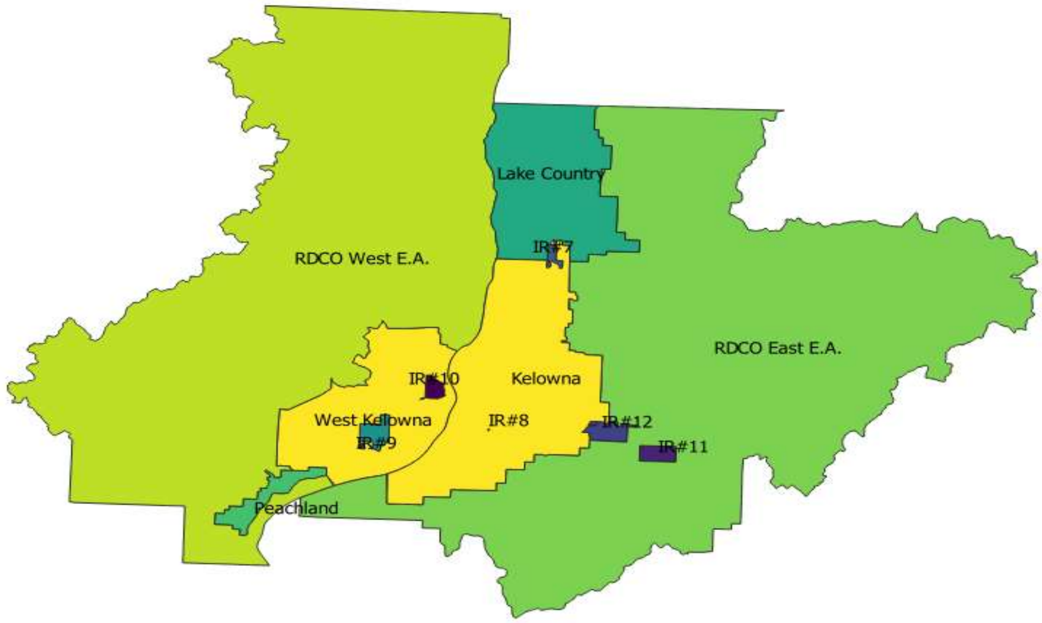

Figure 4-1: Okanagan valley location map

The clip algorithm clipped the vector layer using the features of an additional polygon layer. The polygon features only the parts within the input layer and overlays to the resulting output layer. The attributes of the features are not modified, although properties such as the area or length of the features were modified by the clipping operation. The clipped area was exported as a separate SHP file for later use in Civil 3D, see Figure 4-2. The coordinate system used while importing was UTM83-11, UTM with NAD83 datum, Zone 11, Meter, Central Meridian 117d W. Before drawing 3D pipes the existing ground profile was created in Civil 3D and Step: (2) explains this in detail. The SHP file is then imported to Civil 3D as closed polygons.

Figure 4-2: Clipped area from City of Kelowna municipality

Step: (2) Define existing ground surface from contours: the imported polylines were georeferenced and a ground surface was created as the next step representing the actual ground conditions in the model. This surface has become a context to further develop the 3D model that is georeferenced representing the actual ground conditions. The contour 1m 2019 was obtained from the CoK open-source data which was derived from 2019 DEM [126] see Figure 4-3. Once the surface was created from the GIS data the next step is to create 3D pipes (water and wastewater networks) which is explained in the next step in detail.

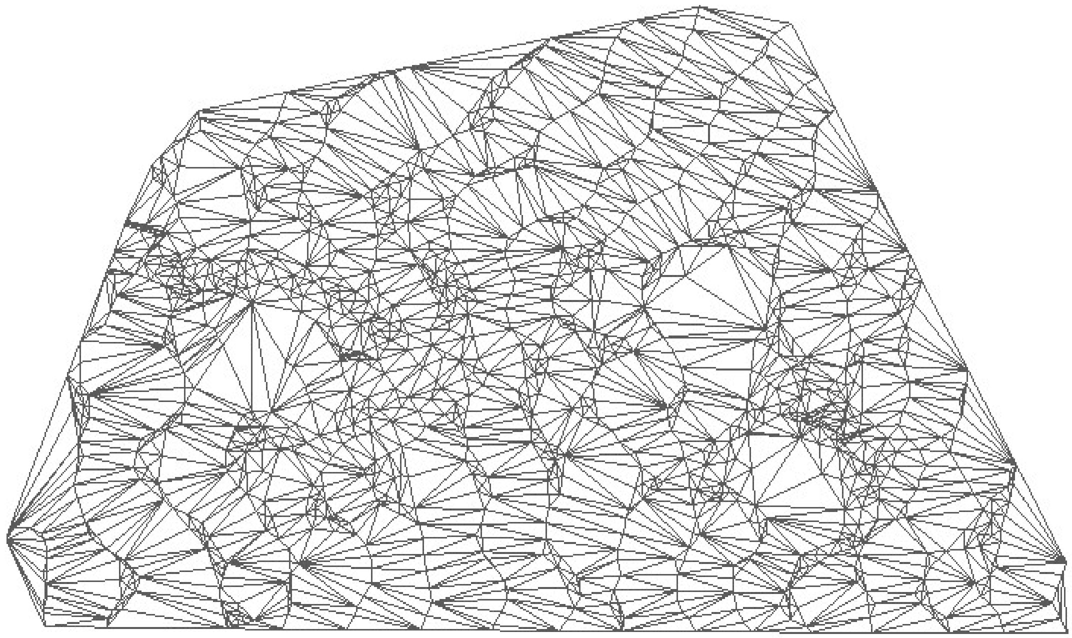

Figure 4-3: Surface area developed using contours 1m for the clipped area

Step: (3) Drawing 3D pipes from polylines: Once the surface has been created the polylines imported from GIS were used as the pipe template to draw the 3D pipe directly for gravity (sanitary and sewer) and pressure pipes (water). Geometrical pipe attributes such as pipe length, diameter, elevation, and slope were imported with the polylines and used as a template to generate the 3D pipe solids. The geometrical information may be automatically extracted from the 3D model once the 3D pipes have been created. Non-geometrical information in GIS shape files, such as pipe material, asset tags, and owner information, must, nonetheless, be updated manually. This is where the property sets are used to maintain the non-geometry information along with creating custom information, *see* Figure 4-5. While creating the 3D pipes, pipe rule sets for cover and slope criterion, length check criterion, pipe to pipe match, and set pipe end location has been utilized as default.

Step: (4) Interference checks: Although the model is as-built from the existing pipe network in the CoK municipality, an interference check is carried out to identify any hard clashes, and the minimum safe distance in the 3D proximity of each pipe was identified using the interference checking tool. This tool was activated by selecting the gravity pipe network and the 3D proximity distance (safe distance) was defined.

The conceptual framework for the development of the 3D model and its application is presented in Figure 4-4.

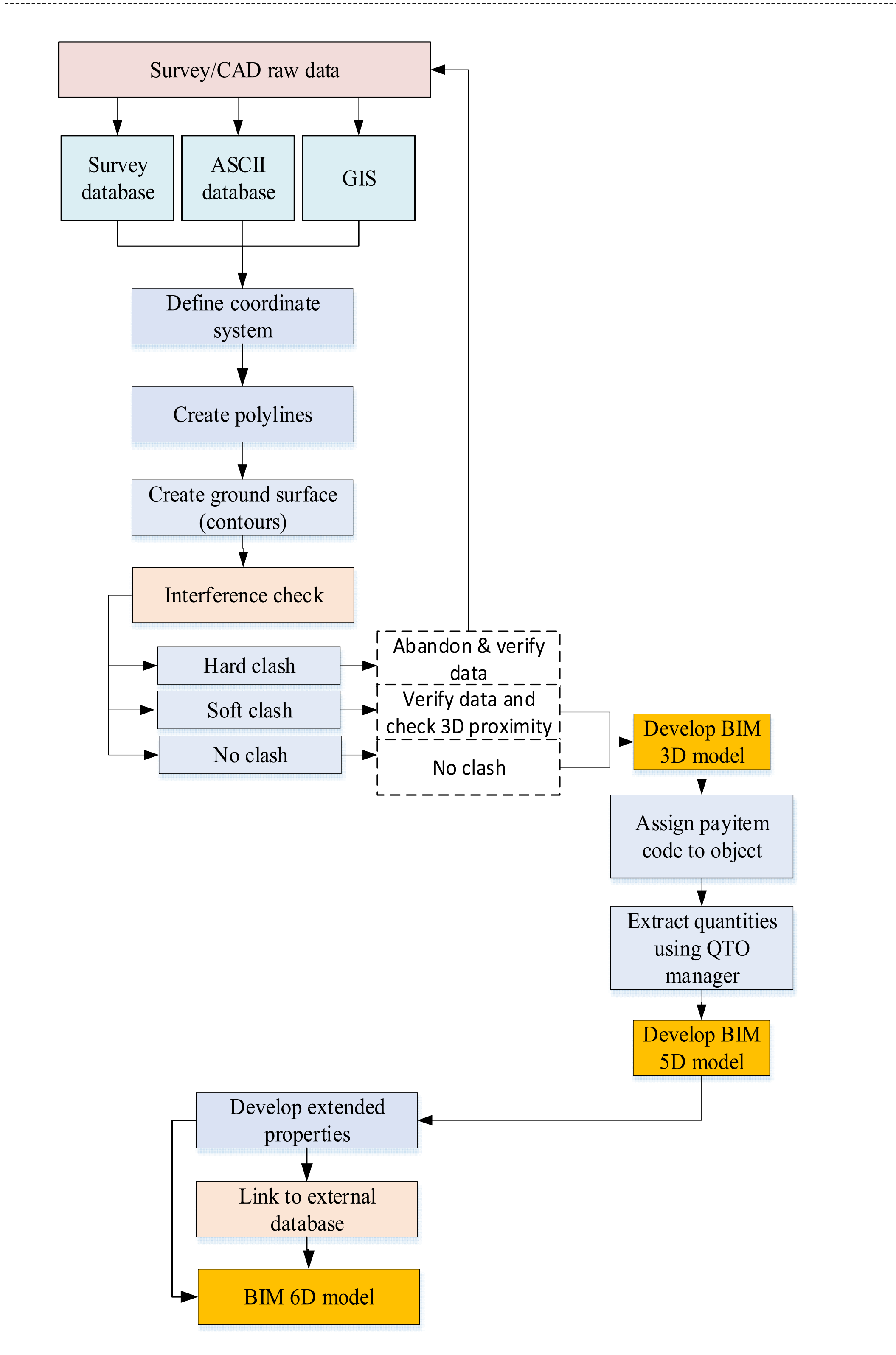

Figure 4-4: Conceptual framework for adopting BIM

4.3 Results and Discussion

4.3.1 3-dimensional Model

The developed 3D model using the clipped GIS shape file of CoK is given in Figure 4-5. The modeled area has different corridors totaling 3.4 km that includes, Sarson's road (0.776 km),

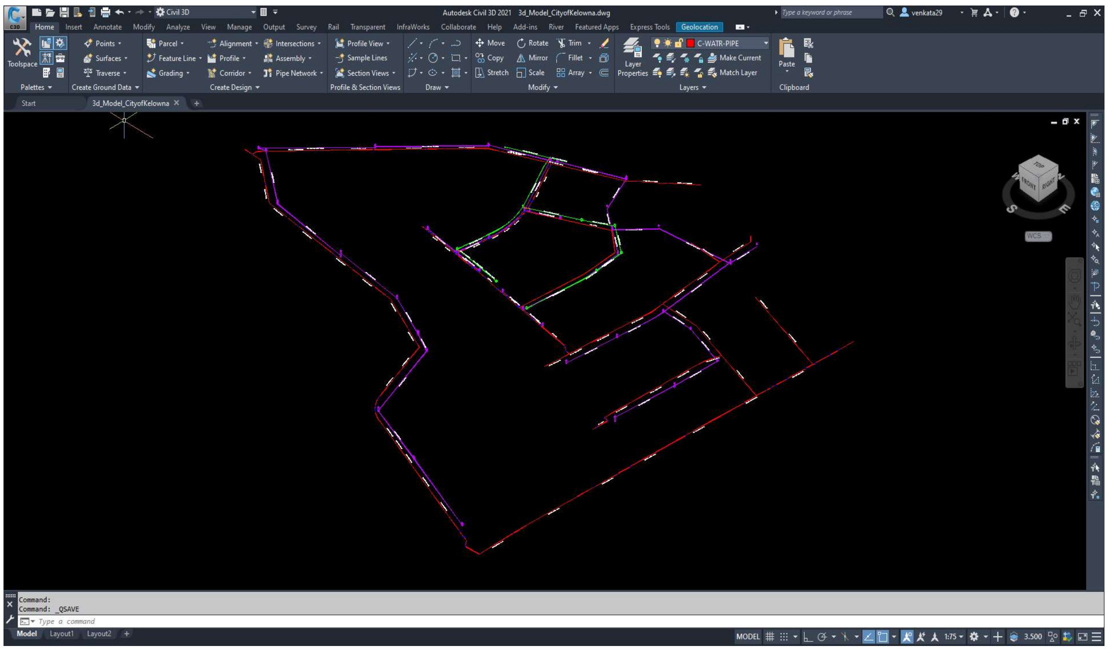

Figure 4-5: BIM 3-dimensional model drawn in Civil 3D

Lysons CR (0.273 km), Lakeshore Road (0.534 km), Hobson road (0.46 km), Uley Road (0.194 km), Kensington DR (0.316 km), Dunvegan CT (0.147 km), Metcalfe Ave (0.273 km), Edinburgh CT (0.147 km), Kirkby CT (0.147 km), and Coryell Rd (0.131 km). These corridors have water and wastewater pipe networks of a total length of 6.52 km, and diameters varying from 4” to 12”. Each pipe has been assigned a pay item and using the QTO the pipe lengths were obtained and then the volumes are calculated as follows, see Figure 4-6:

1. The water network of 3.414 km is made of 2.626 km (32.99 m^3) AC and 0.788 km (2.53 m^3) PVC material.
2. Sanitary sewer network of 2.484 km (10.47 m^3) made of PVC.
3. Storm sewer network of 0.62 km (3.39 m^3) made of PVC

Summary Takeoff Report

Pay Item ID	Description	Quantity	Unit
10000-0101	4-INCH WATERLINE, POLYVINYL CHLORIDE (PVC)	28.341	M
10000-0102	4-INCH WATERLINE, ASBESTOS CEMENT (AC)	416.195	M
10000-0116	6-INCH WATERLINE, POLYVINYL CHLORIDE (PVC)	721.870	M
10000-0117	6-INCH WATERLINE, ASBESTOS CEMENT (AC)	1657.214	M
10000-0131	8-INCH WATERLINE, POLYVINYL CHLORIDE (PVC)	38.177	M
10000-0132	8-INCH WATERLINE, ASBESTOS CEMENT (AC)	103.425	M
10000-0136	8-INCH SANITARY SEWERLINE, POLYVINYL CHLORIDE (PVC)	2484.064	M
10000-0147	10-INCH WATERLINE, ASBESTOS CEMENT (AC)	430.435	M
10000-0156	10-INCH STORM SEWERLINE, POLYVINYL CHLORIDE (PVC)	477.289	M
10000-0171	12-INCH STORM SEWERLINE, POLYVINYL CHLORIDE (PVC)	142.159	M
10000-0192	16-INCH WATERLINE, ASBESTOS CEMENT (AC)	18.850	M

Figure 4-6: BIM quantity report in Civil 3D

Further, an interference check analysis between the gravity pipe networks i.e., sanitary sewer vs storm sewer has resulted in the following conflicts as tabulated in Table 4-1. Typically, the City regulations should define these safe distances and since the current model is from an existing dataset there aren't any hard clashes found. However, the safe distance defined in the model ranges from 0.5 m to 1.5 m has resulted in many conflicts at the locations mentioned in Table 4-1. Mostly, these soft clashes are observed at the junctions or manholes as the pipelines were connected to the junction lowest point.

Table 4-1: Interference check aka clash detection

Conflict type	**# number of conflicts**	**Location (*x, y, z*)**
Hard clash	0	
Safe distance @ 0.5 Meter	1	320612.083276, 5522365.771528, 343.933031
Safe distance @ 1.0 Meter	3	320570.932061, 5522441.471411, 343.467260; 320612.082796, 5522365.770997, 344.021398; 320614.961195, 5522264.300490, 345.088306;
Safe distance @ 1.5 Meter	4	320570.931968, 5522441.471770, 343.468334; 320612.081921, 5522365.770879, 344.022678; 320614.961078, 5522264.300400, 345.111968; 320571.032869, 5522441.533865, 343.469140;

A snapshot of the clash between the storm and sanitary pipe is shown in Figure 4-7, the third color other than magenta (Sanitary sewer) and green (Storm sewer) was the conflict portion of the pipe. The conflicting length has points of varying distance from 0.5 meters to 1.5 meters. However, this sought of clash detection is not possible between pressure and gravity pipes as the Civil 3D version 2021 does not support the interference check between pressure and gravity networks.

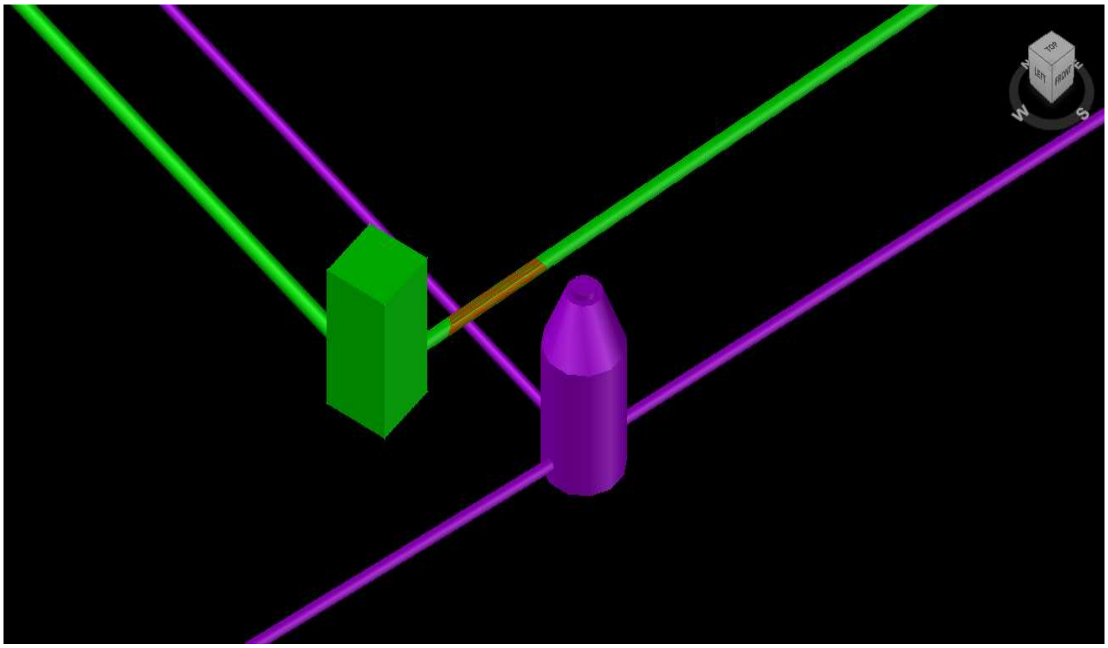

Figure 4-7: A representative snapshot showing the soft clash

The combination of BIM and GIS in the development of the 3D model has resulted in fluid interoperability, allowing the use of real-world project data to visualize the buried infrastructure. Although hard clashes are easy to locate either in BIM or GIS, the added advantage of combining GIS shape files into BIM 3D model was the ability to analyze the soft clashes between pipes of varying distances with exact coordinates.

4.3.2 BIM Database with Asset-data

The developed model was further customized, extended, extracted, and linked the model data from the as-built model to an extended database. The aim of maintaining a data-rich 3D model is for agnostic interchange of information to various standards and software that are involved in asset management. Sharafat et al., 2021 linked the data models of the tunnel construction process to IFC schema based on property sets and indicated efficient data sharing, information integration, data accessibility, and efficient project management

[127]. Attributes or data can be geometric, characteristic, and extended data related to service, technical and business information that makes the 3D model a system.

- **Property Sets:** While the object data is limited to only AutoCAD entities, property set data information is an addition to the model with the extended data. The property data sets can be applied to either objects or styles and definitions. The PS applies to objects when the manual properties of each object are different and style-based PS when these properties are the same at all instances. In the current model, the property sets were applied to only objects such as gravity pipes, pressure pipes, their appurtenances, and fittings. The PS is described using a sample sanitary sewer pipe (CoK_ObjectID:6159), given in Figure 4-8. The pipe characteristics such as material, diameter, and length are categorized under asset attributes and to condition and performance data. The attribute "Handle" is the automatic PS representing model object unique ID and the 3D Length is calculated automatically based on the following code from the model.

```
RESULT="--"
On Error Resume Next
Set oApp=GetObject(, "AutoCAD.Application")
Set oCivilApp=oApp.GetInterfaceObject("AeccXUiLand.AeccApplication.13.3")
Set obj=oCivilApp.ActiveDocument.HandleToObject("[Handle]")
RESULT=obj.Length3D
```

Some fields are manually entered and to reduce the redundancy of entering frequently used values, few fields such as asset type, material, diameter, deterioration environment, have been created with PS lists. This enables a selection of the required attribute from a dropdown menu. The asset attributes such as CoK Asset ID, object unique ID, asset type, installation year, pipe material, diameter, and pipe length are tagged to the asset, shown in Figure 4-8 for reference. Further, the BIM extended database will be updated with the results of chapter 5, see section 5.3.3.

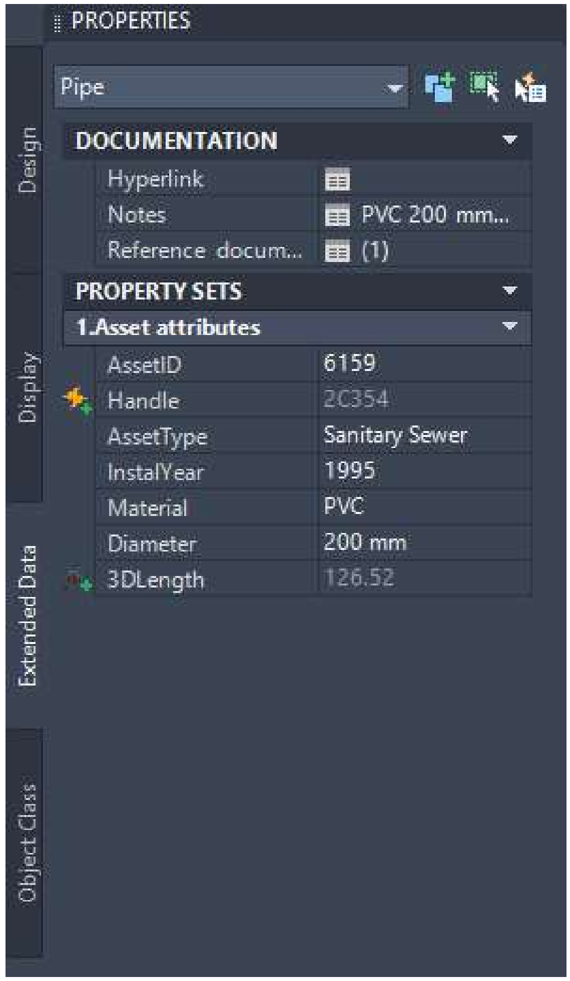

Figure 4-8: A snapshot of the BIM database with asset data

4.3.2.1 Integration with Microsoft Access Database (MDB)

Now the PS are created and when this can be integrated with external databases such as Microsoft Access Database (MDB) any non-BIM user can access the information who are involved in the asset management process. This integration is not a separate process but can be done when creating the PS definition. The connection is bi-directional, which means the attributes can be updated either in the model or in the external database. Under the Field category, the AEC Database is chosen which contains the DatabaseField with an option for 32-bit or 64-bit link. From the datalink, the datalink properties window pops up and Microsoft OLE DB Provider for ODBC Drivers is picked as the connection is being made with Microsoft Access for the sample pipe (CoK_ObjectID:6159). This should link the DatabaseField with the external Access file.

4.4 Summary

This chapter discussed the methods and procedure for the development of the 3D model using the Civil 3D software and the creation of a life cycle database that can integrate with an external relational database such as Microsoft Access or Microsoft Excel. A sample pipe network that contains the water and wastewater pipelines from the City of Kelowna municipality, BC has been selected to describe the BIM process. The data for modeling the water and wastewater pipelines has been retrieved from the City of Kelowna's open source available in GIS shape files. Typically, BIM 3D models are developed from field survey points or existing COGO points from an ASCII file and thus the methods section has also discussed creating 3D models using the field survey data and from COGO points. Alternatively, a new and easy method of creating a 3D model using GIS shape files has also been elaborated as highlighted that the polylines imported to Civil 3D are with the attributes that exist in the shape file. Also, from the developed model, the bill of quantities was retrieved easily using the assigned pay items for each pipe. Lastly, the extended properties were created using the guidelines from the InfraGuide report on storing utility data for a sample pipe and presented the life cycle database using the property sets applied to objects which were then linked to an external source.

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Chapter 5: Life Cycle Sustainability Assessment of Pipes

5.1 Background

Life cycle environmental and economic sustainability is measured quantitatively using the LCA and LCCA tools, respectively. The LCA is a standardized tool (ISO 2006) that estimates environmental impacts in terms of ecosystem deterioration, human health impacts, and natural resource depletion. Previous studies such as Hajibabaei et al., 2018 and Chhipi-Shrestha et al. 2017 investigated an urban water cycle in a single framework combining water supply, water treatment, water distribution, wastewater collection, and wastewater treatment system [128], [129] see Figure 5-1. Within this urban water cycle framework studies done by Slagstad, H., & Brattebø, H. 2014, Amores et al., 2013 has analyzed the entire system [130], [131] while studies done by Barjoveanu et al., 2014, Remy and Jekel 2012 are specific to a particular system [132], [133]. The goal and scope of the study are specific to the analyst research objective and there is no specified boundary that can define the study limit.

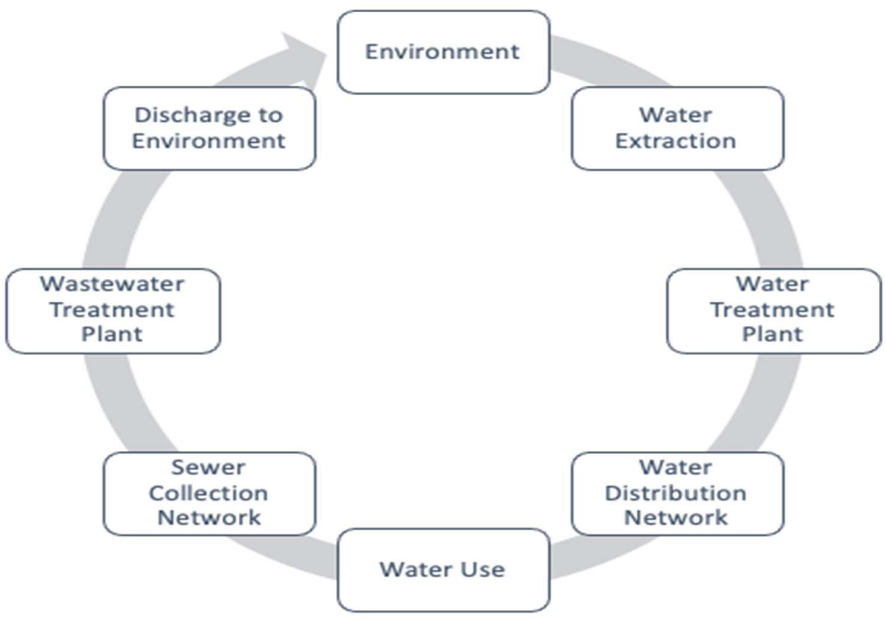


Figure 5-1: Urban water cycle

The sustainability assessment in the present research has been limited to different pipes that are used for drinking water, wastewater, and storm sewer from raw material extraction to disposal at the end of life. The environmental impacts from the study have been aggregated mainly from four lifecycle stages: pipe production, installation, maintenance, and waste treatment. The results have been focused on global warming impact (GWI) described by kg CO_2eq emissions during the lifecycle and the overall life cycle impact.

Repeated excavations for maintenance of water and wastewater systems not only increase the social and maintenance costs but also expose the buried infrastructure frequently to hazards. Multi-purpose utility tunnels (MUT) have been in the market for ages integrating the maintenance activities of water and wastewater systems reducing the repeated excavations, lowering traffic congestion, and providing access in all weather conditions. However, the major disadvantage with MUT is their high initial costs but a major reduction in construction costs from excavation and reinstatement related to buried infrastructure maintenance. Therefore, this study has analyzed the economic consequences of using a common trench in addition to using a single separate trench for water and wastewater pipelines along with its maintenance. Typically, the life cycle costs include the costs associated with engineering, procurement, construction, operation and maintenance, decommissioning, land acquisition costs, and social costs [112].

5.2 Methods and Procedure

This study evaluated the life cycle environmental impacts of different pipes that were considered to be used in the City of Kelowna, BC, Canada [134]. Previous studies have defined the functional unit as "supplying one cubic meter of water" or "per capita per year" when the system efficiency or user behavior has been studied [128]. This study has to compare different pipes, so the functional unit has been defined as "one meter of pipe length". To describe the goal and scope further, Pipe materials AC, CONC, DI, PVC, and VIT with 200 mm diameter, one-meter length, and for a lifecycle analysis period of 100 years have been assessed. The principles and framework for an LCA are considered in ISO 14040, while ISO 14044 sets out the requirements and guidelines to conduct the LCA study.

System Boundary

The system boundary in this study encompasses a series of processes from raw material extraction to disposing of the material back to earth, within the urban water cycle system, see Figure 5-2. The study has excluded the use phase from the system boundary as the pumping energy during the operations is highly influenced by the topography, grid pressure and the efficiency of the pump [135] which varies with each study area and cannot be generalized. Although the influence of pipe corrosion varies with material and the pipe corrosion may impact the pumping energy, still it is excluded from the study to simplify the boundary conditions. The transportation includes pipe transport from the production plant to the construction site, transport of construction material such as gravel, sand for backfill, and concrete. The construction materials were assumed to be available locally, and the pipe manufacturing units nearest to Kelowna, BC, are chosen for the model development. The manufacturing unit for DI and VIT pipes are the farthest of all with 4500 km and 4000 km respectively followed by 1500 km for PVC, and 1295 km for AC and Concrete pipes.

The life cycle phases of different pipe materials mainly include pipe production, installation, maintenance, disposal, and recycle. The raw material extraction, transportation of raw material to manufacturing units, energy consumption for manufacturing and emissions, and transportation of the final products i.e., supply of pipes to construction sites, transportation of disposed pipe to a landfill or recycle unit are all included in the above main phases.

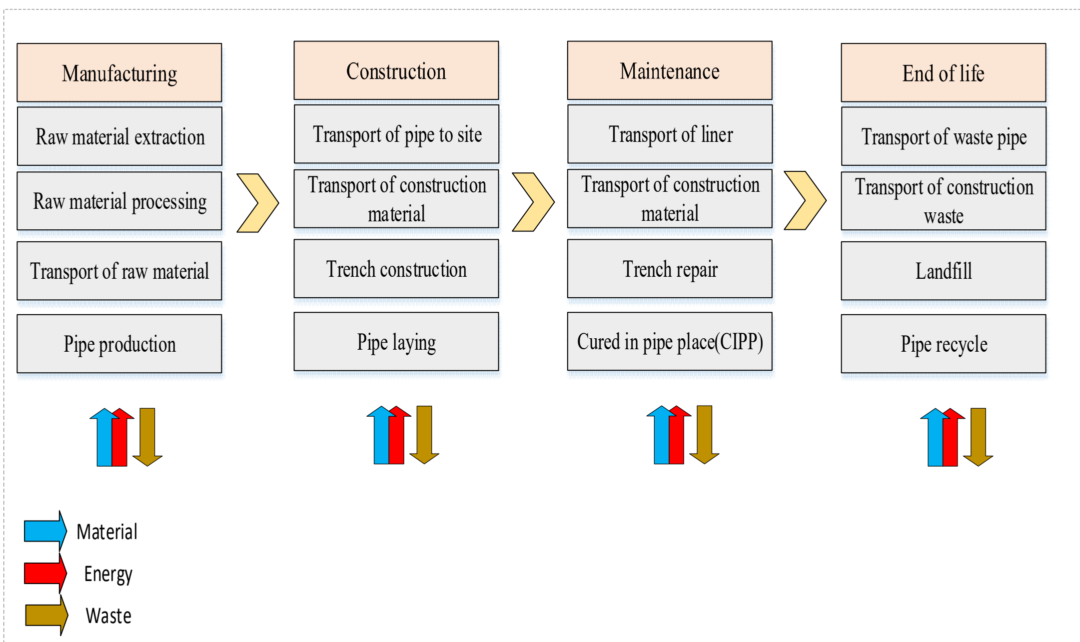


Figure 5-2: System boundary

The following subsections explain the main phases in detail.

5.2.1 Data Collection

Production Phase:

The LCA simulations were performed with LCI of 200 mm diameter to provide a detailed comparison of results related to environmental impacts of different pipe materials made of AC, CONC, DI, PVC, and VIT. Although the production of AC and VIT pipes are obsolete in the current market due to the risk of asbestos fibers in the AC pipes that impact human health, and clay pipes are prone to roots growth leading to blockage or leak, these materials has been still included in the analysis to understand the impact it is causing on the existing infrastructure. The transportation is considered as an inclusive process during the production phase starting from the raw-material extraction till the product pipe leaves the manufacturing facility yard was estimated using the embodied-energy coefficient determined by Ambrose et al., 2002, Recio et al 2005., Marceau and Nisbet 2007, along with the energy required for other production phase activities [24], [136], [137].

Trench Design and Installation Phase:

Pipelines are typically installed using traditional open cut or trenchless technology such as horizontal directional drilling, horizontal auger boring, pipe jacking, and or pipe ramming. Sometimes new pipelines are installed using rehabilitated trenchless methods such as cured-in-place pipe (CIPP), slip-lining, or pipe bursting. The open-cut method includes basic excavation, preparing the foundation, laying the bedding, pipe placement, and backfilling. Typically trenches are excluded from the lifecycle assessment studies depending on the analyst's research objective but studies such as Hajibabaei et al., 2018, Petit-Boix et al., 2014, Fei Du et al., 2013, have all emphasized the impact of pipe trenches apart from other factors that affect the lifecycle assessments [26], [27], [128]. These studies considered trench designs based on ASTM and AWWA standards and analyzed the lifecycle impacts of trench material.

Trench designs and installation requirements related to thermoplastic pipes are specified in Canadian Standards Association (CSA) Standard B182.11, and ASTM Standard D2321. ASTM C 1479, ASCE 15, and AASHTO Standard Specifications for Highway Bridges specify the installation of precast concrete pipes using standard installation methods. While there are different standards according to the type of pipe material, Howard 2011 argued that the trench should be designed based on soil conditions and the construction of embedment but not pipe material-specific [138]. Further, Howard 2011 generalized pipe trench design into five basic types which are applicable for both flexible and rigid pipes. Trench design that gives the maximum haunch support following the CSA, ASTM, and AWWA guidelines is presented in Figure 5-3. The International Union of Operating Engineers (IUOE) based on OSHA trenching and excavation requirements specifies a ¾:1 (H: V) slope and 12 feet trench top width for sloped excavation with greater than 5 feet trench depth and 1-foot bottom width [139].

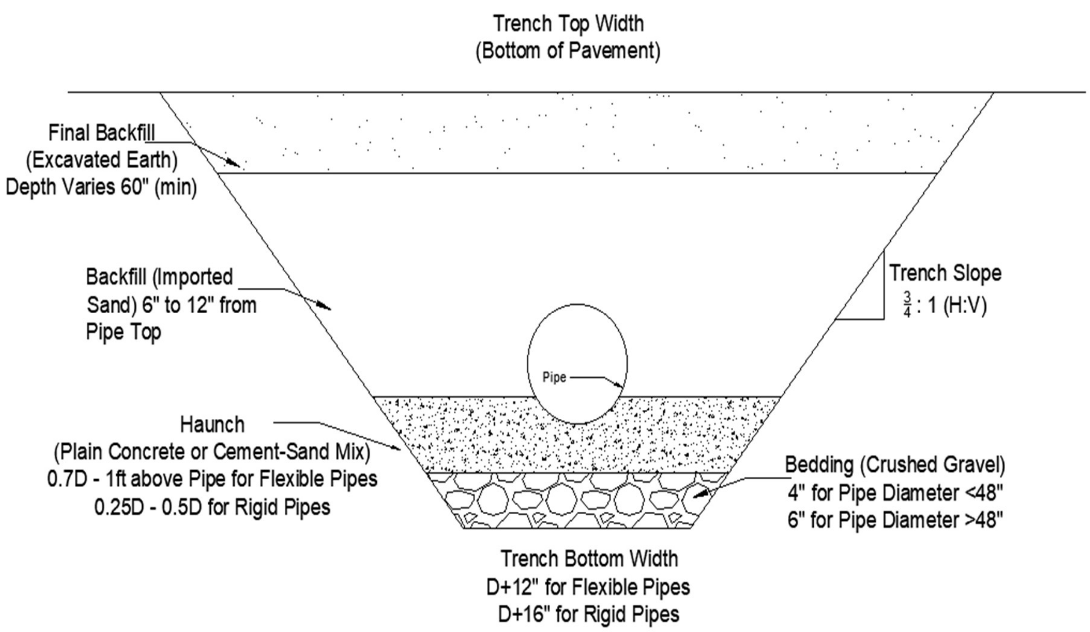


Figure 5-3: Single pipe flat trench cross-section (drawn not to scale)

Maintenance Phase:

Pipe maintenance often involves understanding the asset condition after performing necessary inspections (typically every 10 -15 years [140]) and finding the root causes which have evolved from reactive to predictive maintenance over the years. The type of renewal, repair or rehabilitate or replace (R/R/R) method depends on the type of defect to be repaired or if the system performance has to be improved or a combination of both. The routine pipeline operations include cleaning, cathodic protection, corrosion monitoring, pressure monitoring, leak monitoring, acoustic monitoring of wire breaks are effective in enhancing the life of pipe before a catastrophic failure. The cleaning involves removal of the solids directly by dislodging the solid debris and carrying with water flow using high pressure jetting. The USEPA in its report for force main rehabilitation stated that most ferrous pipelines are often refurbished for corrosion (46%), third-party damage (19%), joint leaks (15%), surge pressure (10%), and inadequate capacity (10%). Whereas for non-ferrous material the common failures are due to corrosion and structural failures (54%), third-party damage (36%), surge pressure (7%), and joint leaks (3%) [140].

Repair: The repair of a failure is often addressed during emergency conditions, relatively minor in nature to reduce the consequence and restore the service as quickly as possible. There is no enhancement seen in the pipe capacity and typically funded by the operating budget. Repairs can be done by an open cut or CIPP or joint repairs. If the primary objective of the repair is corrosion protection spray-on lining is suitable with a further life expectancy of 50 years.

Table 5-1: Pipe useful life

Pipe Material	Useful Life from Literature	Useful Life in this Study	Remark
AC	100 years [26][130]	100 years	
CONC	100 years [26] [130]	100 years	
DI	100 years [130] 75 years [141]	75 years	The lowest is considered as a worst-case scenario
PVC	50 years [26] 120 years [130]	50 years	
VIT	100 years [23]	100 years	

Rehabilitate: Rehabilitation is the replacement of an asset component often sufficient enough to raise the asset LoS above the desired level with minor capacity enhancement. The existing pipe remains a component of the renewal work in rehabilitation. CIPP lining with thermoset resin-saturated material is considered as the rehabilitation strategy for this study. Other techniques like slip-lining and close-fit lining are ignored due to their disadvantage like reduced flow capacity resulting from the rehabilitation [142]. The pipe bursting technique can enhance the flow capacity by upsizing the pipe diameter to a certain extent (up to 25%), but the type of soil affects the ability of the bursting head to expand and upsizing. All these rehabilitation methods are trenchless or with minimal excavation and seem advantageous with low environmental and social costs but require a high level of engineering skills. However, Kaushal et al 2020 argued that the social cost advantage of these trenchless methods over the open-cut method is less than 2% and or negligible [143].

Replacement: Replacement is a substitution of an entire asset with or without capacity enhancement. The most widely applied replacement renewal strategy has been the pipe replacement with open-cut construction and slip-lining [140]. The traditional open-cut method is considered as the pipe replacement strategy for this study which is assumed to be replaced completely by the end of its useful life as presented in Table 5-1 and proceed for recycling or disposal.

Waste/Disposal Scenario: Most LCA studies ignore waste process modeling as waste treatment is complex compared to production phase modeling. SimaPro8 differentiates waste and disposal scenarios, where in the disposal scenario, the products are separated as disassembled products, recycled products, and products that are processed in the waste scenario while different forms of waste materials are sent to waste treatment processes such as landfill, incineration, recycling, and others in the waste scenario. Therefore, it is extremely important to consider the waste treatment or disposal process carefully. For instance, plastic does not magically transform into new pipes when recycled. To make it reusable, the plastic must first be softened and chemically cracked, which is expensive. Henceforth, most plastics turned out to be degraded products such as polyester fabric. Plastics of the different chemical mixture do not shape easily when mixed, for instance, PVC when recycled with PET (polyethylene terephthalate, used to make bottles), requires extreme temperatures to break down different compounds chemically, and mold together. The variation in the color of different plastics also makes it much harder to recycle, and these colors are not easily removed and have a plastic that looks muddy, making it unusable. If the plastic ends up in the landfill and is exposed to rainwater, the plastic absorbs the highly toxic water-soluble compound that it contains, and together they produce a hazardous stew called leachate that can be infiltrated into groundwater, soil, and waterways, poison ecosystems, and harm wildlife. US EPA's HELP (Hydrologic Evaluation of Landfill Performance) model was developed to estimate the leachate amount by analyzing the water balance of landfills. The incineration of waste containing organic chlorine-based substances like PVC releases highly toxic dioxins which are carcinogenic.

Similarly, ductile iron pipe is a result of metallurgical advancement, as these pipes are made with 95% scrapped cast iron or ductile iron [144]. So theoretically, DI should have a significantly low carbon footprint. However, the scrap can vary in grade and quality and the post-industrial waste does not go back directly into the manufacturing units. The high-quality scrap lowers the processing and treatment resulting in reduced emissions and lower costs. On the other hand, recycling still has a benefit with lower environmental impacts by diverting the waste from landfills, lesser energy consumption in processing compared to iron ore extraction and processing, reducing the iron ore mining, encouraging the communities to recycle more for sustainable development. Therefore, this study has considered a minimum of only 10% of the material as clean, well-sorted scrap for recycling and the remaining is treated as a scrap material with high impurities.

Therefore, the waste scenario strategy and the waste treatment process in this research are designed as presented in Table 5-2.

Table 5-2: Waste scenario and waste treatment assumptions

Pipe Material	**Waste Scenario**	**Waste Treatment**
AC	Landfill 100%	Municipal Solid Waste Treatment
CONC	Landfill 100%	Municipal Solid Waste Treatment
DI	Scrap 90%	Recycle 10%
PVC	Combination of Landfill, Incineration	Recycle
VIT	Landfill 100%	Municipal Solid Waste Treatment

Clay pipes are 100% recyclable and can be used as an ingredient for new vitrified clay products. Even if not recycled, vitrified clay pipes are not harmful to the biosphere. However, the challenges involved with clay pipes made them extinct in use. Therefore, clay pipes are considered in the analysis only to study the impact of existing infrastructure. Moreover, concrete waste is often the most common type of construction and demolition waste that ends up in landfills. Despite the high potential for recycled concrete to replace natural aggregates in new concrete, international standards do not accept its widespread use in large-scale industrial production due to its high porosity, low durability, reduced workability, disparity of source concrete, and lack of specifications and guidelines [145]. These limitations of recycled concrete have made this study follow the current practice of disposing concrete debris into landfill for the analysis.

The global statistics for plastic recycling suggest only 9 percent of those plastics have been recycled, 12% was incinerated and 79% was accumulated as landfills [146]. In Singapore, only 7% of plastic waste has been recycled as of 2016 [147]. In Canada, only 9% of plastic waste goes for recycling, and the majority of the plastic ends up in landfills [148]. Further, Canada ships about 12% of its plastic waste outside of North America for recycling mainly to Southeast Asia where it all ends up being incinerated or landfills. In place of these possibilities, a hybrid scenario is also verified with landfill 80%, incineration 10%, and recycle 10%, see Table 5-3. The literature review has revealed that incineration is the most harmful scenario, and landfill with reuse seems to have lower environmental impacts. However, the landfill may be affected by leachate and the estimation of leachate is beyond the scope of this research. The possible waste scenarios considered in this research are as follows:

Table 5-3: PVC waste scenario and waste treatment assumptions

Scenario (PVC)	**Waste Scenario**	**Waste Treatment**
S1	Incineration 90%	Recycle 10%
S2	Incineration 100%	-
S3	Landfill 90%	Recycle 10%
S4	Landfill 100%	-
S5	Landfill 80% Incineration 10%	Recycle 10%

Life cycle inventory is a critical component of lifecycle analysis which relates the inflows (material, energy) and outflows (emissions) of all unit processes to the functional unit and aggregating them (ISO 2006). The life cycle inventory was developed using secondary data sources such as published literature and based on Ecoinvent, see Appendix-B. Ecoinvent is the most popular database with the largest datasets and universal credibility as it is impractical to quantify the emissions from all the flows of all processes, *see* Table 5-4. The life cycle environmental impacts were evaluated using SimaPro 8, one of the most widely accepted LCA software that consists the Ecoinvent database.

Table 5-4: Life cycle inventory for water and wastewater systems

Life Cycle	Inventory Category	Data Source
Manufacturing	Raw material, transport for pipe production, embodied energy,	Ecoinvent, Literature [25], [26], [128], [136], [137], [149]–[152]
Construction	Construction material and energy, pipe supply, transport, construction equipment,	Ecoinvent, Literature, Transport for pipe supply from nearest manufacturers by road [153]–[156] Assumed construction materials are available near Kelowna within 50 km. Trench material quantities calculated from a CAD design.
Maintenance	Raw material, production, transport, embodied energy	Ecoinvent, Literature [25], [26], [128], [136], [137], [149]–[152]
End of life	Transport embodied	Ecoinvent, Literature [25], [157]

5.2.2 Life Cycle Impact Assessment

The LCIA by definition involves the selection and definition of a set of impact categories. The LCIA methods vary by a different set of impact categories available for the LCA study. The steps involved in LCIA as outlined in the ISO 14040:2006 standard illustrate the mandatory and optional elements. SimaPro software with the latest version, ReCiPe 2016 V 1.13 life cycle impact assessment method was used for this research on this consensus and due to lower uncertainties associated with the midpoint indicators compared to the other methods, and simplicity in environmental modeling [158]. The uncertainties that arise during the conversion and aggregation of life cycle inventory to midpoint and endpoint impact categories are incorporated in the method in the form of different perspectives as Individualist (I), Hierarchist (H), Egalitarian (E).

Table 5-5 addresses the midpoint impact categories of ReCiPe with the associated sets of characterization factors. These 18 midpoint impact categories are transformed and combined into the 3 end point impact categories. These end point impact categories are aggregated into a single score value to compare different products or processes. In this study, a life cycle impact index was obtained by multiplying the assigned weight with the LCI indicator score. The details and reasoning for the usage of assigned weights are discussed in detail in section 5.3.1.10.2.

Table 5-5: ReCipe LCIA method impact categories and damage assessment

Midpoint Impact category	**Unit**	**Endpoint impact category**
climate change	kg CO_2 to air	Damage to Human health (DALY)
ozone depletion	kg CFC-115 to air	
human toxicity	kg 14DCB to urban air	
particulate matter formation	kg PM10 to air	
ionizing radiation	kg U235 to air	
photochemical oxidant formation	kg NMVOC6 to air	
terrestrial acidification	kg SO2 to air	Damage to ecosystem diversity (species. yr)
terrestrial ecotoxicity	kg 14DCB to industrial soil	
agricultural land occupation	$m^2 \times yr$ agricultural land	
urban land occupation	$m^2 \times yr$ urban land	
natural land transformation	m^2 natural land	
marine ecotoxicity	kg 14-DCB7 to marine water	
marine eutrophication	kg N to freshwater	
freshwater eutrophication	kg P to freshwater	
freshwater ecotoxicity	kg 14DCB to freshwater	

Midpoint Impact category	**Unit**	**Endpoint impact category**
water depletion	m^3 water	Damage to resource availability (cost increase in $)
mineral resource depletion	kg Fe	
fossil fuel depletion	kg oil	

Where,

DALY: disability-adjusted loss of life years,

Species. yr: Loss of species during a year,

The cost increase in $: increased cost

The DALY is a default setting in ReCiPe for assessing the damage contributing to the human health area of protection under LCA. It adds together years of life lost (YLL) and years of life disabled (YLD) without age weighting or discounting.

$$DALY = YLL + YLD$$

YLD = *w* x D where *w* is the severity factor between 0 (completely healthy) and 1 (dead) and D is the duration of the disease.

The potentially disappearing fraction of species (PDF) is used to represent ecosystem quality through time and space. The total of the PDF multiplied by the species density can be used to determine the harm to ecosystem diversity endpoint categorization.

$$CF_{ED} = PDF_{terr} \times SD_{terr} + PDF_{fw} \times SD_{fw} + PDF_{mw} \times SD_{mw}$$

Where

CF_{ED} is the endpoint characterization factor for ecosystem damage,

PDF_{terr} is the characterization factor in $PDF.m^2.yr$

SD_{terr} the species density factor for terrestrial systems, in $species/m^2$,

PDF_{fw} is the characterization factor in $PDF.m^3.yr$

SD_{fw} the species density for freshwater systems in $Species/m^3$,

PDF_{mw} is the characterization factor in $PDF.m^3.yr$

SD_{mw} the species density for marine water systems in $Species/m^3$.

The marginal cost increase (MCI) is the factor that represents the increase of the cost of a commodity r ($/kg), due to extraction or yield (kg) of the resource r. The unit of the marginal cost increase is dollars per kg squared ($/kg^2)

$$\mathrm{MCI_r} = \frac{\Delta Costr}{\Delta Yieldr}$$

The entire cost to society from material extraction can thus be determined by multiplying the marginal cost rise per kg by the annual consumed amount times the net present value of a dollar, adjusted for the discount rate. As a result, the general formula for endpoint resources is as follows:

$$\text{Damage (\$)} = \frac{\Delta Costr}{\Delta Yieldr} \text{ x } \mathrm{P_r} \text{ x } \sum_{\mathrm{T}} \frac{1}{(1-d)\hat{}t}$$

Where,

Δ $Cost_r$ is the cost increase for resource r ($/kg)

Δ $Yield_r$ is the extracted yield of resource r that caused the price increase (kg)

P_r is the global production amount of the resource per year (kg/yr)

d is the discount rate and

T is the time interval that is taken into account

5.2.3 Life Cycle Cost Analysis

The LCCA in this study considered the pipe supply and installation costs, trench construction costs, and maintenance costs. All future costs are calculated using the present value technique and the discount rate is considered as outlined in the *Treasury Board of Canada Secretariat 2007* [159]. The Present Value (PV) converts the future cash flows to present value or vice versa by discounting to a common point in time, usually the base date. The interest rate used for discounting is a rate that represents the investor's capital opportunity over time. The PV can be determined by **Equation (2)**, where PV is the present value, FV is the future value of costs, n is the number of years between the time of analysis i.e., base date and time of expense, and *i* is the discounted rate.

$$PV = FV \left(\frac{1}{(1+i)^n}\right) \qquad \textbf{Equation (2)}$$

5.2.4 Multi-criteria Decision Making

The economic and environmental implications have been evaluated as conflicting criteria and their effects have been assessed based on the consideration of several stakeholder priorities. Multicriteria decision making (MCDM), by considering multiple attributes, can be used to evaluate alternatives to each other [160]. The life cycle impacts were considered as the parameters, and the different pipe materials were considered as alternatives. Decisions involving multi-faceted criteria were all based on multi-criteria analysis techniques that allow data normalization, elaboration, comparison, and ranking to select the best alternative [161]. Kabir et al., 2014, Sharma et al., 2008 discussed and reviewed the feasibility of multi-criteria decision methods for infrastructure asset management [162], [163]. The characteristic feature of the multi-criteria techniques is that a value is assigned to each alternative and then multiplied by their respective weights and methods vary in how these values are assigned and combined.

It is impractical to generalize the weighting scheme to criteria indicators that can be applied commonly under any decision context. Hence this study has analyzed scenario prioritization based on the following three weighting schemes:

- Holistic/neutral approach,
- Pro-economic approach,
- Pro-environmental approach.

Performance indicators under each criterion were assigned with weights based on decision-makers' priorities. In the neutral approach, all the criteria were given equal weights whereas, in the pro-economic context, the economic performance of the pipe materials was given the highest preference and hence allocated with 80% of the weight. Under the pro-environmental decision scenario, performance indicators under the environmental category were given a higher preference with 80% of weight allocation. However, these weights can be changed depending on the utility’s priorities, allowing for customizable decision-making. The summary of the weighting scheme is shown in Table 5-6.

Table 5-6: Weighting schemes for scenario prioritization

Weighting scheme	Performance indicator	
	LCC	LCI Index
Pro-economic	0.8	0.2
Neutral	0.5	0.5
Pro-environment	0.2	0.8

5.2.4.1 Weighted Sum Method (WSM)

The weighted sum method is a popular technique in MCDM methods due to its simplicity in the calculation [115]. In this study, the WSM is used to calculate the life cycle impact index to assess the life cycle impacts using ReCiPe's midpoint categories for the decision scenario prioritization, see Figure 5-4. The ReCiPe method has 18 impact categories which are incommensurable as each impact category has its unit of measurement. To compare each alternative on each of the attributes, the data was normalized and the ideal value was obtained from the minimum sum of the values after normalization. The Linear sum based normalization method was used which has the following general form [164]:

$$a_{ij} = \frac{r_{ij}}{\Sigma r_{ij}} \qquad \text{for } i = 1,2,\ldots m \text{ and } j = 1,2,\ldots.n$$

Where r_{ij} is the original ratings of the decision matrix and a_{ij} is the normalized value of the decision matrix. The life cycle impact index was estimated and described in section 5.3.1.10.2.

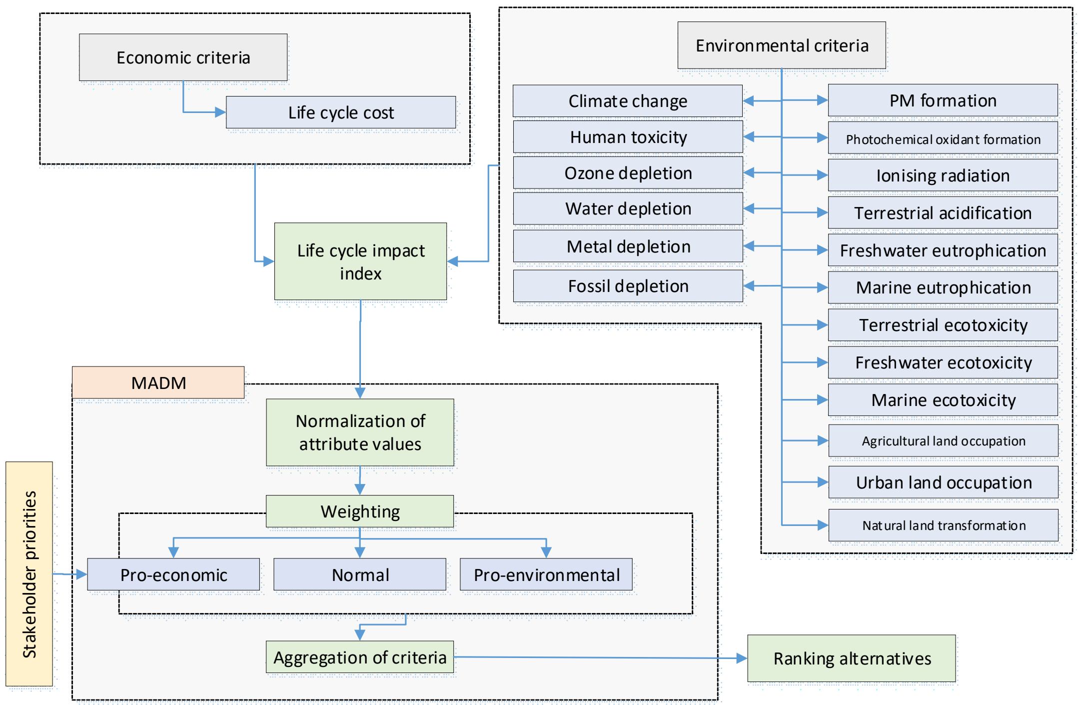


Figure 5-4: WSM for Scenario Prioritization

5.3 Results and Discussion

This section presents the LCA and LCC results obtained in the study.

5.3.1 Life Cycle Environmental Impacts

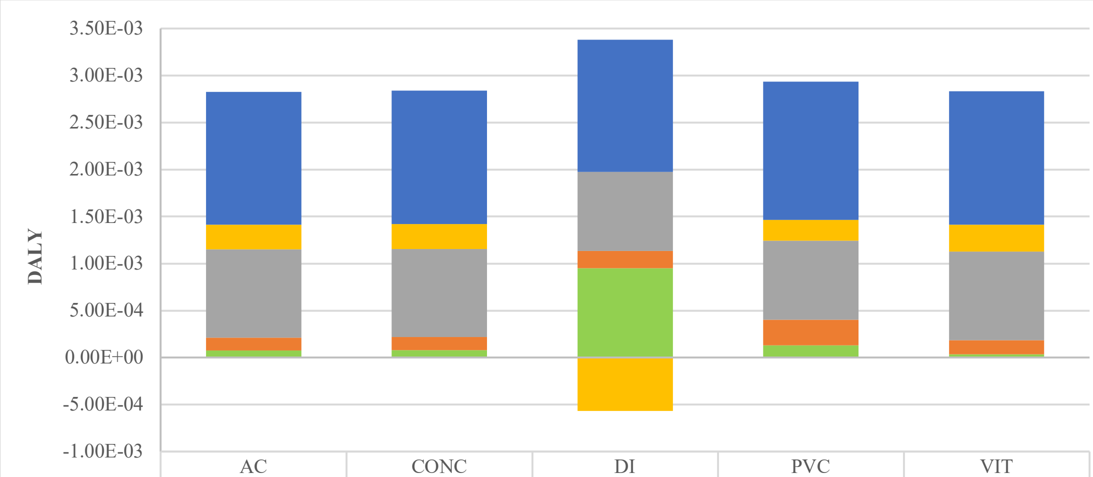
The results from the LCA simulation are from cradle to grave system boundary approach. The midpoint impact, endpoint impact, and the single score value are presented in the following sections. The LCA results were compared for AC, CONC, DI, PVC, and VIT of one meter in length and 200 mm in diameter with useful life as defined in Table 5-1 for an analysis period of 100 years. This means materials (DI and PVC) with less than 100 years of useful life are prorated for equivalent comparisons. For instance, PVC with 50 years of useful life is assumed to be replaced after 50 years and hence the production, installation, maintenance, and end phase life cycle inventories are doubled during the 100 years analysis period.

5.3.1.1 Climate Change Human Health

Climate change causes several environmental mechanisms that affect both the endpoint of human health and ecosystem health. Climate change models are generally assessed for the future environmental impact of different policy scenarios. The environmental mechanism in this impact category for ReCiPe estimates the radiative force from CO_2 and other substances using the IPCC equivalence factors. The CO_2 emissions are linked to temperature increase and classify under the endpoint damage to human health and damages to ecosystem diversity [111]. To express the life years affected by climate change, Disability-Adjusted Life Years (DALYs) are used as a measure. In this study from the results for climate change human health using SimaPro simulations, the following analysis was discussed:

From Figure 5-5, DI and PVC production processes are the most toxic compared to other pipe materials (AC, CONC, and VIT) with an estimated 271 kg CO_2eq and 38 kg CO_2eq respectively. This is due to the high heat (energy) involved in the manufacturing process of DI and PVC which are 1,200 MJ/meter (38.2 MJ/kg [136]) and 1,293 MJ/meter (74.9 MJ/kg [136]) respectively. In addition to that, although DI is manufactured from scrap material, no credits were considered for the cast iron material in the inventory of production phase. The trench has been designed in this study in such a way that they are typical for all rigid pipe materials and with slightly higher specifications for flexible pipe material. Therefore, the emissions during construction are relatively low compared to other processes. The transportaion of pipe from manufacturing plant to construction site is included under the installation phase. The installation of PVC pipe is relatively more toxic in-spite of its nearest manufacturing location with 79 kg CO_2eq compared to DI with 53 kg CO_2eq and VIT with 44 kg CO_2eq. However the nearest manufacturing unit for Vitrified clay is found at a distance 2.5 times higher than PVC manufacturing unit and still the emissions are half compared to PVC. . The reason for PVC being the most toxic pipe material during the trench construction or any other process is due to its useful service life of 50 years compared to DI (75 years) and VIT (100 years). The toxic emissions during the production of DI and PVC pipe material were offset during the maintenance as the number of CIPP maintenance cycle times are relatively less than the other three materials. The end of life phase has a significant impact in this category as 10% of the DI and PVC used pipe material is considered to be recycled and remaining 90% of DI pipe material is scraped and 10% of PVC material is assumed to end up in incineration with 80% in the landfill. The recycling of DI has resulted in negative (credit) environmental impacts for the end-of-life phase and in particular for the climate change midpoint impact category. Whereas the recycling of PVC has no negative environmental impacts for this category. The other pipe materials (AC, CONC, VIT) are assumed to wind up in landfills completely. After considering all the four life cycle phases and the assumptions made for waste treatment the

DI is the most sustainable material followed by AC, VIT, and CONC. PVC is the most unsustainable material in this impact category. An average of 1.41 years of disability adjusted life years are lost i.e., equivalent years of full health, due to the production of one kilometer of AC and DI pipes and 1.42 years for CONC and VIT, wheras 1.47 years for PVC pipes under this impact category.



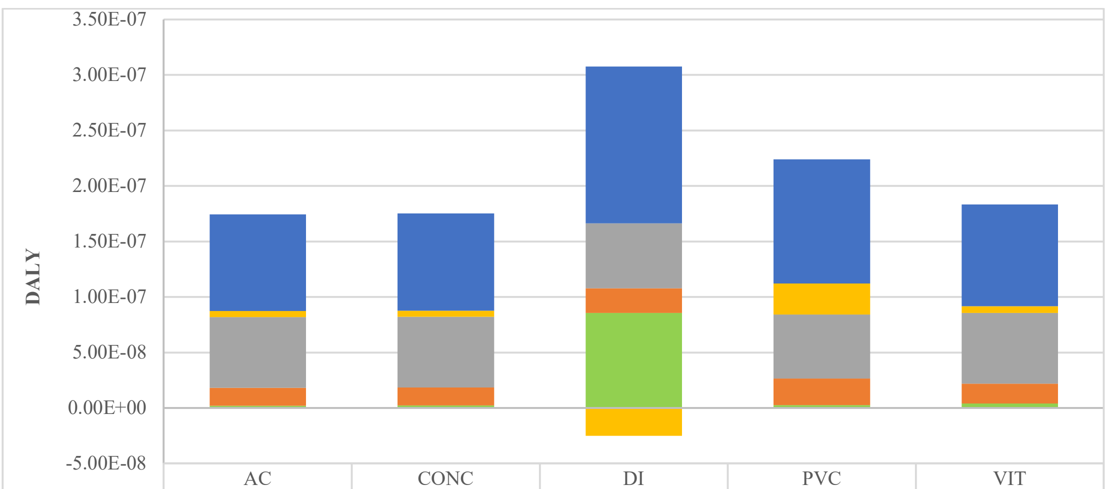
	AC	CONC	DI	PVC	VIT
Overall	1.41E-03	1.42E-03	1.41E-03	1.47E-03	1.42E-03
End of life	2.63E-04	2.63E-04	-5.67E-04	2.24E-04	2.90E-04
Maintenance	9.40E-04	9.40E-04	8.40E-04	8.40E-04	9.40E-04
Installation	1.36E-04	1.36E-04	1.84E-04	2.71E-04	1.50E-04
Production	7.57E-05	8.18E-05	9.51E-04	1.33E-04	3.68E-05

Figure 5-5: Overview of the climate change human health impact category

5.3.1.2 Ozone Depletion

Ozone depletion potential is the relative amount of degradation to the ozone layer caused by a chemical. Ozone depletion is caused by the fugitives of anthropogenic chemicals in the atmosphere. Stratosphere ozone is crucial to life as it prevents UV-B radiation from occurring in the solar sector. The UV-B radiation has the potential to impact the human health risk of skin cancer, cataract, premature ageing, and immune system abolition. It could also affect life on earth and and aquatic habitats [111]. To express the life years affected by ozone depletion, Disability-Adjusted Life Years (DALYs) is used as a measure. In this study from the results for ozone depletion using SimaPro simulations, the following analysis was discussed:

The ozone-depleting substances (ODS) known as recalcitrant chemicals containing chlorine and bromine atoms are chlorofluorocarbons and halons respectively. These chemicals are released abundantly during DI pipe production. The inventory of DI includes production of magnesium, ferrosilicon are the chemicals that are contributing to the ozone depletion. The DI is manufactured by processing cast iron with extensive heat to handle the molten metal in the blast furnace. Therefore the production of DI was found to be most deleterious, impacting all categories during the production stage and has a considerable detrimental impact on ozone layer depletion. Similarly PVC is the largest user of chlorine and chlorine is a component of chlorofluorocarbon known to cause ozone depletion. The extraction and processing of these raw materials is the main contributor of ozone depletion. However, the recycling of DI has compensated the effect with negative (credit) environmental impacts for the end-of-life phase and in particular for the ozone depletion midpoint impact category. Whereas the recycling of PVC has no negative environmental impacts for this category. Overall, after considering all the life cycle phases AC pipe material is the most sustainable material with lowest DALY followed by CONC, VIT, and PVC. DI is the most unsustainable pipe material in this impact category with highest DALY. However, the DALY in this impact category is less significant in terms of absolute value compared to Climate Change Human Health, see Figure 5-6.



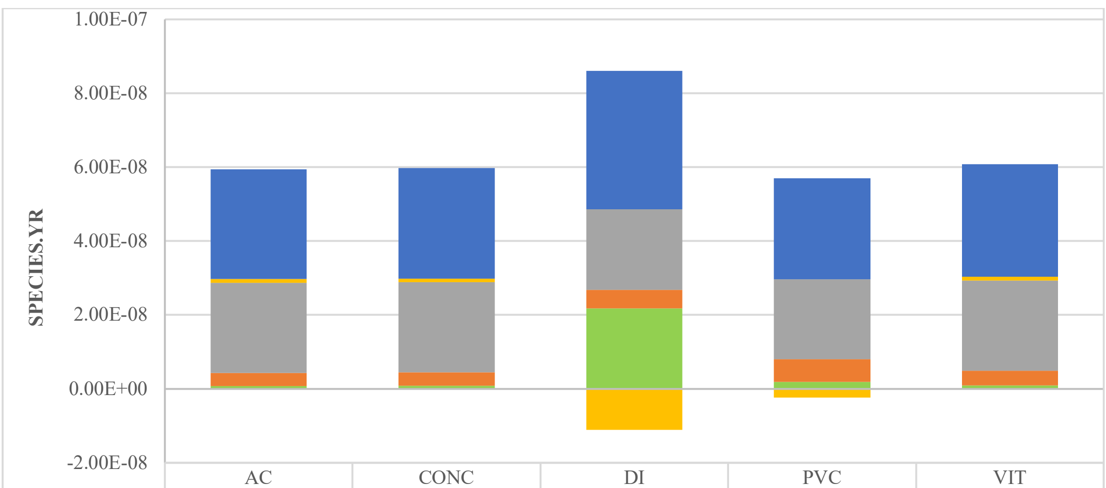
	AC	CONC	DI	PVC	VIT
Overall	8.72E-08	8.75E-08	1.41E-07	1.12E-07	9.16E-08
End of life	5.22E-09	5.23E-09	-2.51E-08	2.78E-08	5.78E-09
Maintenance	6.38E-08	6.38E-08	5.88E-08	5.77E-08	6.38E-08
Installation	1.61E-08	1.61E-08	2.19E-08	2.40E-08	1.82E-08
Production	2.00E-09	2.31E-09	8.57E-08	2.46E-09	3.77E-09

Figure 5-6: Overview of the ozone depletion impact category

5.3.1.3 Terrestrial Acidification

Acidity changes in the soil are caused by sulfates (SO_4), nitrates (NOx, NH3), and phosphates that are deposited in the atmosphere. When acidity rises above a certain threshold, it becomes harmful to the (plant) species that deal with these substances. As a result, as acidity levels change, shifts in species occurrence will occur represented by species in a year. To express the species affected due to acidification, loss of species during a year is used as a measure. In this study from the results for terrestrial acidification using SimaPro simulations, the following analysis was discussed:

From Figure 5-7, DI has the highest concentration of acidification during production followed by PVC. Cast iron, magnesium and ferrosilicon contribute to the emissions of DI during their production. Whereas the polymer and the pipe extrusion process contributes to the terrestrial acidification for PVC pipe during production. The trench for flexible pipes (PVC) is with the highest specification with involvement of more construction material which has resulted in higher acidification compared to DI and other pipe materials. The maintenance and end-of-life phases have offset the acidification values for DI and PVC. The recycling of DI and PVC has resulted in a negative (credit) environmental impact for the end of life phase and in particular for the terrestrial acidification midpoint impact category. Overall, after taking all the life cycle phases into consideration PVC pipe material is the most sustainable material followed by AC, CONC, and VIT. DI is the most unsustainable pipe material in this impact category with highest number of species lost during one year.



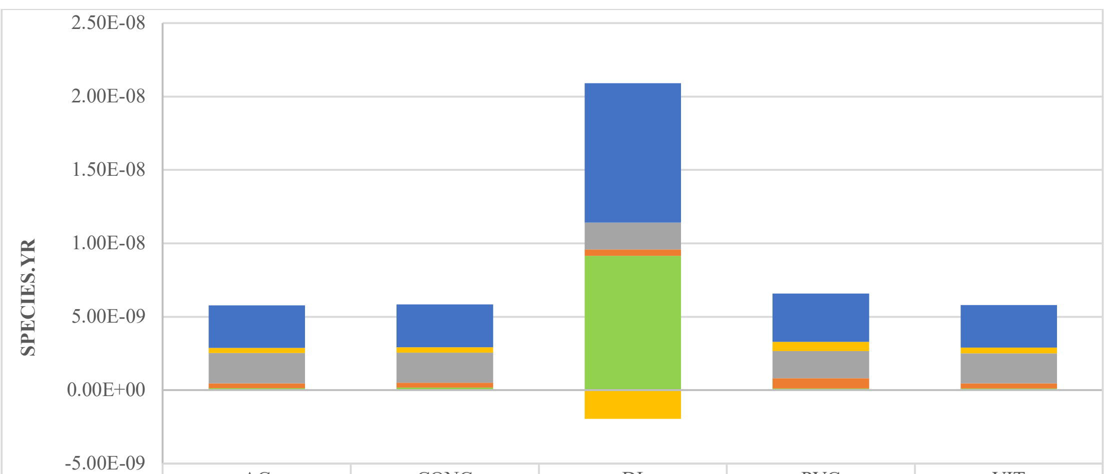
	AC	CONC	DI	PVC	VIT
Overall	2.97E-08	2.99E-08	3.74E-08	2.73E-08	3.04E-08
End of life	9.79E-10	9.82E-10	-1.11E-08	-2.36E-09	1.09E-09
Maintenance	2.44E-08	2.44E-08	2.18E-08	2.17E-08	2.44E-08
Installation	3.64E-09	3.64E-09	4.93E-09	6.11E-09	4.01E-09
Production	6.98E-10	8.37E-10	2.18E-08	1.88E-09	8.68E-10

Figure 5-7: Overview of the terrestrial acidification impact category

5.3.1.4 Freshwater Eutrophication

Freshwater Eutrophication is the enrichment of water with nutrients that determines the ecological quality. The characterization of freshwater eutrophication is the limited growth of algae due to these nutrients (phosphorous and nitrogen). To express the species affected due to freshwater eutrophication, the loss of species during a year is used as a measure. In this study from the results for freshwater eutrophication using SimaPro simulations, the following analysis was discussed:

From Figure 5-8, DI has the highest concentration of nutrients during production followed by CONC which is due to the use of aggregates in their production. The spoil treatment containing lignite and hard coal, leachate due to the sludge landfill is what causing for the freshwater eutrophication emissions. Similarly, as the trench for flexible pipes (PVC) is with the highest specification with the involvement of more construction material it has resulted in higher eutrophication followed by DI and other materials. The maintenance and end-of-life phases have offset the eutrophication values for DI and PVC. The recycling of DI has resulted in negative (credit) environmental impacts for the end of life phase and in particular for the eutrophication midpoint impact category. Whereas the recycling of PVC has no negative environmental impacts for this category. Overall, after considering all the life cycle phases AC pipe material is the most sustainable material followed by VIT, CONC, and PVC. DI is the most unsustainable pipe material in this impact category with highest number of species lost during one year similar to terrestrial acidifcation .



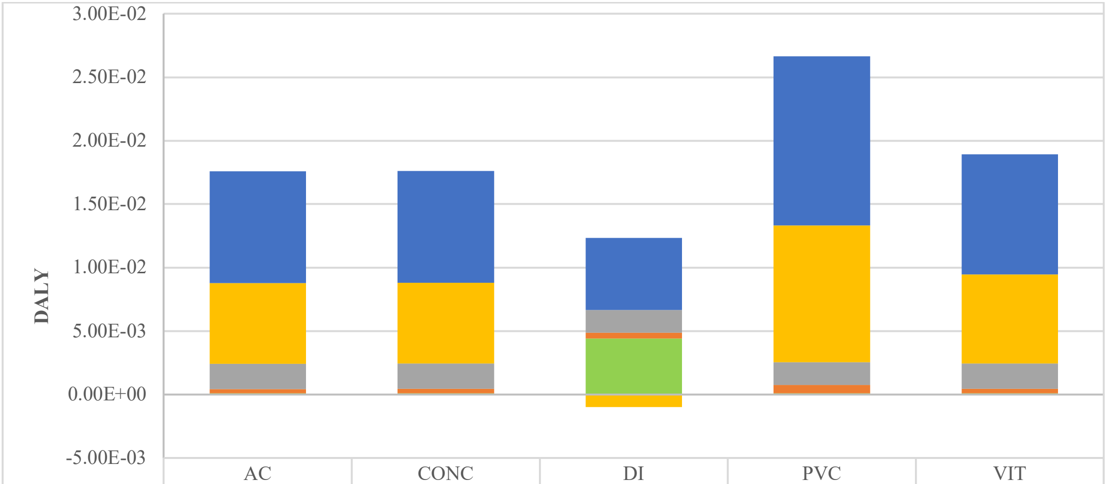
	AC	CONC	DI	PVC	VIT
Overall	2.88E-09	2.92E-09	9.46E-09	3.30E-09	2.90E-09
End of life	3.52E-10	3.53E-10	-1.97E-09	6.37E-10	3.90E-10
Maintenance	2.05E-09	2.05E-09	1.84E-09	1.85E-09	2.05E-09
Installation	3.26E-10	3.26E-10	4.37E-10	6.95E-10	3.39E-10
Production	1.51E-10	1.87E-10	9.15E-09	1.22E-10	1.18E-10

Figure 5-8: Overview of the freshwater eutrophication impact category

5.3.1.5 Human and Eco-Toxicity

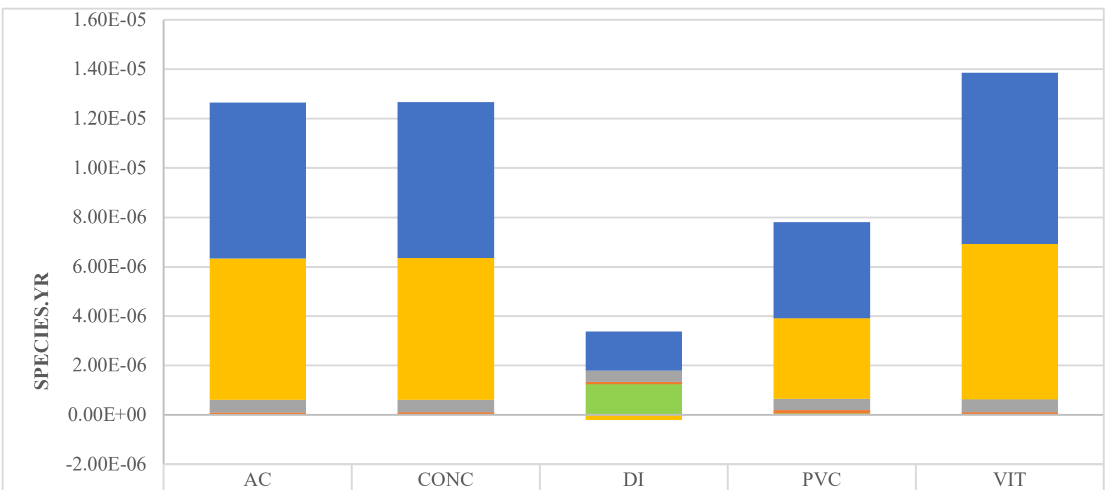
A chemical's environmental persistence (fate), accumulated in the human food chain (exposure), as well as its toxicity (effect) is characterized by the human toxicity and ecotoxicity (terrestrial, freshwater, and marine) impact category. Effect factors can be produced from human and laboratory animal toxicity data and fate and exposure factors are estimated utilising multimedia 'evaluative' destinies and models of exposure. The USES-LCA is a widely used model of a multimedia fate, exposure, and effect, a uniform system for the evaluation of LCA-adapted substances. To express the life years affected by human toxicity, Disability-Adjusted Life Years (DALYs) is used as a measure, and the species affected by eco-toxicity is measured by the loss of species during a year. In this study from the results for human and eco-toxicity using SimaPro simulations, the following analysis was discussed:

DI has the highest urban air fate and exposure in the terrestrial environment, whereas the lowest concentration on rural air and freshwater emissions in the freshwater and marine environments respectively. The human exposure routes of these emissions are through inhalation, and root and leaf crops consumption. The pipe materials other than DI and PVC are mostly dumped into landfills and this affects the surrounding soil which has resulted in more impact in the end-of-life phase. As the DI is either scrapped or recycled, it has turned out to be the friendliest material in this impact category. The recycling of DI has resulted in negative (credit) environmental impacts for the end-of-life phase and in particular for the eco-toxicity midpoint impact category. Whereas the recycling of PVC has no negative environmental impacts for this category. Overall, DI pipe material is the most sustainable material with a DALY of 5.68 and PVC is the most toxic with a DALY of 13.33 for human toxicity. However, VIT is the most unsustainable pipe material with highest number of species lost in a year due to eco-toxicity impact category, see Figure 5-9, Figure 5-10.



	AC	CONC	DI	PVC	VIT
Overall	0.008790983	0.008811007	0.005678009	0.013331894	0.009461982
End of life	6.38E-03	6.38E-03	-9.84E-04	1.08E-02	7.03E-03
Maintenance	0.001991823	0.001991823	0.001793035	0.001789842	0.001991823
Installation	0.000340256	0.000340256	0.00045726	0.000660519	0.000358753
Production	7.79E-05	9.46E-05	4.41E-03	9.82E-05	7.94E-05

Figure 5-9: Overview of the human toxicity impact category



	AC	CONC	DI	PVC	VIT
Overall	6.33E-06	6.34E-06	1.58E-06	3.90E-06	6.93E-06
End of life	5.72E-06	5.73E-06	-2.11E-07	3.26E-06	6.31E-06
Maintenance	5.11E-07	5.11E-07	4.59E-07	4.55E-07	5.11E-07
Installation	8.10E-08	8.10E-08	1.10E-07	1.38E-07	8.89E-08
Production	1.64E-08	2.02E-08	1.22E-06	4.96E-08	2.02E-08

Figure 5-10: Overview of the eco-toxicity impact category

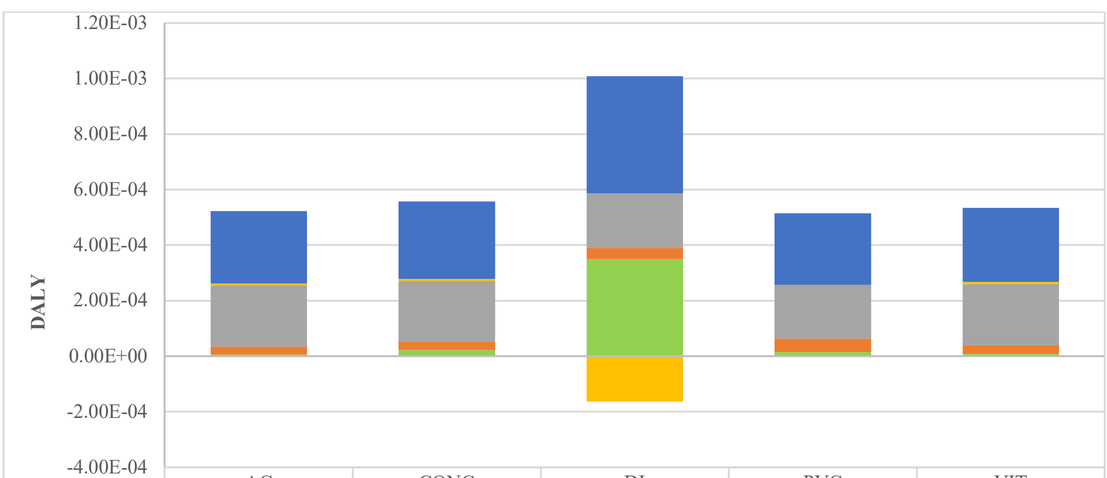
5.3.1.6 Human Health Damage due to PM_{10} and Ozone

Fine Particulate Matter is a complex mixture of organic and inorganic substances with a diameter of fewer than 10 µm (PM10) that has both anthropogenic and natural sources. PM10 enters the upper portion of the airways and lungs and causes health problems. Sulfur dioxide (SO2), nitrogen oxides (NOx), and ammonia (NH3) are examples of secondary

PM10 aerosols that form in the air. PM2.5 is responsible for the consequences of stress PM exposure on life expectancy.

Ozone is created by photochemical reactions that are not immediately discharged into the atmosphere between NOx and non-methane volatile organic compounds (NMVOCs). Ozone is harmful to humans because it irritates the airways and damages the lungs. Asthma and chronic obstructive pulmonary disease (COPD) are more common and severely affected by human respiratory distress if the ozone levels are high. Disability Adjusted Life Years (DALYs) is a measure used to express the number of years lost due to respiratory health damage caused by PM10 and ozone exposure. In this study from the results for photochemical oxidant formation and particulate matter formation using SimaPro simulations, the following analysis was discussed:

The PM10 and ozone pollutants have higher emissions for DI and PVC pipe materials during production and construction phases respectively and lower during maintenance and end of life phases. The recycling of DI has resulted in negative (credit) environmental impacts for the end of life phase and in particular for human health damage due to PM10 and ozone pollutants. Whereas the recycling of PVC has no negative environmental impacts for this category. Overall PVC is the most sustainable material after considering all the life cycle phases in this impact category with the lowest DALY of 0.26 followed by AC, CONC, and VIT. DI is an unsustainable material with a high level of pollutant emissions in this impact category with 0.42 DALY, see Figure 5-11.



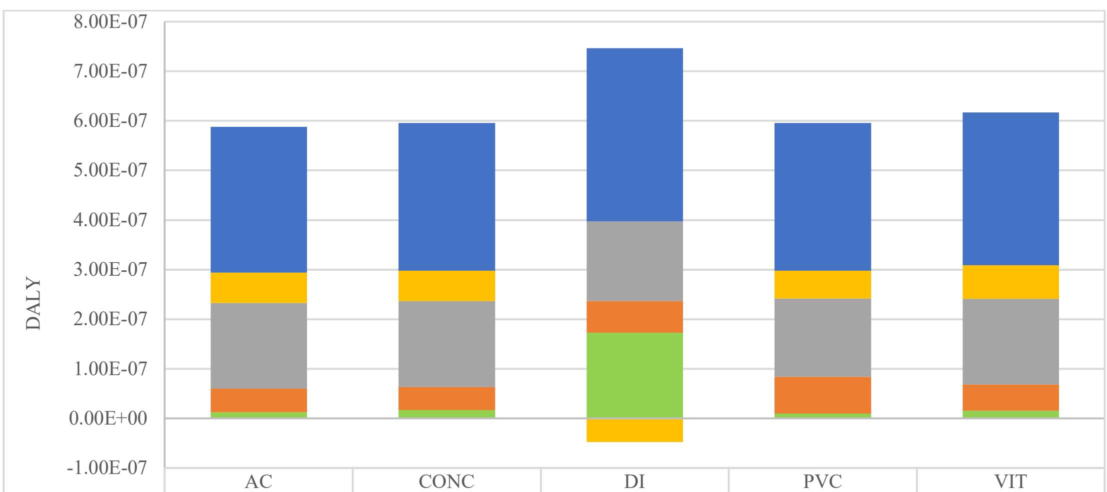
	AC	CONC	DI	PVC	VIT
Overall	2.62E-04	2.78E-04	4.22E-04	2.57E-04	2.67E-04
End of life	6.60E-06	6.65E-06	-1.63E-04	-9.09E-07	7.44E-06
Maintenance	2.20E-04	2.20E-04	1.96E-04	1.94E-04	2.20E-04
Installation	2.93E-05	2.93E-05	3.97E-05	4.84E-05	3.25E-05
Production	6.11E-06	2.24E-05	3.50E-04	1.48E-05	7.46E-06

Figure 5-11: Overview of the photochemical oxidant and PM impact category

5.3.1.7 Ionising Radiation

Ionizing radiation describes the damage to human health related to the routine releases of radioactive material into the environment. The damage analysis focuses on carcinogenic and hereditary effects which determine the number of instances resulting from calculated exposure. Disability Adjusted Life Years (DALYs) is a measure used to express the ionizing radiation in the number of years the damage to human health caused by the release of radioactive material. In this study from the results for ionizing radiation using SimaPro simulations, the following analysis was discussed:

The radioactive material atmospheric releases are highly concentrated during the production of DI pipe materials. The recycling of DI has resulted in negative (credit) environmental impacts for the end-of-life phase and in particular for the ionizing radiation impact category. Whereas the recycling of PVC has no negative environmental impacts for this category. Overall AC is the most sustainable material after considering all the life cycle phases in this impact category followed by CONC, PVC, and VIT. DI is an unsustainable material with a high level of radioactive atmospheric emissions in this impact category with highest disability adjusted life years compared to other materials, however, the DALY is significantly lower compared to other midpoint impact categories, see Figure 5-12.



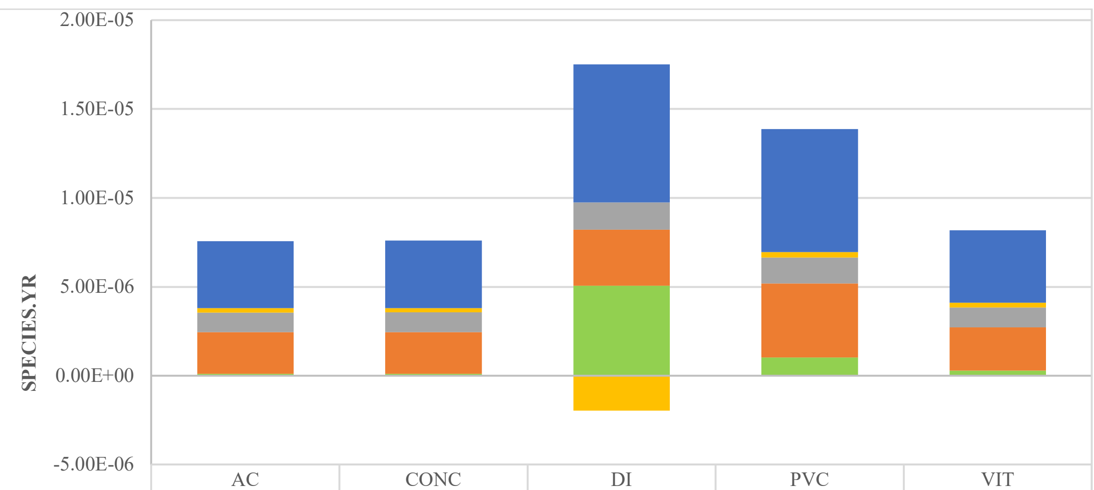
	AC	CONC	DI	PVC	VIT
Overall	2.94E-07	2.98E-07	3.49E-07	2.98E-07	3.09E-07
End of life	6.12E-08	6.13E-08	-4.76E-08	5.62E-08	6.76E-08
Maintenance	1.73E-07	1.73E-07	1.60E-07	1.58E-07	1.73E-07
Installation	4.71E-08	4.71E-08	6.39E-08	7.47E-08	5.26E-08
Production	1.28E-08	1.66E-08	1.73E-07	9.41E-09	1.55E-08

Figure 5-12: Overview of the ionizing radiation impact category

5.3.1.8 Land Use

The land use impact category reflects the damage to ecosystems due to the effects of occupation and transformation of the land. The effects of land use are the loss of biodiversity and are measured using the mechanism that occupation of a certain area of land during a certain time; and transformation of a certain area of land. At times these two mechanisms are combined as an occupation of land is followed by transformation and or occupation occurs in a land that is already transformed. To express the species affected due to land occupation or transformation, the loss of species during a year is used as a measure. In this study from the results for agriculture land occupation, urban land occupation, and natural land transformation using SimaPro simulations, the following analysis was discussed:

Production of the PVC pipe material has the most severe impact on land use followed by DI. The recycling of DI has resulted in negative (credit) environmental impacts for the end-of-life phase and in particular for the land use impact category. Whereas the recycling of PVC has no negative environmental impacts on agricultural land and urban land occupation except for natural land transformation. Overall AC is the most sustainable pipe material in terms of land use with lowest loss of species and DI is the unsustainable pipe material with highest number of species lost followed by PVC, see Figure 5-13.



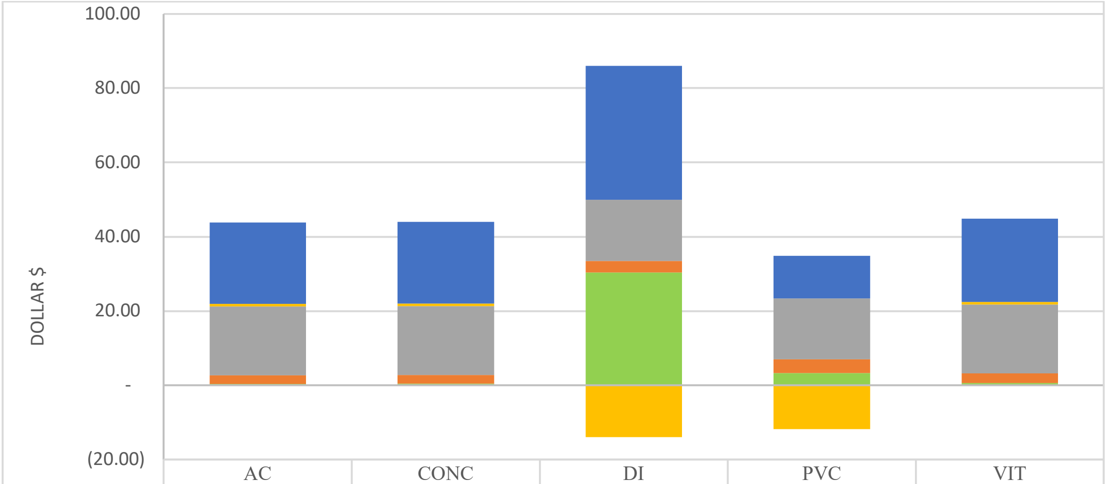
	AC	CONC	DI	PVC	VIT
Overall	3.78E-06	3.80E-06	7.77E-06	6.94E-06	4.09E-06
End of life	2.46E-07	2.47E-07	-1.97E-06	3.01E-07	2.74E-07
Maintenance	1.09E-06	1.09E-06	1.53E-06	1.46E-06	1.09E-06
Installation	2.36E-06	2.36E-06	3.16E-06	4.17E-06	2.43E-06
Production	9.00E-08	1.03E-07	5.06E-06	1.01E-06	2.93E-07

Figure 5-13: Overview of the land use impact category

5.3.1.9 Mineral Resource Depletion

Minerals are naturally occurring substances with a specific chemical composition, atomic structure, and physical properties that are formed through geological processes. When the earth was formed, minerals were present, and geological processes created places that concentrated minerals when the earth was cooled. At nature, a mineral is extracted from a deposit (extracted in a mine) and the majority of deposits are made of numerous minerals. Eventually, a mining operation produces minerals or metals, which are often referred to as commodities. There is one mineral in different deposits and many mines can generate the same sort of deposits (producing the same metal). To express the loss of minerals due to mining, economic output in terms of dollars is used as a measure. In this study from the results for metal depletion and fossil depletion using SimaPro simulations, the following analysis was discussed:

DI has the metallic composition in this research, the economic output of the minerals and metals mined for the production of DI costs more followed by PVC. The recycling of DI has resulted in negative (credit) environmental impacts for the end-of-life phase and in particular for the metal and fossil depletion impact categories. Whereas the recycling of PVC has resulted in a negative environmental impact for water and fossil depletion but a positive impact for metal depletion. Overall PVC is the pipe material that has a significantly less economic impact and is the most sustainable in this impact category followed by AC, CONC, and VIT. DI is the unsustainable pipe material with the highest economic impact to the tune of 3 times that of PVC, see Figure 5-14. The total cost to the society due to extraction of raw material for one kilometer of pipe production is around \$36k for DI. Whereas it is \$22k for AC, CONC and VIT and only \$11.5k for PVC.



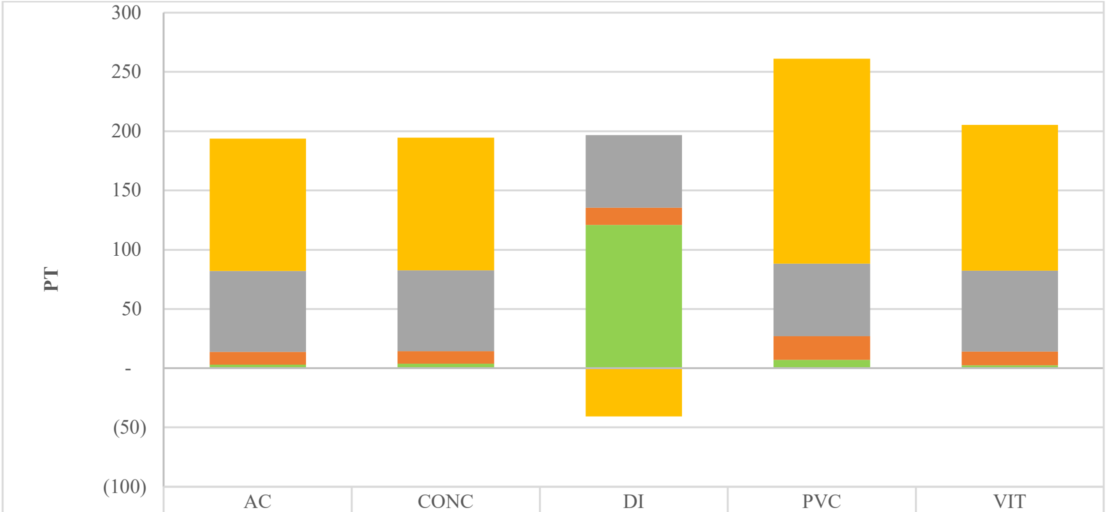
	AC	CONC	DI	PVC	VIT
Overall	21.88	21.97	36.07	11.54	22.43
End of life	6.08E-01	6.10E-01	-1.39E+01	-1.18E+01	6.77E-01
Maintenance	1.86E+01	1.86E+01	1.65E+01	1.64E+01	1.86E+01
Installation	2.29	2.29	3.10	3.69	2.55
Production	0.39	0.47	30.37	3.28	0.61

Figure 5-14: Overview of the mineral resource depletion impact category

5.3.1.10 Overall Life Cycle Impacts

5.3.1.10.1 ReCiPe's Single Score

The overall impacts of pipes (1-meter pipe of 200 mm diameter) analyzed in this study using the ReCiPe single score values are presented here. Summarising the LCA results into the endpoint damage assessment, the human health (DALY), ecosystems (Species. yr), and resource depletion (Dollars $) are severely impacted by DI pipe production followed by PVC. The total single score of DI is 113 Pt higher than the next impacted material, i.e. PVC with the maximum impact caused to human health followed by resources, see Figure 5-15. The damage assessments during construction and maintenance are relative with closer values and less significant. The end-of-life phase for DI has a huge impact on the overall LCA results as the waste treatment for DI is 90% scrapped and 10% recycled. This scrap is assumed to be not having any environmental risk. The end of life phase alone takes off 40 Pt for where other materials accumulate Pt even during this phase. Overall, the total single score of DI is comparatively less than all other materials considered in this research. The DI can be concluded as the sustainable pipe material and PVC is the unsustainable pipe material.



	AC	CONC	DI	PVC	VIT
End of life	112	112	(41)	173	123
Maintenance	68	68	61	61	68
Installation	11	11	14	20	12
Production	3	4	121	7	3

Figure 5-15: Overview of the end point damage assessment single scores

Table 5-7 presents the ranking of pipes analyzed in this study using the ReCiPe single score values. However, the single score calculation is based on a simple linear weighted sum method ignoring the impact of dominating alternatives (those with high values across all end points) and the interdependency of the indicators being analyzed. The simple linear weighted sum method used in the ReCiPe single score calculation is incapable of accounting for the effect of weighting strategies and thus cannot represent stakeholder's perspectives [165]. For instance, Canadian 2030 Sustainable Development Goals include reduction of per capita environmental impact of cities with a focus on air quality and municipal waste management. Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities is the target indicator [8]. Therefore, the weight used should accommodate such policy objectives to regionalize the LCI results.

Table 5-7: Single score and ranking of pipes

Pipe material	Single Score	Ranking
DI	156.20	1
AC	193.62	2
CONC	194.40	3
VIT	205.42	4
PVC	261.17	5

Normalization, weighting, and aggregation of LCIA results are optional, according to the ISO 14044 2006 framework. These ISO guidelines state that weighting cannot be used for comparative assertions intended for public disclosure as most of the customers are not LCA experts and would be unaware of the consequences of seeing a single, weighted environmental impact score. The weighting involves multiplying each of the impact categories' normalized outcomes by a weighting factor that reflects the impact category's relative significance which is a contentious move because the weighting factors selected will affect the LCA's findings and conclusions. On the contrary, weighting is useful for several reasons. It displays LCA results as a single score, making it simple to compare the environmental impacts of various products. Decision-making is easier because it is obvious whether a product's environmental effect is high, low, or closer to the alternatives [166].

For instance, in the current study, DI is the most toxic material (among the analyzed pipe types) in terms of carbon emissions to the environment at 447 kg CO_2eq per meter length for 8" diameter and PVC (Scenario with 80% landfill, 10% incineration, 10% recycle) is the lowest carbon-emitting pipe material at 268 kg CO_2eq. However, considering all the midpoint impact categories and the single score value arrived using the weighting by ReCiPe LCIA method DI is the most sustainable material and PVC is the most unsustainable material with 156 and 261 pt respectively. This signifies the importance of proper weighting for impact categories and the necessity to understand how the weighting factors are determined.

5.3.1.10.2 Estimated Life Cycle Impact Index

The study estimated the LCI index using midpoint impact categories and their assigned weights for pipes (1-meter length with 200 mm diameter) from cradle to grave including the trench construction. Several LCIA methods have their predefined weighting schemes, each with its process of assessing them. It is important to understand the logic behind the weighting variables because they will have a big impact on the LCA's performance. Although each procedure takes a different approach to deciding weighting factors, the following categories are common to consider [166]–[168]:

- **Single item**: To characterize or weight the life cycle inventory, physical properties or equivalents are used (example: Cumulative energy demand).
- **Distance to policy target**: When the LCA study aims to derive an environmental policy, such as policy on climate change, higher weighting is given to the specific impact category in focus. However, since policies are influenced by costs and other political considerations, policy preferences do not accurately reflect the severity of the problem (example: EDIP 97, Ecological scarcity method).
- **Distance to scientific target**: These weighting factors have a similar approach as that of distance to policy target, but instead of policy targets this approach uses scientific targets as safe benchmarks. The higher the weighting, the farther the actual condition deviates from the safe level. The drawback of this approach is that not every impact category has empirical evidence-based targets, and hence the available scientific targets are not always up to date.
- **Monetization**: The relative importance of an impact category is expressed in monetary value. This monetary significance is determined by the costs of avoiding or restoring the damage. The monetization approach has the drawback of requiring a response to the question of how much harm is permissible and how much human life is worth (example: BEES, TRACI).
- **Panel weighting**: Taking the opinion of people on the importance of impact categories is the most straightforward approach of deciding weighting factors but these opinions can easily be skewed by the panelist's attributes (example: Eco indicators 99, ReCiPe 2008).
- **Meta-models**: Multiple weighting factors arising from the combination of other weighting sets are used to weight impacts.

Seeing the complexity in weighting, the endpoints method was applied in this study, where the midpoint indicators are compiled into three standard endpoints, based on scientific factors. However, most LCA studies for pipe materials such as Alsadi 2019, Petit-Box 2014, Hajibabaei 2018, Fei Du 2013, Slagstad 2014, Vahidi 2016 [25]–[27], [128], [130], [149] focused only on carbon impact and has not given any attention to weighting and aggregating all the midpoint impact categories but similar endpoint strategies are commonly seen in other LCA studies [122], [165], [169], [170]. Therefore, in this study, the weights proposed by Sala et al 2018 were used for aggregating midpoint impact categories to estimate the life cycle impact (LCI) index. Table 5-8 provides the weights assigned for each indicator in this study [168].

Table 5-8: Weighting schemes for LCI data aggregation

Impact category	**Weight**	**Damage category**
Climate change	0.18	Damage to human health
Ozone depletion	0.05	
Human toxicity	0.03	
Particulate matter formation	0.08	
Ionizing radiation	0.04	
Photochemical oxidant formation	0.04	
Terrestrial acidification	0.05	Damage to ecosystem
Freshwater eutrophication	0.02	
Marine eutrophication	0.03	
Terrestrial ecotoxicity	0.02	
Freshwater ecotoxicity	0.02	
Marine ecotoxicity	0.02	
Agriculture land occupation	0.07	
Urban land occupation	0.07	
Natural land transformation	0.07	
Water depletion	0.07	Damage to resource
Mineral depletion	0.07	
Fossil depletion	0.07	

Using the weighted sum method and the weighting scheme for LCI data aggregation in Table 5-8, the life cycle assessment of pipes is given in Table 5-9.

Table 5-9: Life cycle impact index of pipes

Pipe material	Calculated LCI index	Ranking
AC	0.97	1
CONC	0.96	2
PVC	0.93	3
VIT	0.91	4
DI	0.57	5

The ranking has significantly changed from the ranking based on ReCiPe results from SimaPro. Ductile Iron was the most sustainable pipe material according to ReCiPe single score value and PVC is the most toxic material. The weighting scheme in Table 5-8 for LCI data aggregation has given an 18% weightage to climate change with an overall 43% to damage to human health which is of prime importance. This has resulted in having Asbestos Cement as the environmentally friendly pipe material and Ductile Iron as the most toxic material to human health.

5.3.2 Life Cycle Cost

Table 5-10, presents the life cycle cost analysis of 1 m pipe length with 200 mm diameter modeled for this research. The LCCA in this study are estimated with a discount rate of 8% [159] and considered costs associated with the pipeline only; the land acquisition, operating energy costs are excluded from the analysis. The initial costs include pipe supply costs directly obtained from the manufacturers' website and the trench construction costs estimated in RS Means. The cost index in RS Means has been set up to the Kamloops location which is nearest to Kelowna. The future costs include the maintenance using the cured in pipe place method. The frequency of maintenance is designed according to the schedule devised in Chapter 6. A complete pipe replacement costs are considered for DI and PVC at the end of the 75^{th} and 50^{th} years. The recycling costs are excluded as no data is available. However, pipe salvage costs are included in the calculation of DI pipes. From Table 5-10, DI is the most expensive pipe material estimated at $ 3491 per meter followed by PVC. The AC and Concrete pipes are turned out to be the cheapest pipe materials.

Therefore, from economic perspective DI is the most expensive pipe material while AC and Concrete are the cheapest.

Table 5-10: Life cycle cost analysis of 1m pipe length and 200 mm diameter

Pipe material	**AC**	**CONC**	**DI**	**PVC**	**VIT**	**Reference**
Useful life in years	100	100	75	50	100	
Discount rate	8.00%	8.00%	8.00%	8.00%	8.00%	[159]
(IC) Pipe supply cost	98.9	98.9	2,836.0	360.5	119.0	[171]–[174]
(IC) Trench const cost	174.2	174.2	196.2	254.3	174.2	RS Means
(FC) pipe replace cost			910,936	16,907		
(FC) CIPP cost	132,614	132,614	100,815	127,599	132,614	
(FC) salvage cost			(1606)			[175]
Initial costs (IC) in present dollars $	273	273	3,032	615	293	
Future costs (FC) in present dollars $	60	60	459	66	60	
Life Cycle Cost: Sum	333	333	3491	680	353	
Ranking	1	1	5	4	3	

IC: Initial costs, FC: Future costs

The LCA results from Table 5-9 and LCC results from Table 5-10 clearly illustrate that cementitious pipe materials i.e., AC and CONC are most sustainable in terms of environmental and economic impacts with the assumptions made in this study. In addition to that, DI was turned out to be the most unsustainable pipe material both in terms of environmental and economic impacts. This was contrasting to the ReCiPe single score value obtained from SimaPro simulations where DI was the top performer for environmental impacts. On a similar note, PVC was the most toxic material as per SimaPro single score but was improved its performance based on the estimated life cycle impact index. Overall, the LCA and LCC results are straightforward in this analysis and it was easily interpreted without any scenario prioritization. Typically, when the LCA and LCC are conflicting, the weighted sum method and the weighting scheme discussed for scenario prioritization presented in Table 5-6, are used to define the sustainable material based on pro-environmental, pro-economic, and holistic scenarios. Although PVC and VIT have conflicting LCA and LCC criteria, PVC is the second most toxic material after DI from both pro-environment and pro-economic perspectives followed by VIT.

Table 5-11: Selection of sustainable pipe material

Pipe material	LCA Ranking	LCC Ranking	Pro-environment	Pro-economic	Holistic
AC	1	1	1	1	1
CONC	2	1	2	2	2
VIT	4	3	3	3	3
PVC	3	4	4	4	4
DI	5	5	5	5	5

5.3.3 BIM Database with Lifecycle-data

In continuation to section 4.3.2, the BIM database was updated with lifecycle environmental and economic data i.e., kg CO_2eq and pipe supply cost for the sample pipe, from the results of this chapter, *shown in Figure 5-16 for reference*. The key advantage of the BIM database with life cycle data for each asset can easily identify the environmental hotspots and so the community level emissions. Since the lifecycle data is automatically retrieved, asset replacement can easily be assessed for its impact before making any decision to consider a change in the asset attributes such as length, diameter, and material. Figure 5-16, is showing the lifecycle data of the sample pipe (CoK Asset ID 6159) and for simplicity, only the kg CO_2eq and pipe supply cost are shown herewith. The BIM extended database is further updated with the results of Chapter 6 in section 6.3.5.

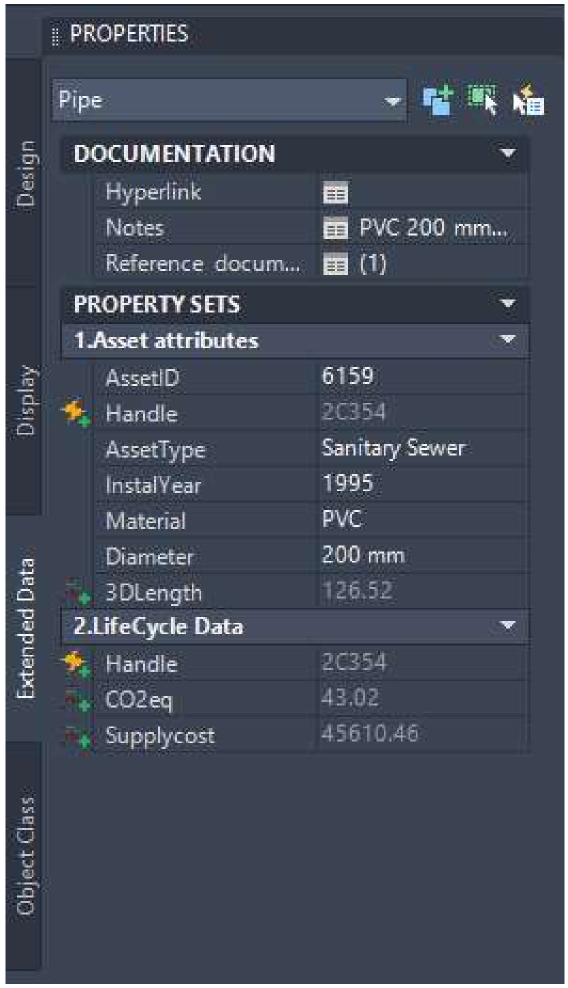


Figure 5-16: A snapshot of the BIM database with lifecycle data

5.4 Summary

Previous studies have ignored the sustainability assessment of pipe materials as the environmental emissions from pipes are significantly low when compared to the energy demand during the use phase. The life cycle costs of pipes are significantly less compared to the life cycle energy costs. The sustainable product certifications issued to pipe products are subjective as they are obtained typically using a set criteria for points. Therefore, this research investigates the sustainability of pipes within the transparent system boundary defined for the research and identifies the adverse environmental and economical effects of pipes in the urban water system. The main goal of this chapter is to quantify the environmental and economic impacts of different pipe materials based on a life cycle thinking approach. The chapter has discussed the development of life cycle assessment (LCA) and life cycle cost (LCC) based models and any conflicts between the models are assumed to be dealt with using WSM multi-criteria decision-making techniques. The ReCiPe life cycle impact assessment method has been chosen for the LCA simulation as it is capable of handling the uncertainty in the life cycle characterization model through egalitarian, hierarchies, and individualist perspectives. The results show that AC is the most sustainable pipe material from a life cycle assessment perspective compared to PVC, AC, CONC, and VIT pipe materials based on the estimated life cycle impact index. The LCC results have also shown that AC is having the lowest life cycle cost compared to other pipe materials.

Chapter 6: Integrated Management of Buried Infrastructure

Typically, municipalities measure the quality of services they provide in terms of the level of service (LoS) which is a composite indicator of asset condition, cost, customer satisfaction, and environmental acceptability [5]. This chapter outlines the condition assessment of buried infrastructure using deterministic and stochastic approaches, which is described by condition rating and presents the advantages of integrated asset management in terms of lifecycle costs and environmental impacts.

6.1 Background

Knowing the current condition and the remaining service life of the asset is important to prioritize the maintenance strategies. The current asset condition can be determined using various physical testing methods as mentioned in Section 3.1.3. These physical testing methods are expensive and not always feasible for scheduled maintenance. Overcoming this, literature has identified many deterioration models that are based on asset failure history to understand the failure pattern and predict the future failures of the asset. These deterioration prediction models can be classified as physical and statistical depending on the modeling techniques. While the physical models simulate the mechanical performance, statistical models develop mathematical equations based on historical data. Further, the physical and statistical models can be deterministic and probabilistic based on handling the randomness [15], [176]. These models could be useful if proper data is available through asset management processes. *What happens if the municipalities cannot assess the current state of their infrastructure due to the non-availability of previous asset's history?* The Canadian Infrastructure Report Card (CIRC) has identified this discrepancy and suggested few strategies as follows:

1) Knowledge management through management systems such as GIS/stand-alone database, software applications, etc.
2) Speaking a common language for reporting consistency on the standardized asset condition grading system and outlined few terms like very good, good, fair, poor, and very poor/critical.

Further, CIRC 2012 has given a guideline on estimating the remaining service life based on the asset condition grade as 80 – 100% service life for very good, 60 - 79% service life for good, 40 – 59% service life for fair, 20 – 40% service life for poor, and <20% service life for very poor.

CIRC 2012 believes that this type of estimation is a good starting point to maintain the consistency of grading and assessing the condition of the asset. However, this analysis is dependent on expert judgment which could be ambiguous and is always not feasible. A comprehensive literature review on the subject has revealed that a regression model that describes the relationship between deterioration and independent variables avoids ambiguity in the estimation of condition grade. The study done by Veshosky et al 1994 using the Federal Highway Administration’s National Bridge Inventory, has concluded that age is the only primary determinant of deterioration that takes the convex shape. However, the mathematical equations that best describe the functional relationships of deterioration and independent variables could be linear, concave, or convex patterns. The convexity was not only indicated by the regression coefficients but also by other function forms. A concave deterioration curve is consistent with the accelerated depreciation model, which has been validated by empirical studies, for determining the periodic depreciation costs of assets in the industry. The reason for the convex deterioration trend, on the other hand, includes the asset inspector's subjectivity, who is reluctant to reduce the condition rating when the asset approaches the lower end of the scale, where such a reduction could result in immediate asset rehabilitation. The presumption of decelerated degradation of the asset in a stronger setting is another potential reason for the convex pattern. Nevertheless, these discrete ratings are useful to reduce the computational complexity of the decision-making process. To the contrary, incremental models predicts changes in condition as a function of previous state and other explanatory variables such as age, soil conditions, traffic, maintenance and environment. These incremental models are more realistic and with the discrete nature of asset condition, models like Markovian transition models are developed as discrete incremental deterioration models. Therefore, the deterioration models are developed using the discrete models and then using the Markovian-chain transition probabilities. The asset deterioration pattern has been studied from this analysis and recommended the best maintenance strategy to lower both life cycle costs and environmental impacts. The results of this research could be set as a benchmark for buried infrastructure condition assessment.

6.2 Methods and Procedure

This section discusses the methods and procedures of both the deterministic and stochastic approaches that were used to assess the condition of the asset. One of the challenges municipalities encounter in reporting assets health precisely is the lack of evidence of condition information. Canadian Infrastructure Report Card, Asset Management Primer recommended the use of estimated service life remaining to assess the condition grade in the absence of a reliable rating system [177]. The current utility practice and industry indicates that age-based replacement and material-based replacement is a feasible option alongside the failure history [140]. Therefore, the condition assessment in this study is built on this fundamental assumption.

6.2.1 Deterministic Models

Most statistical models are comprised of a deterministic models and a stochastic model. The deterministic model establish direct relationships between the condition rating and the explanatory variable i.e., the age of the asset. This approach can not handle the uncertainty and the data inaccuracy. However, these models are good for simplified evaluation and absolute relationships [15]. Veshosky et al 1994, illustrated that the deterioration takes the form of a convex shape over time and [178] the regression equation for the convex model and concave model are explained by equation (1) and equation (2).

$$R = R_{max} * (1-(t/T)^2) \qquad \text{Equation (1)}$$

$$R = R_{max} * ((t/T-1)^2) \qquad \text{Equation (2)}$$

where R_{max} is the maximum rating measured on a scale of 1 to 6 [22]; t is the current age of the pipe; T is the maximum estimated service life based on the pipe material, *see* Table 6.

The above deterministic models are a mathematical formulation of deterioration rate as a function of asset age, ignoring the random error or inherent stochasticity observed due to the uncertainty. Deterministic models are efficient in performing network analysis having a large population (data), nevertheless, they can estimate deterioration only for no maintenance strategy and overlook the current condition of the asset. To overcome these limitations this study has extended the condition assessment further exploring stochastic models which are explained in the next section.

6.2.2 Stochastic Models

Markovian transition models have been effective and extensively used in infrastructure asset management to forecast the deterioration of the asset and to determine the optimal intervention strategies [179]–[183]. This stochastic technique is computationally tractable and captures the uncertainty and randomness by obtaining the probability of a future asset condition during the transition from one condition state to another. The core of the

Markovian model is in the estimation of this transition probabilities [184] typically using the asset condition data. There are several methods to estimate the transition probabilities and examples include percentage prediction [182], regression-based optimization [181], Poisson distribution and negative binomial models [185], ordered probit and random effects models [184], Bayesian statistics [179]. The regression-based optimization method is the most common method for estimating transition probabilities [186] that uses a nonlinear optimization function to minimize the error between regression curve and condition curve developed by Markov-chain model [185]. However, the regression model is sensitive to the prior maintenance action and the fundamental assumption of this study is that there is no prior knowledge of asset condition. Markov process can be defined as the probability of a future state depends on the current state and not on how it was attained to such state [187].

The development of unit jump Markov chain modeling is mathematically described below:

Consider a sequence of random variables $X_0, X_1, X_2 \ldots\ldots, X_n$ with a set of possible random variables $\{0, 1, 2, \ldots\ldots M\}$ where X_n is the state of the system at time n and $X_n = i$, where $0 \leq i \leq M$. The system is said to be in the state of i at time n and here, $X_0, X_1, X_2 \ldots\ldots, X_n$ represent the Markov chain, if

$P\ \{X_{n+1} = j \mid X_n = i, X_{n-1} = i_{n-1} \ldots. X_1 = i_1, X_0 = i_{0,}\}$

$= P\ \{X_{n+1} = j \mid X_n = i\}$

$= P_{ij}$

P_{ij} is the transition probability i.e. the probability that the system is in state i and it will turn to state j. $P_{ij} \geq 0$ and $\sum_{j=0}^{M} P\text{ij} = 1$, $i = 0,1,2\ldots M$

Therefore, the transition matrix P is given as

$$P = \begin{bmatrix} P_{00} & \cdots & P_{0M} \\ \vdots & \ddots & \vdots \\ P_{M0} & \cdots & P_{MM} \end{bmatrix}$$

A transition probability matrix P of a Markov chain contains all of the transition probabilities of that chain. A unit jump Markov chain model is shown visually as below, where the transition matrix P is given as

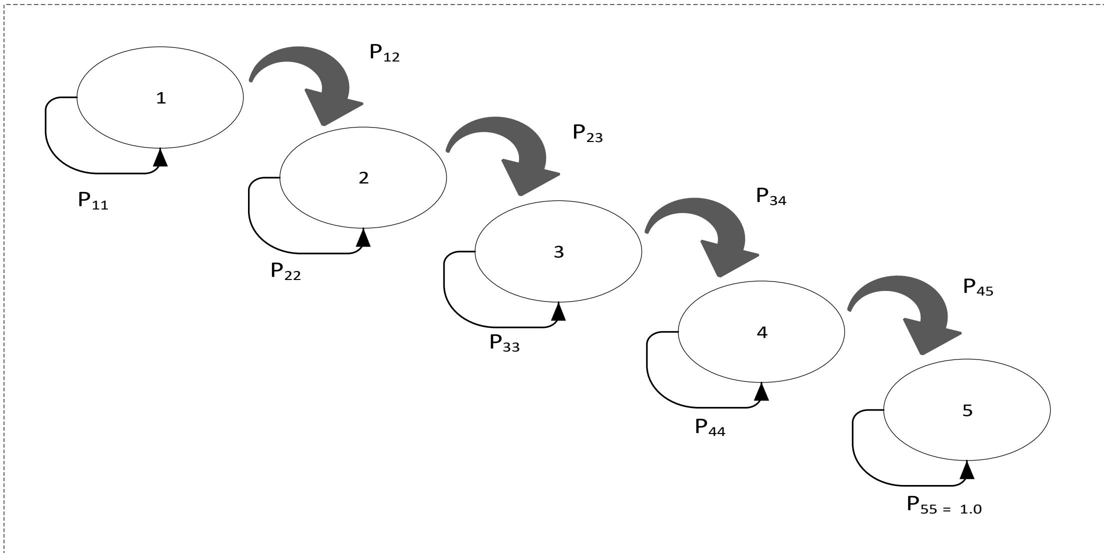


Figure 6-1: Unit jump Markovian-chain model

$$P = \begin{matrix} P11 & P12 & 0 & 0 & 0 \\ 0 & P22 & P23 & 0 & 0 \\ 0 & 0 & P33 & P34 & 0 \\ 0 & 0 & 0 & P44 & P45 \\ 0 & 0 & 0 & 0 & 1 \end{matrix}$$

This research has not developed transition probabilities as it requires accumulated condition data and subjective expert judgment. The study has assumed the transition probabilities developed by Morcous and Lounis, 2005 which is based on percentage prediction method. The condition prediction vectors for assets in their discrete condition states accumulates the probabilities during phase transition from one state of condition to another over a predefined time intervals (unit jump i.e., one year) [78]. A Markov chain is a subset of the Markov process whose evolution can be described as a series of transitions between different states. Morcous et al 2003 developed transition probability matrices for different deterioration environments considering the exposure to the external environment and traffic loads, see Table 6-1 [188]. The only limitation with the Markovian model is it considers only the current state of the asset overlooking the condition history even though the deterioration is a nonstationary process for simplicity [189].

The discrete condition rating highlighted in green ranges from 6 to 1, where the condition rating 6 represents the excellent condition and 1 represents a failed state. The ratings 5,4,3,2 represent the intermediate levels of damage. The given matrix in Table 6-1 is for Do-Nothing maintenance strategy and the probabilities are explained as follows: The chance of asset being in condition state 6 is 98% (0.98) and being in state 5 is 2% (0.02) at a given time. The other states are displayed as zeros for clarity. Similarly, after a predetermined time (one year in this study), the probability of being in condition state 6 decreases from 98% (here it is shown as 0 for clarity) and the probability of being in condition state 5 increases from 2% (0.02) to 96% (0.96) and the asset enters a new condition state 4 with a probability of 4% (0.04). This will proceed until the likelihood of reaching the end condition state of 1 is 100% (failed state). At any point in time, the complete number of all states equals unity. Therefore, in other words, these models predict the probability of a given asset to remain in the current state or change to another state within a time. The transition probability matrices for the maintenance alternatives of repair, rehabilitate, and replace for any of the above deterioration environments are given in Table 6-2. These matrices are assumed to represent the maintenance alternative on the asset condition. Once the condition vectors and maintenance alternative (only if the condition rating is less than the required LoS), are determined for the respective deterioration type, the condition rating is calculated by doing a sum-product with the asset condition states. For example, consider an asset in an undamaged initial condition state of 6 with 100% probability and a benign deterioration environment. First, the matrix product of initial condition [1 0 0 0 0 0] and the matrix for benign environment in Table 6-1 gives [0.98 0.02 0 0 0 0]. Then, the sum product of this matrix with the condition state [6 5 4 3 2 1] results in a condition rating of 5.98 (0.98 x 6 + 0.02 x 5). In the same example, if the initial/previous condition is 4 (for an LoS requirement of 4.5), a suitable maintenance alternative (Repair, Rehabilitate, Replacement) is chosen and the respective matrix from Table 6-2 is included in the matrix product to calculate the condition rating. These matrix product calculations in this study are performed in Microsoft Excel using the MMULT function. The MMULT function returns the matrix product of two arrays. The result is an array with the same number of rows as array1 and the same number of columns as array2. The syntax for the MMULT function is MMULT (array1, array2) [190].

Table 6-1: Transition probability matrices for different deterioration environments

	6	5	4	3	2	1
6	0.98	0.02	0	0	0	0
5	0	0.96	0.04	0	0	0
4	0	0	0.93	0.07	0	0
3	0	0	0	0.84	0.16	0
2	0	0	0	0	0.92	0.08
1	0	0	0	0	0	1

Benign environment

	6	5	4	3	2	1
6	0.93	0.07	0	0	0	0
5	0	0.93	0.07	0	0	0
4	0	0	0.94	0.06	0	0
3	0	0	0	0.94	0.06	0
2	0	0	0	0	0.9	0.1
1	0	0	0	0	0	1

Low environment

	6	5	4	3	2	1
6	0.83	0.17	0	0	0	0
5	0	0.86	0.14	0	0	0
4	0	0	0.95	0.05	0	0
3	0	0	0	0.91	0.09	0
2	0	0	0	0	0.84	0.16
1	0	0	0	0	0	1

Moderate environment

	6	5	4	3	2	1
6	0.77	0.23	0	0	0	0
5	0	0.81	0.19	0	0	0
4	0	0	0.87	0.13	0	0
3	0	0	0	0.93	0.07	0
2	0	0	0	0	0.88	0.12
1	0	0	0	0	0	1

Severe environment

Table 6-2: Transition probability matrices for different maintenance alternatives

	6	5	4	3	2	1
6	1	0	0	0	0	0
5	1	0	0	0	0	0
4	0	1	0	0	0	0
3	0	0	1	0	0	0
2	0	0	0	1	0	0
1	0	0	0	0	1	0

Repair

	6	5	4	3	2	1
6	1	0	0	0	0	0
5	1	0	0	0	0	0
4	0	1	0	0	0	0
3	0	1	0	0	0	0
2	0	0	1	0	0	0
1	0	0	1	0	0	0

Rehabilitate

	6	5	4	3	2	1
6	1	0	0	0	0	0
5	1	0	0	0	0	0
4	1	0	0	0	0	0
3	1	0	0	0	0	0
2	1	0	0	0	0	0
1	1	0	0	0	0	0

Replace

6.2.3 Case study

Buried infrastructure is considered the most critical and vital link for any municipality because the failure of these systems has a cascading effect on the entire city that may lead to severe catastrophes. A network of water and wastewater pipelines from the City of Kelowna (CoK) Municipality was selected as a "proof of concept" application of the proposed methodology, however, a similar strategy can be applied to any infrastructure. The data required for the condition rating calculations were obtained from the CoK open-source database, which is a part of a comprehensive system for managing the city's buried infrastructure in the Okanagan valley. The data includes inventory data, which consists of pipe identification (Feature ID and Object ID), description, and geometry. However, the maintenance and condition data are not available from the open-source dataset and hence few assumptions were made for the case study like undamaged initial condition, the water distribution network was in severe deterioration environment, sanitary sewer network in a moderate environment, and storm sewer in the low environment. The pipe inventory of the entire CoK municipality includes different pipe materials and diameters and the majority are made of plastic (70%), cementitious (25%), metallic (3%), and Clay (2%) with the diameter ranging from 25 mm to 3000 mm. Figure 6-2 represents the pipe distribution according to material in the CoK municipality.

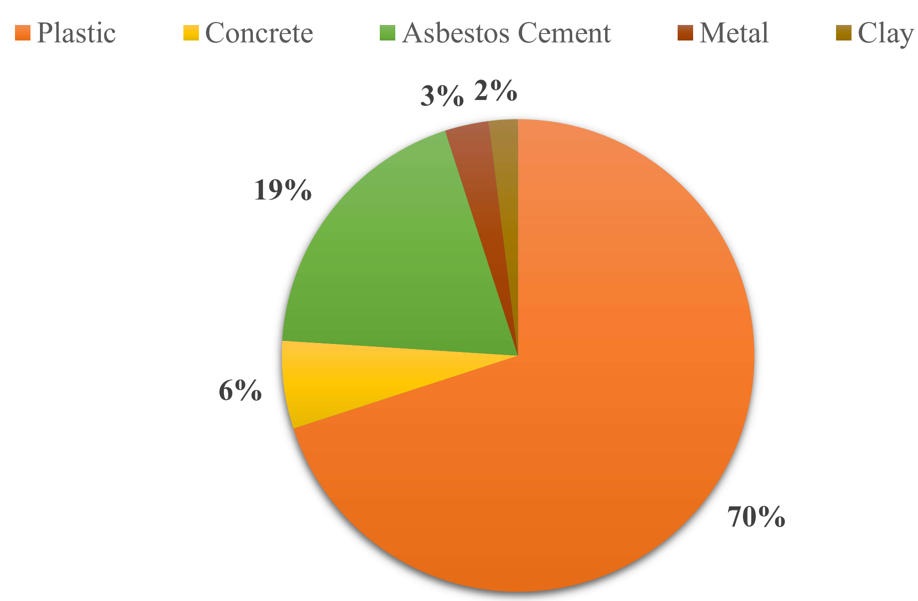


Figure 6-2: Pipe distribution according to material

Further, the estimated costs for the pipe maintenance actions, expected time for recommended maintenance, and rehabilitation strategies were missing from the opensource dataset. While most LCA studies have established the life cycle analysis with a functional unit that does not represent the actual buried infrastructure network comprehensively which is typically integrated and interdependent in reality. Countries with vast landmass such as Canada and the US can afford sprawled town planning and thus separate trenches for each pipe network system to prevent congestion in the buried infrastructure. However, the fundamental criticism of urban sprawling is a costly development pattern and inefficient low-density development. Moreover, the Commission of the European Communities states that urban densification is a sustainable way of urbanization [37]. According to this, a common trench has been verified for its feasibility in this study. Schedule 4 of Bylaw 7900 of City of Kelowna, BC design standards has a provision for sewers (sanitary and storm) in a common trench with a horizontal clearance of not less than one meter between the pipes [124]. Similarly, the Washington Suburban Sanitary Commission (WSSC), State of Maryland standard detail M/18.0, and Part 3 section 3 of common design guidelines illustrates the specifications of the common trench where a minimum vertical clearance of half a meter when water pipes are placed in parallel to sewer in a common trench [191]. WSSC is the largest water and wastewater utilities in the US with a network of nearly 5,844 miles of water and 5,610 miles of sewer pipelines. Considering these provisions, a common trench has been designed following American Concrete Pipe Association's Standard installations, which can be flat or benched at the bottom with vertical spacing as mandated by local laws. However, this study has considered a hybrid design with both flats (for sewer pipes) and benched (for water pipes), see Figure 6-3 and Figure 6-4.

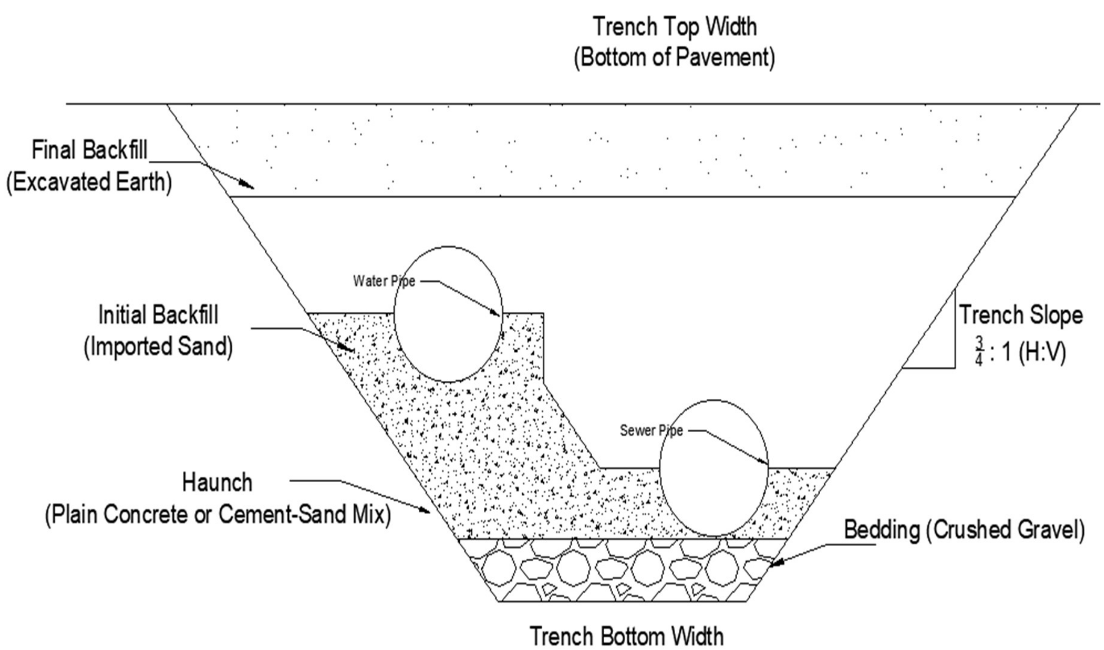


Figure 6-3: Multiple pipes benched trench cross-section

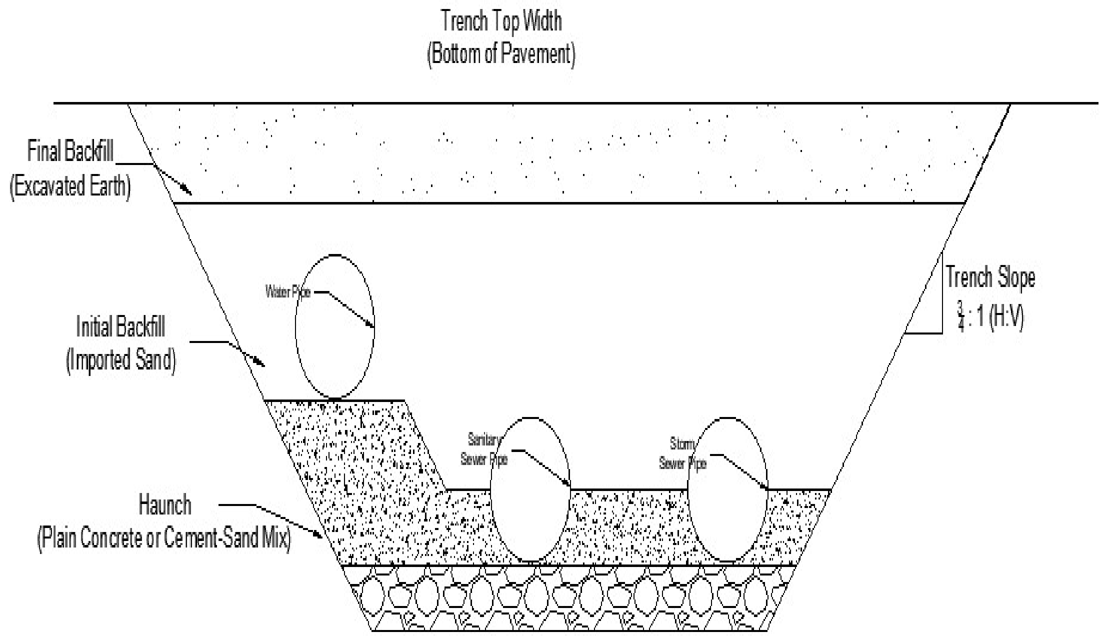


Figure 6-4: Multiple pipes benched trench cross-section

6.3 Results and Discussion

6.3.1 Condition Assessment

The condition assessment was performed for an analysis period of 100 years for water and wastewater (sanitary sewer and storm sewer) systems separately using the data from the City of Kelowna. Initially, the deterioration curves were plotted for the Do Nothing strategy and then with a rehabilitate maintenance strategy. Further for simplicity, the transition probabilities for the water network are assumed to be in a severe environment as any changes to internal water pressure/transient pressure alters stresses acting on the pipe causing severe deterioration [192]–[194]. Sanitary sewer under gravity flow but with a large pollutant load is considered to be in a moderate environment, and storm sewer under gravity flow with a low pollutant load is assumed to be in low deterioration environments. A Level of Service of 3.5 on a Likert scale of 1 to 6, where 1 is failed state and 6 is an excellent state, was considered as a worst-case scenario and the utility owners can choose their own. The preliminary condition rating was calculated for the selected pipe network using the deterministic model equations and further verified with the Markovian-chain model transition probabilities, defined in the methods and procedure section of this chapter to avoid any uncertainty in the data. The condition rating calculated using the convex model gave optimistic results and the concave models resulted in pessimistic condition rating values. The condition rating obtained from the Markovian-chain model is in between the optimistic and pessimistic values and is the most likely value which has considered not only the pipe age but the deterioration environment also, see Figure 6-5. The RMSE of the Concave model and the Markovian-chain model is 2.1 for the selected pipe network.

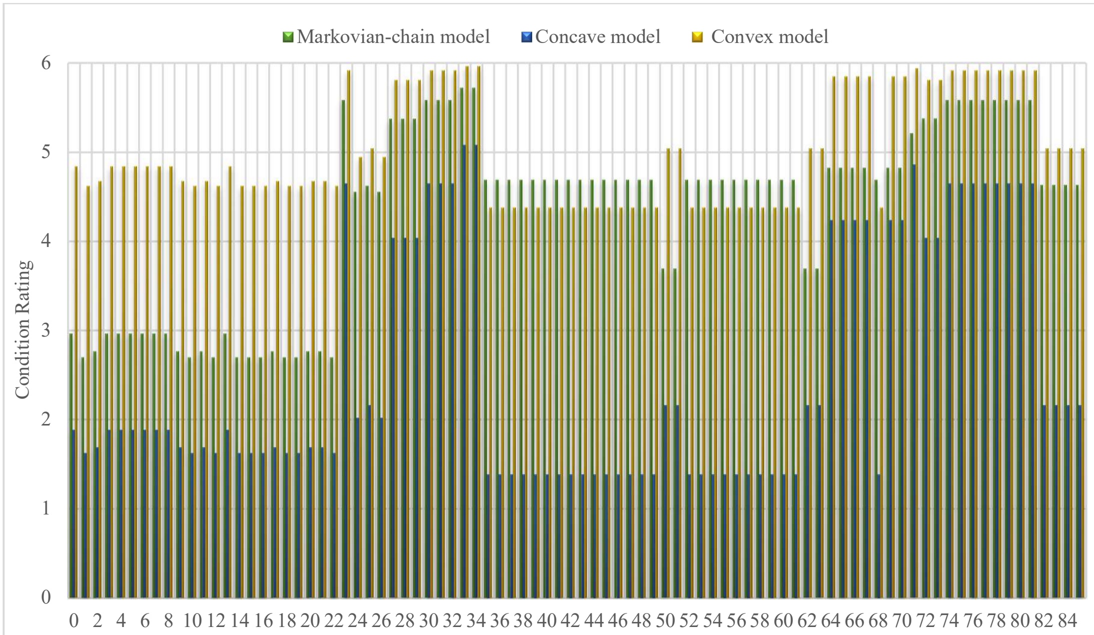


Figure 6-5: Condition assessment for the selected pipe network

The calculated condition rating from deterministic (convex and concave) and stochastic model (Markovian-chain) were compared for the Do Nothing strategy where the deterioration curve is allowed to degrade on its own without any maintenance action. The resulting graphs, Figure 6-6, Figure 6-7, and Figure 6-8 illustrate that the Markovian-chain model aligns with the concave model.

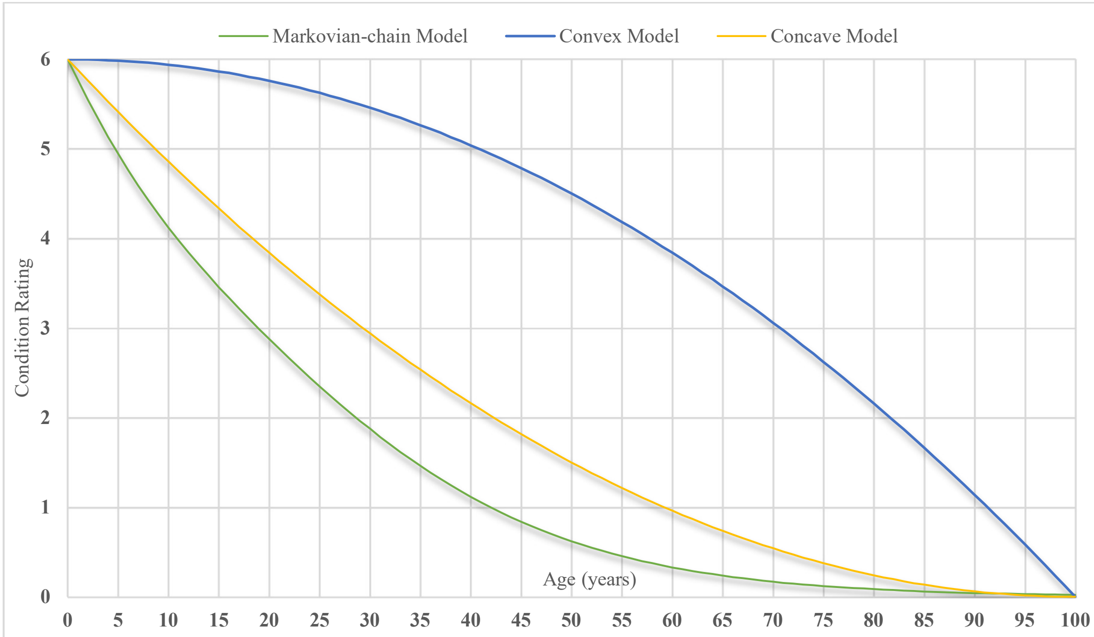


Figure 6-6: Deterioration curve in a severe environment with Do Nothing strategy

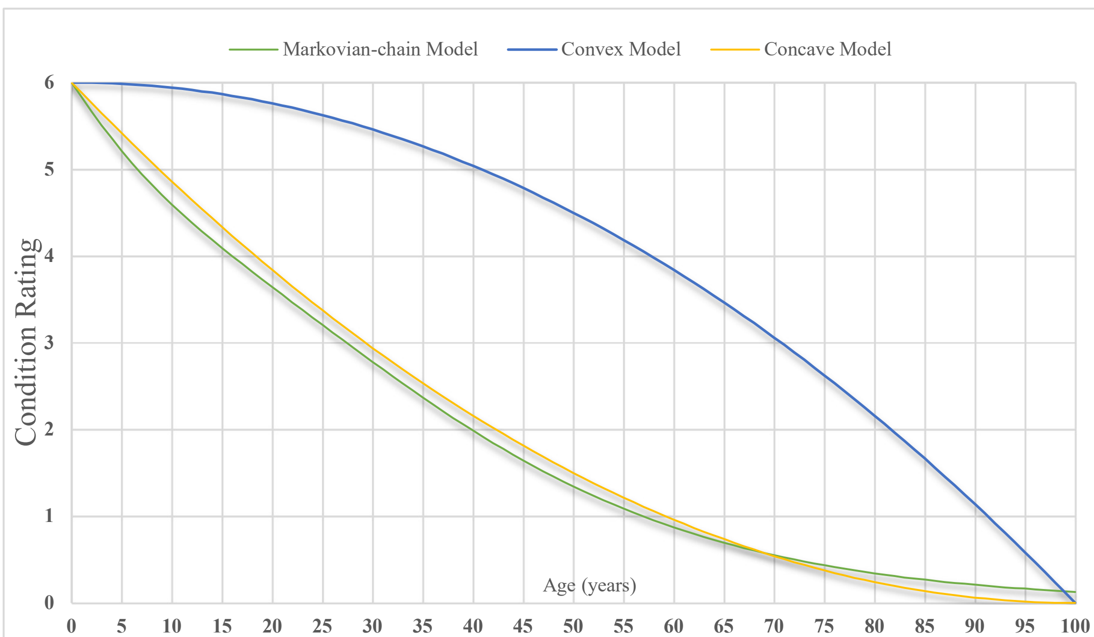


Figure 6-7: Deterioration curve in a moderate environment with Do Nothing strategy

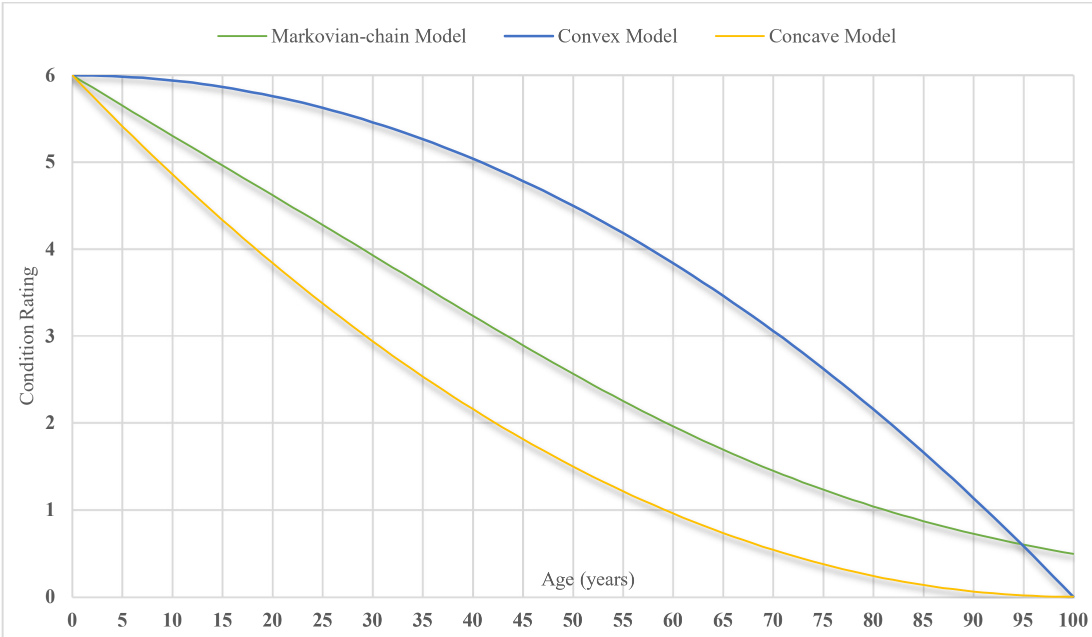


Figure 6-8: Deterioration curve in a low environment with Do Nothing strategy

The Markovian-chain model curve makes sense as it moves closer to the concave model curve and passes beyond it when the deterioration environment is changed from severe deterioration environment to moderate, and then low. A suitable maintenance action for rehabilitating the pipe such as cured-in-place pipe (CIPP) is considered whenever the pipe condition reaches an LoS less than 3.5. A detailed explanation of different maintenance strategies such as repair, rehabilitation, and replacement was already discussed in Chapter 5. The condition rating and the condition vectors for water and wastewater systems are tabulated with complete replacement maintenance strategy considered at the end of service life at the 100th year in Appendix A.

As the initial condition is assumed to be undamaged so year 0 has the condition rating of 6.00 and with each year passing the condition rating keeps reducing and at year 15 the rating dropped to less than 3.5. Therefore, the rehabilitate maintenance strategy, CIPP is considered at year 15 and the condition rating has jumped to 5.01, see Figure 6-9. The condition rating calculated for the Do Nothing strategy keeps falling from 6.00 at year 1 to 0 in the 100th year. This means if no (maintenance) action is taken on the asset, the deterioration at the 100th year fails. As the pipe is assumed to be replaced completely at the end of its service life i.e., 100 years the condition rating has changed to the new condition of 6.00 at the 100th year.

The lower service life of pipe, for instance, PVC, the pipe's service life is only 50 years, where the complete replacement maintenance is considered at the end of the 50th year and the rehabilitate maintenance strategy with CIPP whenever the LoS is less than 3.5 remains valid. The condition rating for the Do Nothing strategy in this case would be 0 at the end of the 50th year. Similar approaches are taken for sanitary sewer and storm sewer pipes with moderate and low deterioration environments respectively resulting in different renewal planning schedules.

Overall, the deterioration curves have shown that the LoS has dropped to less than 3.5 at every 12 years of operation for the water pipe network as shown in Figure 6-9, 17 years of operation for sanitary sewer (Figure 6-10), and 25 years of operation for storm sewer network (Figure 6-11) in a 100-year lifecycle analysis period. The reason behind the different maintenance (repair, rehabilitate, and replacement) times is due to their various deterioration environments such as severe for the water system, moderate for the sanitary sewer system, and low for storm sewer system with the rehabilitate maintenance strategy. Table 6-3, illustrates the maintenance schedule for rehabilitation for water and wastewater systems having 100 and 50 years of total service life.

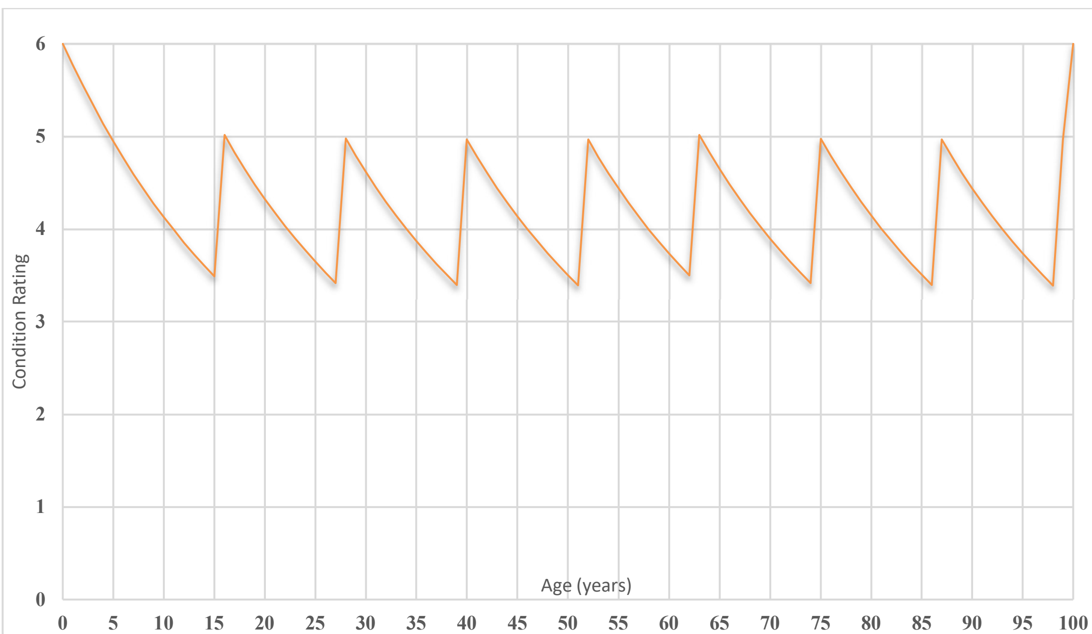


Figure 6-9: Deterioration curve for water network with pre-defined LoS

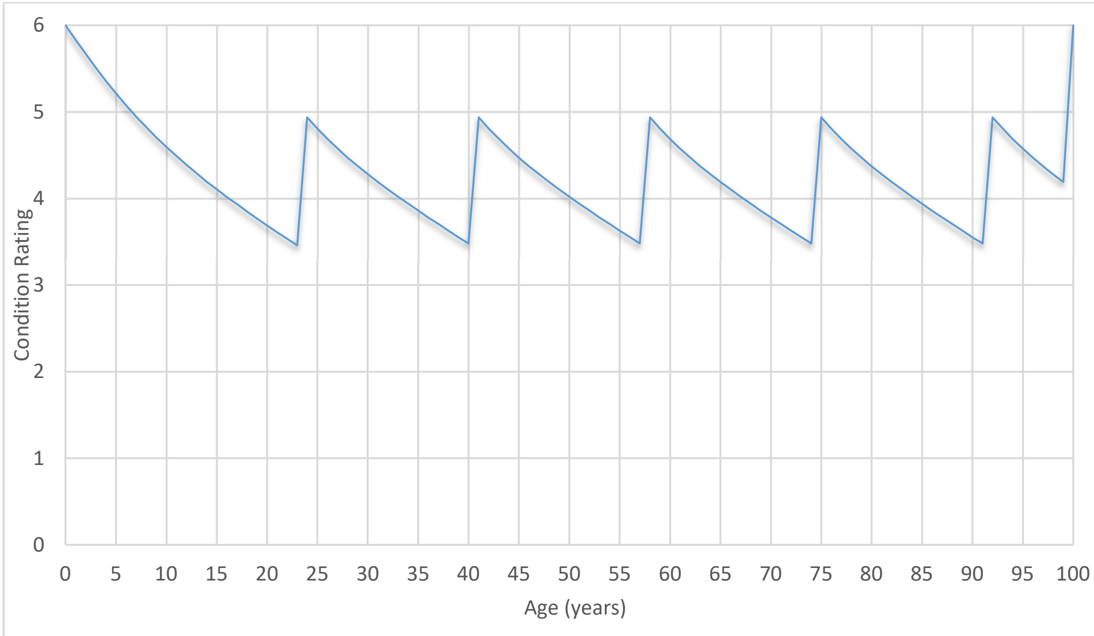


Figure 6-10: Deterioration curve for the sanitary network with pre-defined LoS

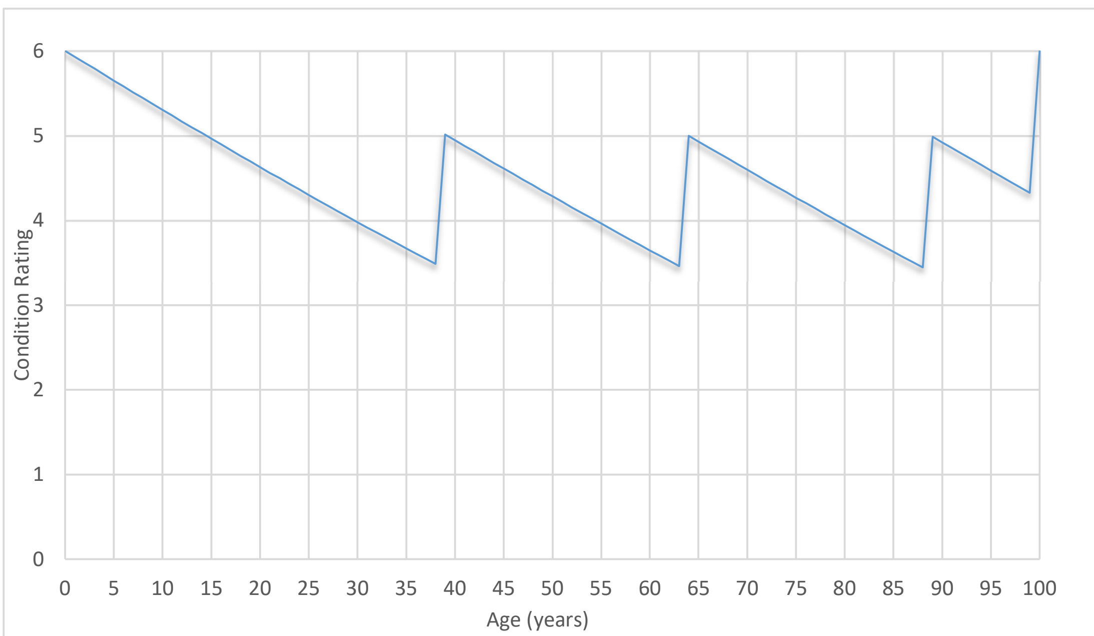


Figure 6-11: Deterioration curve for storm network with pre-defined LoS

6.3.2 Asset Maintenance Strategies

Typically, municipalities follow the maintenance strategies independently according to their respective maintenance schedule which has resulted in higher maintenance, social, and life cycle costs over the years. Repeated road excavations and frequent traffic disruptions are the results of independent maintenance schedules increasing the life cycle costs to municipalities. Centralizing the buried infrastructure is a possible solution as InfraGuide has foreseen and suggested exploring integrated asset management [3].

The integrated schedule in Table 6-3, was developed using the integrated deterioration curve of the water and wastewater network. All the lowest points are captured and in the combination of schedules, some pipelines are recommended ahead of their maintenance schedule and some are delayed with a preference given to the critical assets i.e., in this case, the pipelines in severe deterioration environment, see Figure 6-12.

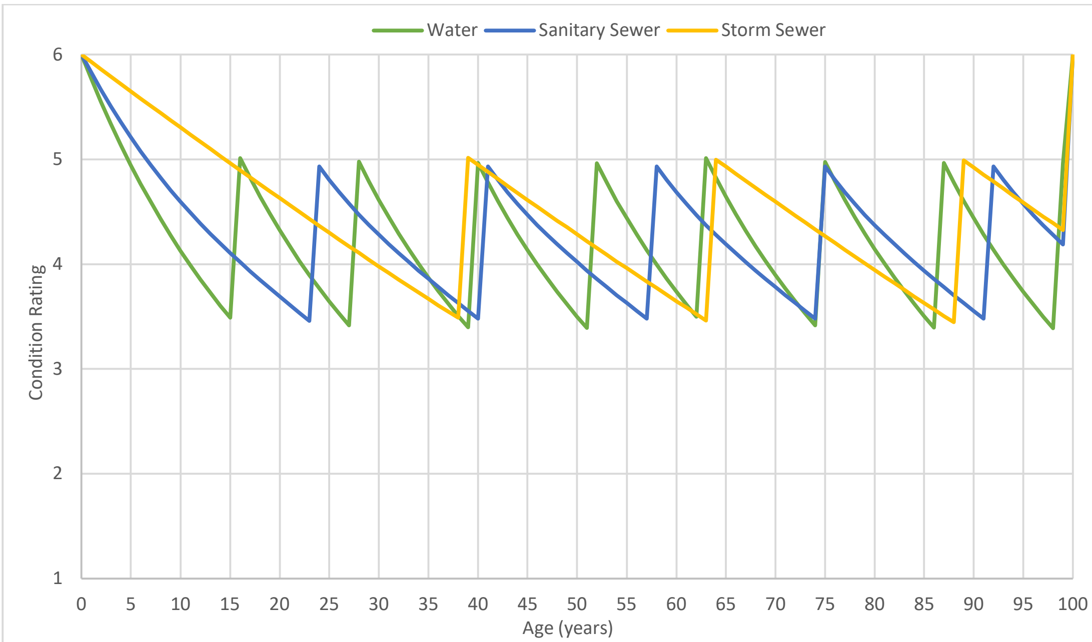


Figure 6-12: Overlapped deterioration curves with pre-defined LoS

The integrated schedule requires a common or combined trench to overcome the difficulties in repeated excavations and frequent disruptions to traffic. The details of the combined trench were discussed in Chapter 6, a case study. The benefits of the integrated schedule were analyzed using the criterion lower life cycle costs, lower life cycle impact index, and lower environmental impacts mainly kg CO_2eq.

Although the deterministic models are new to buried infrastructure, they are used for preliminary condition assessment as a benchmark, and the stochastic Markov-chain models were used extensively to model the pipe deterioration curve and develop the maintenance schedule from there because of their ability to capture the time dependence and uncertainty of the deterioration process in addition to their computational efficiency and reliability especially at the network level. Nevertheless, the major limitation with the Markov-chain model is that they are assumed to be in either benign, low, moderate, or severe deterioration environments and the classification of these environments is subjective and has been applied in an ad hoc manner in this research, which may result in either overestimating or underestimating the pipe deterioration. However, the goal of this research remained to find combinations of deterioration patterns for each water and wastewater system that best represents the actual condition.

Table 6-3: Water and wastewater systems pipe maintenance schedule

Pipe type	**Pipe network**	**Scheduled maintenance activity (Cured-in place pipe) at Year**							
AC, CONC, and VIT (100 years)	Water	15	27	39	-	51	62	74	86
	Sanitary	-	23	40	-	57	-	74	-
	Storm	-	-	38	-	-	63	-	88
PVC (50 years)	Water	15	27	39	50*	-	65	77	89
	Sanitary	-	23	40	50*	-	-	73	90
	Storm	-	-	38	50*	-	-	-	88
AC and PVC (combined)	Integrated	15	27	39	50^	-	62	74	86

* Replace

^ CIPP for AC & Replace for PVC

Concludingly, the research showed the feasibility and capability of the proposed framework in correlating the deterioration environmental categories accurately and efficiently. The common trench has been verified for its environmental impact and mainly the CO_2 emissions, as the trench size has been increased in volume due to its optimistic design that can accommodate pipe size ranging 4”–12”. The design has also been verified by altering the concrete benching with gravel and earthen benching to verify for any further significant reduction in life cycle impacts. The tonne CO_2eq for a separate trench is 383 tonne for 6.52 km, having 59 kg CO2eq per meter. Whereas the integrated trench has an emission of 134 kg CO_2eq per meter when the trench was designed with gravel or earthen materials and 269 kg CO_2eq per meter when the integrated trench was designed with a concrete bench. However, the integrated trench has only 3.4 km in length that covers the same area by the separate trenches. Therefore, the increase in tonne CO_2eq for an integrated trench with concrete and gravel benching options are 139% and 19% respectively. The life cycle environmental impact has drastically reduced with gravel as the option in terms of tonne CO_2eq. The comparison results of the Life Cycle Assessment with concrete and gravel/earthen materials are tabulated in Table 6-4 and compared to separate trenches. When these trench designs were analyzed considering the estimated life cycle impact index in chapter 5, the separate trench has a total score of 1430 for the entire network and whereas the common trench with concrete option has 917 points and that with gravel option has significantly dropped to 647 which are 36% and 55% less compare to separate trenches.

Table 6-4**:** Environmental impacts of separate and integrated trench construction

Environmental impacts	**Separate trench**	**Common trench with concrete benching**	**Common trench with gravel benching**
Trench length	6.52 km	3.39 km	3.39 km
Tonne CO_2eq	383	913	457
LCI index	1,430	917	647

Further, the trench designs were also analyzed for their life cycle costs to see any significant cost impact in the construction of the common trench. The trench costs were estimated in RS means with cost index set up to Kamloops which is nearest to Kelowna. The cost of these common trenches was calculated with concrete and gravel benching having either 2 pipes i.e., water and sanitary pipes, or 3 pipes i.e., water, sanitary, and storm pipes. The unit cost of the trench with concrete benching and for 2 pipes and 3 pipes are $ 309 and $ 542 respectively. Similarly, the unit cost of the trench with gravel benching and for 2 pipes and 3 pipes are $ 272 and $497 respectively. Using this unit cost of the trench, the life cycle cost of the separate and common trench is tabulated below. The common trench length has reduced to half of the total trench length when there are separate trenches for each pipeline system. Although the unit cost of the separate trench is only $ 217 per meter the total life cycle costs are much higher than the common trench due to its trench length.

Table 6-5**:** Life cycle cost of separate and integrated trench construction

Life cycle cost	**Separate trench**	**Common trench with concrete benching**	**Common trench with gravel benching**
Trench length	6.52 km	3.39 km	3.39 km
Initial costs Million CA$	1.41	1.1	0.99
Future costs Million CA$	34.83	34.77	31.04
LCC Million CA$	36.24	35.87	32.03

6.3.3 Scenario Prioritization

Table 6-4 and Table 6-5 presents the results of the life cycle impacts of a separate trench when compared to a common trench with concrete benching and a common trench with gravel or earthen benching. The results were analyzed using the three weighting schemes discussed in 5.2.4 according to Table 5-6 for scenario prioritization. An interesting observation is that the separate trenches had a higher impact score than the integrated trench with both concrete and gravel benching, from a pro-environmental perspective. On the contrary, when the climate change impact alone was analyzed ignoring all other environmental impacts the separate trench is having lesser kg CO_2eq emissions than the integrated trench. This is because the integrated trench was designed considering multiple pipes (which made the trench bigger) and with a pipe range up to 12’ (maximum pipe size in the case study), whereas the separate trench is only suitable for particular pipe diameter, i.e.,8’. Overall, considering the estimated LCI index as the criteria for selecting the separate or common trench, the strength of the decision to chose a common trench over the separate trench is 152%. Similarly, from a pro-economic perspective, the comparison analysis made between separate and integrated trenches has revealed that the integrated trenches are much cheaper with shorter trench lengths to the tune of 13% less which are resulted from multiple pipe accommodations in the trenches. The strength of the decision to chose a common trench over a separate trench is 177%. Lastly, taking the neutral approach has also suggested for the common trench over a separated trench and decision strength is around 163%. The common trench with gravel benching is the best option among the other options having the lowest life cycle costs to the tune of 18% less compared to the separate trench and 55% less environmental impacts with the LCI index estimated using the assigned weights.

6.3.4 City of Kelowna

The results from the common trench are promising with significant cost savings and an overall life cycle impact index. Further using these results, the life cycle impacts of the chosen pipe network were estimated to establish the impact magnitude at the network level. The life cycle impacts of pipe production, maintenance (repair, rehabilitate, replace), end of life phases was kept similar for separate and integrated maintenance schedules, but are differed only in the trench construction. The selected network modeled in BIM, as discussed in chapter 4, includes approximately 6.52 km that includes 3.41 km (0.8 km PVC & 2.6 km AC) of the water network, 2.48 km (PVC) of sanitary sewer network, and 0.62 km (PVC) of the storm sewer network.

Table 6-6 presents the life cycle impact of the selected pipe network with separate and common trenches in place with a focus given to the global warming impact, described in terms of a ton of CO_2eq, which was estimated from the BIM database discussed in section 5.3.3 and Table 6-7 presents the life cycle impact of the selected pipe network with separate and common trenches in place with an estimation of life cycle impact index. The base-case scenario is the existing water and wastewater network with the actual composition of pipe combination from the CoK municipality with AC and PVC. Two different scenarios had been verified replacing AC and PVC with DI respectively from the base-case pipe combination and five other scenarios, with the entire network having single material either AC, CONC, DI, PVC, or VIT. Overall, both DI and PVC are the most toxic materials for carbon impacts and estimated life cycle impact index. The AC and concrete pipe materials are the most sustainable when both life cycle environmental and life cycle costs are considered.

Table 6-6: Life cycle environmental impact for the selected pipe network

	Scenario	Pipe combination	Separate maintenance	Integrated maintenance with concrete benching	Integrated maintenance with gravel benching
			Tonne CO_2eq	Tonne CO_2eq	Tonne CO_2eq
1	Base-case: existing pipes with AC and PVC	AC & PVC	2,067	2,598	2,141
2	AC pipes replaced with DI	DI & PVC	2,414	2,916	2,459
3	PVC pipes replaced with DI	AC & DI	2,665	3,292	2,836
4	PVC pipes replaced with AC	AC	2,012	2,693	2,237
5	Both AC & PVC pipes replaced with CONC	CONC	2,023	2,704	2,247
6	Both AC & PVC pipes replaced with DI	DI	3,012	3,610	3,154
7	AC pipes replaced with PVC	PVC	2,087	2,536	2,079
8	Both AC & PVC pipes replaced with VIT	VIT	2,010	2,667	2,211

Table 6-7: Life cycle environmental impact for the selected pipe network

	Scenario	Pipe combination	Separate maintenance	Integrated maintenance with concrete benching	Integrated maintenance with gravel benching
			LCI index	LCI index	LCI index
1	Base-case: existing pipes with AC and PVC	AC & PVC	2,492	1,979	1,709
2	AC pipes replaced with DI	DI & PVC	3,026	2,392	2,121
3	PVC pipes replaced with DI	AC & DI	2,887	2,608	2,337
4	PVC pipes replaced with AC	AC	2,054	1,997	1,726
5	Both AC & PVC pipes replaced with CONC	CONC	2,067	2,009	1,739
6	Both AC & PVC pipes replaced with DI	DI	3,421	3,020	2,750
7	AC pipes replaced with PVC	PVC	2,730	1,968	1,697
8	Both AC & PVC pipes replaced with VIT	VIT	2,264	2,111	1,841

The sample network is also studied for its economic impacts, estimating the lifecycle costs. The life cycle costs are compared with existing pipes in separate trenches for water and wastewater and with their respective maintenance schedule independently to the proposed integrated schedule and combined trench for an analysis period of 100 years**.** The results from Table 6-8, are significant which showed a total savings of around 18% with the integrated schedule when compared to a separate maintenance schedule for the selected case study, see Figure 6-13**.** The total savings have been increased by an additional 6% (24% total) when the integrated schedule shifted one year ahead and 12% (30% total) when the integrated schedule shifted two years ahead. After three optimizations these savings in life cycle costs start decreasing due to addition of a CIPP maintenance cycle. Two other pipe combinations were also verified with DI pipes replacing AC and PVC which turned out to be the most expensive options. The entire pipe networks were also verified with homogeneous pipe types and the concrete, AC, and clay pipes were having the lowest life cycle costs among all. When these savings are analyzed, it is found that the initial costs including the first two scheduled maintenance are higher with the integrated maintenance than separate maintenance, but the overall savings are a result of the present value of the money with the integrated maintenance schedule**.**

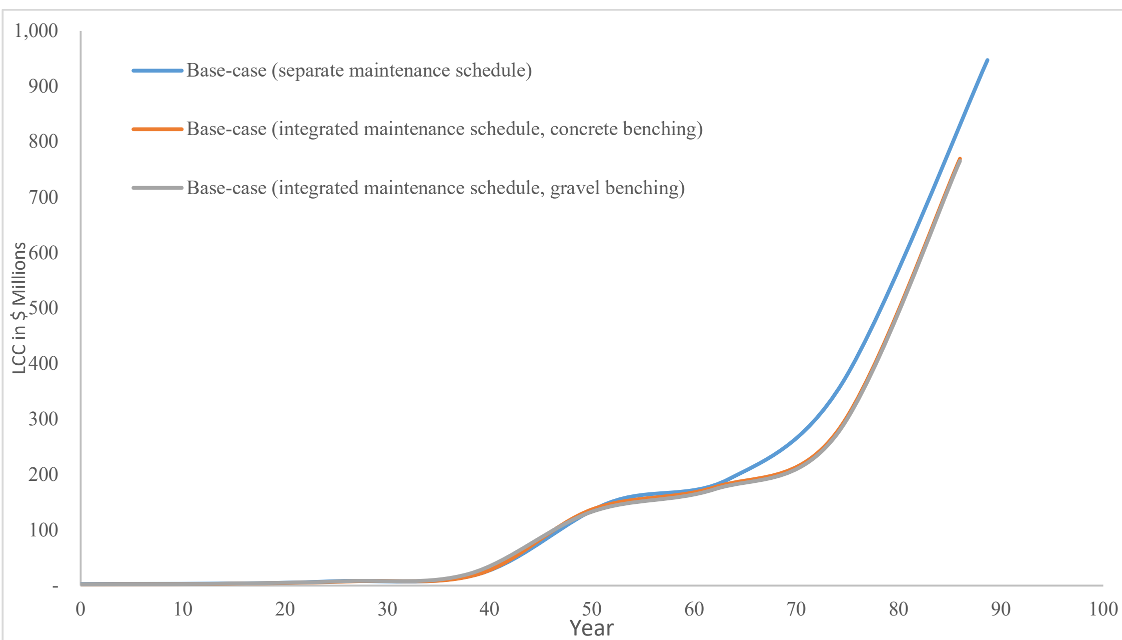


Figure 6-13: LCC comparison of separate and integrated management

Table 6-8: Life cycle cost of the selected pipe network

	Scenario	Pipe combination	Separate maintenance	Integrated maintenance with a trench having concrete benching	Integrated maintenance with a trench having gravel benching
			LCC Million $ CAD	LCC Million $ CAD	LCC Million $ CAD
1	Base-case: existing pipes with AC and PVC	AC & PVC	936	770	766
2	AC pipes replaced with DI	DI & PVC	3,299	2,696	2,668
3	PVC pipes replaced with DI	AC & DI	4,209	4,132	4,109
4	PVC pipes replaced with AC	AC	862	761	761
5	Both AC & PVC pipes replaced with CONC	CONC	861	761	761
6	Both AC & PVC pipes replaced with DI	DI	7,153	5,791	5,767
7	AC pipes replaced with PVC	PVC	1,177	875	871
8	Both AC & PVC pipes replaced with VIT	VIT	861	761	761

6.3.5 BIM Database with Condition-data

In continuation to section 5.3.3, the BIM extended database was further updated for future studies, with the results of this chapter i.e., the asset condition rating, the deterioration environment and the current estimation of assets remaining service life for the sample pipe (CoK Asset ID 6159), shown in Figure 6-14 for reference

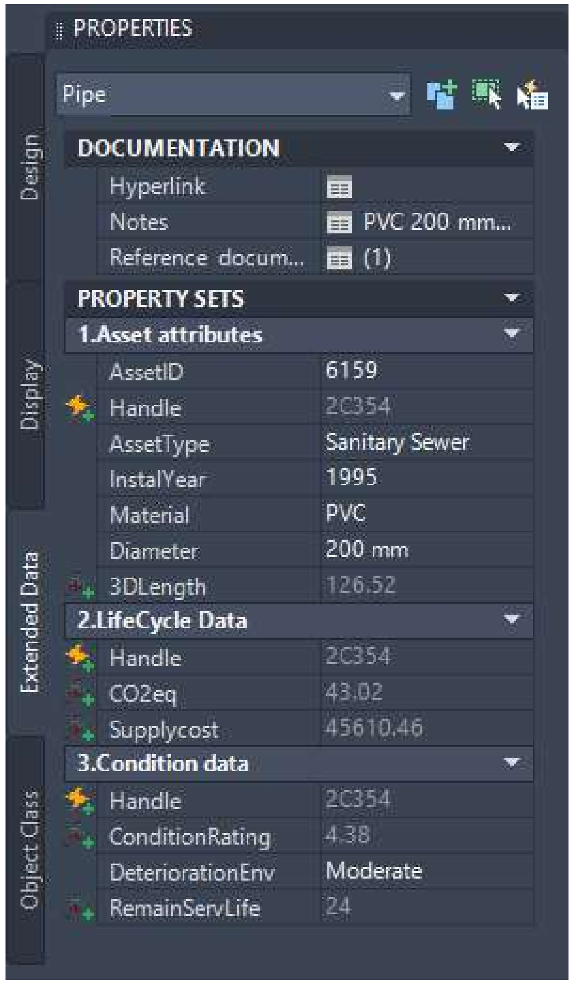


Figure 6-14: A snapshot of the BIM database with condition data

6.3.6 Applicability of the proposed framework

The proposed framework has only included water and sewer pipelines, for which the municipality is the only stakeholder, however, the integration with other third-parties is very much feasible and less tedious with an integrated BIM approach. The workflow for including additional utilities would include corresponding shape files. This can be extended to develop the corridors which require information like pavement's horizontal and vertical crust details and the profiles. The life cycle environmental and economical impacts were quantified using established ISO methodologies and typically IFC data sharing format is used for extraction of information from the BIM model for real-time comparison of alternatives. This IFC data sharing format for Infrastructure is under development in the industry and as a workaround this research has explored the inclusion of environmental properties in the BIM objects. Wastiels L and Decuypere R 2019 has discussed such workflow for the integration of LCA and BIM [36]. Therefore a life cycle database is developed in the BIM model with LCA information so that several alternatives can be easily explored whenever a decision has to be made. Deterioration models were developed as an integral component of the asset management to derive the failure pattern and devise a maintenance schedule. But this study focused only on a single deterioration environment for each of the asset systems, i.e., water distribution system as severe deterioration, sanitary sewer as moderate deterioration, and storm sewer as low deterioration environments, and assumed that the same deterioration environment would continue after maintenance. However, the same framework can be applied with different deteriorating environmental conditions of each system specific to any location using the given transition probabilities. Similarly, the trench has been designed in this study following the guidelines of North American standards such as CSA, ASTM, ASCE, and AASHTO. Nevertheless, the trench design has also been verified with local municipal bylaws and OSHA guidelines for safe trenching and excavation requirements. Remarkably, the design can be extended within the proposed framework according to the work or construction practice changes depending on the local requirements. Furthermore, the proposed framework can be used for pipes and other infrastructure with new materials, for which life cycle assessment and cost analysis have to be conducted to put in the framework. Concludingly, the proposed BIM approach in this study has strong generalizability as it can be applied to a wide range of study areas. The adoption of the BIM approach shows that the integrated environment can benefit from performing structural conditional assessments, hydraulic analysis, life cycle assessments, energy analysis, information retrieval, space management, and real-time data analysis through sensors directly on the geometry of the building with variations in specifications.

6.4 Summary

This chapter discussed a methodology for condition assessment of water and wastewater buried infrastructure mainly pipelines through the use of historical data obtained from the City of Kelowna municipality. Condition assessment techniques such as deterministic (convex and concave model) and stochastic (Markovian-chain model) were developed based on Do-Nothing and Rehabilitate maintenance strategy to identify the deterioration pattern in the systems. The Deterioration models constitute an integral part of the asset management process because of their ability to predict the failure pattern in the future and, consequently, their maintenance needs. Using the deterministic model, a standard deterioration pattern was determined for the Do Nothing strategy and then verified with the Markovian-chain model. The root means square error (RMSE) of the Markovian-chain model when compared to the concave model for water infrastructure with severe deterioration environment is 2.54 and with the moderate environment is 2.58 and with low deterioration, the environment is 2.64. RMSE is the standard deviation of the residuals which is a measure for best fit. A polynomial trendline of order 3 with R^2 0.99 is the best fit for the data. A polynomial trendline is a curved line that is used when data fluctuates while analyzing large data sets. The order of the polynomial is determined by the number of fluctuations in the data. Further, A case study was devised with Chapter 5 and Chapter 6 results as a proof of concept and to test the feasibility of the methodology. A new integrated maintenance approach as a potential alternative was proposed for a network of infrastructure systems. A common trench has been designed with two alternatives for a trench with water and sanitary sewer and a trench with water, sanitary, and sewer pipes. These common trenches were verified for regulations, construction safety, life cycle environmental impacts, and life cycle costs. The Markov-chain prediction models in this research have accounted for the uncertainty in the deterioration patterns and have optimized the life-cycle cost for the proposed common trench and the output of this approach has provided a specific integrated maintenance schedule in a planning horizon. This planning horizon has minimized the life cycle cost and ensured that the required level of service is within the acceptable range. The results show that there is a cost-saving with the common trench and integrated maintenance schedule to the tune of 18% when compared to separate trenches for each of the water and wastewater pipelines and separate maintenance schedules. At the same time, the common trench (with concrete haunch) has more Kg CO_2eq emissions to the tune of 139% when compared to separate trenches. Nevertheless, this increase in environmental emissions can be reduced by replacing the concrete haunch with gravel/earth to 19% making it feasible.

Chapter 7: Conclusion

This research has proposed a BIM-based Life Cycle Thinking framework to foster sustainable infrastructure installation and management in utilities. Integration of BIM with LCA is a promising way to safeguard the environment while also empowering both sustainability and decision-making processes in the AEC industry. Both the information about construction materials and their asset managment can be harmonised by BIM. This research has focussed on the integration of BIM and LCA in methodologies rather than in software,, which has been achieved by adding the life cycle impacts of buried infrastructure to the BIM objects. Owners can realize the benefits of BIM processes by supporting the life cycle value of the as-built model. The 3D model developed in this study isable to analyze both hard and soft clashes, which is beneficial for conflict resolution during operations and maintenance. Furthermore, adopting the BIM approach allows better coordination and better space management between public and private stakeholders for any utility relocations, replacements, repairs, and or during any catastrophic failures. The research studies done previously are in the early adoption stages for integrated asset management and there is a lack of a comprehensive research framework that can analyze the feasibility of an integrated maintenance strategy. This study thereby addressed the gap in the feasibility evaluations of the integrated maintenance schedule with a BIM-based life cycle thinking approach and conducting a case study to measure the impact at the municipality level. A case study was conducted with the City of Kelowna municipality data and the findings of the study revealed a significant reduction in the life cycle costs and environmental impacts as well. Therefore this framework can be considered as an alternative strategy of inclusive business model for sustainable practices. .

7.1 Summary and Conclusions

Below is an overview of the major findings in this research from each of the chapters:

Chapter 3: A comprehensive literature review was conducted on the buried infrastructure asset management process and emerging technologies for digitalizing the asset management at the municipality level, its collaboration, and interoperability. The findings of the literature review revealed that implementation of the Building Information Modeling for buried infrastructure was feasible and the data exchange across the various platforms can assist the utility managers to make smart decisions.

Chapter 4: A 3D model was developed to represent the physical assets digitally and visualize the actual topography. The 3D model evaluated the case study conducted on an integrated asset management approach by estimating the life cycle impacts of separate maintenance schedules and the integrated maintenance schedule. The 3D model was also analyzed for its maintenance management data exchange process by developing a life cycle database in the model that can integrate with external relational database management systems such as Microsoft Access. The outcomes of this chapter are found to be a research basis for further enhancement towards digital twinning in the buried infrastructure.

Chapter 5: It presents the sustainability aspect of the pipe materials where different pipe types are analyzed for their life cycle impacts and evaluation of single score method. The chapter has also discussed the shortfall of ReCiPe's single score calculation and has estimated the life cycle impact index using assigned weights. The conflict of interest between environmental and economic impacts is evaluated based on the multi-criteria decision method. The results from the chapter have been considered in the case study discussed in Chapter 6, for integrated asset management, and the option with lower life cycle impacts has been considered as the best solution.

Chapter 6: It presents the methodology for condition assessment of the buried infrastructure (water and wastewater). Deterministic deterioration models such as concave and convex models are new to buried infrastructure but have been used to estimate the condition rating of bridge decks for many years and have shown reliable results, particularly when there is no prior history of asset's health. Nevertheless, the condition assessment in this research has also developed a markovian-chain model which is a stochastic model, which can handle the uncertainty and randomness errors effectively. The root means square error (RMSE), a statistical parameter to evaluate the strength of the model is found reasonable. The markovian chain models in this research generated the deterioration patterns of water and wastewater infrastructure systems and the different maintenance strategies such as do nothing, repair, rehabilitate and replacement has determined the maintenance schedules. Further using the developed 3D model from Chapter 4 and the life cycle impact results from Chapter 5, a case study was developed to analyze the feasibility of an integrated maintenance schedule that has optimized the life cycle impacts. The results have revealed significant life cycle cost savings and lower life cycle environmental impacts when the trenches for water and wastewater systems are combined rather than keeping them separate.

However, the high initial costs for the bigger trenches are discouraging but keeping the life cycle costs in mind the common trenches are highly recommendable.

7.2 Originality and Contributions

This research delivers the following original contributions, which assist utility managers in developing cost-effective and sustainable asset management strategies.

Proposed a BIM-based life cycle thinking framework for integrated asset management of buried infrastructure: This research has drawn attention to the buried infrastructure asset management and the recurring annual expenditure, Canadian municipalities are spending annually. The primary reason for this is the lack of interoperability and collaboration among the asset systems. Each asset system has its own set of stakeholders, resulting in different perspectives, systems, and priorities. Following a comprehensive review of literature, and addressing the above issue, it was determined that BIM could serve as a common platform that can collaborate and integrate various asset systems. So, this study has implemented a BIM-based framework for buried infrastructure asset management. BIM is the first step in the evolution of Digital Twin technology, with the added benefit of being able to manage multiple asset systems (for future studies) such as roads, other utilities, bridges, and all other infrastructure that contributes to the development of cities and communities. Furthermore, this technology advancement was combined with a life cycle thinking approach to reduce the environmental impact caused by these infrastructure developments for cities and communities to make them sustainable.

Investigated Building Information Modeling process adaptability and asset maintenance management at the city level: While building information modeling processes are used widely in the buildings sector, investigations of its adaptability in the buried infrastructure are lacking. The study conducted a comprehensive literature review and investigated the process feasibility of implementing building information modeling at the city level. The research has contributed to the body of knowledge by discussing several strategies for developing a BIM 3D model and how the developed model can interact with external databases for data exchange.

Established the feasibility of implementing an integrated maintenance schedule by reducing the cost and environmental impacts associated with the construction of a common trench for buried infrastructure: Integrated asset management as a sustainable strategy has gained less attention in the literature. The proposed research framework which is the first of its kind has integrated BIM with the life cycle thinking approach has formed a research basis for future studies. The results obtained from the life cycle environmental and cost assessments conducted in this study can be considered as a benchmark for assessing the sustainability of different municipal buried infrastructure pipe materials. Although earlier researchers have studied multi-utility purpose tunnels for buried infrastructure, designing and analyzing a common trench following the municipality bylaws for water and wastewater systems using life cycle impacts at the municipality level is a novel contribution. The knowledge developed in this area will contribute to future research.

A proposed comprehensive framework for sustainability assessment of pipe types: Most life cycle assessment studies have ignored the end of life phase and stop at the use phase. This is due to the complexity involved in designing a waste scenario and the waste treatment process. However, this study has conducted the life cycle assessment from cradle to grave life cycle phases. The conflict of interest between the life cycle environmental impact and life cycle cost analysis has been analyzed by a multi-criteria decision technique. This research has addressed these major limitations in the body of knowledge considering the sustainability assessment at the municipality level.

7.3 Limitations

In conducting this study, the following constraints and problems were met. The impacts of these constraints have been adjusted.

Uncertainties in life cycle data: Evaluation and pricing of the life cycle demand a large volume of information, and data collecting is a difficult process for performance evaluations. The data available in the literature show a considerable degree of diversity. Furthermore, the study carried out a case study evaluating the applicability of the suggested integrated research framework for asset management, which may have variabilities with different municipalities and varying buried infrastructure assets. The uncertainty has been minimized by analyzing several options and selected the worst-case scenario with the most economical trench design.

Limited investigations on digital twinning for water and wastewater system: The study has assumed that the introduction of the Buried Information Modeling process is the first evolutionary step towards digital transformation in the buried infrastructure asset management. However, the research could not integrate artificial intelligence with digital twins to make the model dynamic.

Social consent of common trench design was not analysed: The social approval of the common trench design is an important factor in research feasibility for public customers. However, because to lack of available social approval data from such popular trench designs, social approval was not included in the multiple criteria analysis..

Environmental impacts of leachate were not considered: The study has analyzed the environmental impacts of PVC pipe material for sustainability. If this PVC is disposed of in a landfill and is exposed to rainwater, the plastic retains the highly volatile water-soluble compound it contains, resulting in a dangerous stew known as leachate, which can contaminate the ecosystem and this study has not analyzed the leachate effect in the life cycle impacts.

7.4 Future research

The current study focused on assessing the initial condition of the asset and eliminate the subjectivity in grading the buried infrastructure asset condition. Asset age has played a major role in determining the condition of the asset and ignored the other spatial and temporal characteristics such as pipe physical, structural and hydraulic parameters, soil and environmental characteristics, and the pipe breakage or failure history. Therefore, this study has proposed the following research directions to improve the current first efforts of the proposed research framework for condition assessment.

Conventional stochastic optimization techniques for future prediction models: The proposed strategy for maintenance optimization should utilize traditional stochastic optimization approaches, such as stochastic dynamic programming, which can support the usage of Markov chains for performance predictions. Markov decision processes are a subclass of stochastic dynamic programmes in which the underlying stochastic process is a stationary process with the Markov property. This comparison could take into account the most recent advances in Neuro-dynamic programming, which use artificial neural networks and other approximation structures to overcome the limits of traditional dynamic programming.

Extending the research framework to multiple deterioration environments: The study has only focused on a single deterioration environment type for each system, for example, the water distribution system is assumed to be severe deterioration environment, sanitary sewer in moderate deterioration environment, and storm sewer in low deterioration environment. Although the same framework can be applied to any infrastructure system, future work is required to verify the challenges involved in dealing with multiple deterioration environments for each system.

Expand the system boundary of the study to include the use phase: The study has excluded the use phase since the pumping energy during operations is heavily affected by topography, grid demand, and pump power, which varies with each sample region and cannot be standardized. Future work should try to standardize the use phase, which has significant environmental impacts. It is also important that the available approaches to estimate energy demand throughout the use phase are considered and the environmental consequences evaluated by widening the system boundary to include the holistic impact of the life cycle evaluation in future research.

Investigate the effect of leachate in the end-of-life phase: The study has ignored the effect of leaching and the emissions during the treatment of leach from the landfill during the end-of-life phase. Rainwater filters through wastes in a landfill, forming leachate. When this liquid comes into contact with buried wastes, it leaches (or draws out) chemicals or constituents. The leachate can affect underground water quality, soil characteristics, release toxic emissions to the environment (while treating), and can also affect the hydraulic conductivity of natural clay. Future work should evaluate the environmental effect due to this leachate and include it in the end-of-life phase.

References

[1] Oxford Economics, "Global Infrastructure Outlook," *GI Hub*, p. 64, 2017, [Online]. Available: https://outlook.gihub.org/.

[2] T. M. Harchaoui, F. Tarkhani, and P. Warren, "Public infrastructure in Canada: Where do we stand?," *Insights Can. Econ.*, 2003.

[3] InfraGuide, "An Integrated Approach to Assessment and Evaluation of Municipal Road, Sewer and Water Networks," 2003. [Online]. Available: https://fcm.ca/sites/default/files/documents/resources/guide/infraguide-integrated-approach-assessment-evaluation-municipal-road-sewer-water-networks-mamp.pdf.

[4] Federation of Canadian Municipalities, "Monitoring the State of Canada's Core Public Infrastructure," 2019. [Online]. Available: http://canadianinfrastructure.ca/downloads/canadian-infrastructure-report-card-2019.pdf.

[5] G. Y. Félio and Z. Lounis, "Model framework for assessment of state, performance, and management of Canada's core public infrastructure," *Natl. Res. Counc. Canada*, 2009.

[6] L. A. Coad, "Improving Infrastructure Management: Municipal Investments in Water and Wastewater Infrastructure," 2009.

[7] M. Najafi and G. Kulandaivel, "Pipeline condition prediction using neural network models," in *Pipelines 2005: Optimizing Pipeline Design, Operations, and Maintenance in Today's Economy*, 2005, pp. 767–781.

[8] "Goal 11 - Sustainable cities and communities." https://www144.statcan.gc.ca/sdg-odd/goal-objectif11-eng.htm (accessed May 24, 2021).

[9] "Climate and sustainability | Federation of Canadian Municipalities." https://fcm.ca/en/focus-areas/climate-and-sustainability (accessed Aug. 17, 2021).

[10] "Sources of Greenhouse Gas Emissions | Greenhouse Gas (GHG) Emissions | US EPA." https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions (accessed Jul. 03, 2021).

[11] B. Soust-Verdaguer, C. Llatas, and A. García-Martínez, "Critical review of bim-based LCA method to buildings," *Energy Build.*, vol. 136, pp. 110–120, 2017, doi:

10.1016/j.enbuild.2016.12.009.

[12] W. Yang and S. S. Wang, "A BIM-LCA framework and case study of a residential building in Tianjin," *Model. Comput. Eng. II - Proc. 2nd SREE Conf. Model. Comput. Eng. C. 2013*, pp. 83–88, 2013, doi: 10.1201/b14896-14.

[13] M. Marzouk, S. Azab, and M. Metawie, "BIM-based approach for optimizing life cycle costs of sustainable buildings," *J. Clean. Prod.*, vol. 188, pp. 217–226, 2018, doi: 10.1016/j.jclepro.2018.03.280.

[14] Winnipeg (Man.). Committee on Works and Operations, *Strategic Infrastructure Reinvestment Policy: Report & Recommendations*. Task Force, 1998.

[15] B. Rajani and Y. Kleiner, "Comprehensive review of structural deterioration of water mains: physically based models," *Urban Water*, vol. 3, no. 3, 2001, doi: https://doi.org/10.1016/S1462-0758(01)00032-2.

[16] C. Fazal and Z. Tarek, "Infrastructure Condition Prediction Models for Sustainable Sewer Pipelines," *J. Perform. Constr. Facil.*, vol. 22, no. 5, pp. 333–341, 2008, doi: 10.1061/(ASCE)0887-3828(2008)22:5(333).

[17] G. Vladeanu and J. Matthews, "Wastewater Pipe Condition Rating Model Using Multicriteria Decision Analysis," *J. Water Resour. Plan. Manag.*, vol. 145, no. 12, p. 4019058, 2019.

[18] G. Kabir, S. Tesfamariam, A. Francisque, and R. Sadiq, "Evaluating risk of water mains failure using a Bayesian belief network model," *Eur. J. Oper. Res.*, vol. 240, no. 1, pp. 220–234, 2015, doi: https://doi.org/10.1016/j.ejor.2014.06.033.

[19] R. Jafar, I. Shahrour, and I. Juran, "Application of Artificial Neural Networks (ANN) to model the failure of urban water mains," *Math. Comput. Model.*, vol. 51, no. 9, pp. 1170–1180, 2010, doi: https://doi.org/10.1016/j.mcm.2009.12.033.

[20] J. Q. Zhao, "Trunk sewers in Canada." pp. 75–89, 1998.

[21] E. Allouche and P. Freure, "Management and maintenance practices of storm and sanitary sewers in Canadian Municipalities," *ICLR Res. Pap.*, no. 18, pp. 1–52, 2002.

[22] Federation of Canadian Municipalities, *Canadian infrastructure report card Volume 1: 2012 Municipal Roads and Water Systems*, vol. 1. 2012.

[23] S. Akhtar, B. Reza, K. Hewage, A. Shahriar, A. Zargar, and R. Sadiq, "Life cycle

sustainability assessment (LCSA) for selection of sewer pipe materials," *Clean Technol. Environ. Policy*, vol. 17, no. 4, pp. 973–992, 2015, doi: 10.1007/s10098-014-0849-x.

[24] J. M. B. Recio, P. J. Guerrero, M. G. Ageitos, and R. P. Narváez, "Estimate of energy consumption and CO2 emission associated with the production, use and final disposal of PVC, HDPE, PP, ductile iron and concrete pipes," *Univ. Politécnica Catalunya*, no. December, pp. 1–59, 2005, [Online]. Available: https://scholar.google.co.uk/scholar?q=recio+Estimate+of+energy+consumption&btnG=&hl=en&as_sdt=0%2C5#1.

[25] A. Alsadi, "Evaluation of carbon footprint during the life-cycle of four different pipe materials," College of Engineering and Science Louisiana Tech University, 2019.

[26] A. Petit-Boix *et al.*, "Environmental Assessment of Sewer Construction in Small to Medium Sized Cities Using Life Cycle Assessment," *Water Resour. Manag.*, vol. 28, no. 4, pp. 979–997, 2014, doi: 10.1007/s11269-014-0528-z.

[27] F. Du, G. J. Woods, D. Kang, K. E. Lansey, and R. G. Arnold, "Life cycle analysis for water and wastewater pipe materials," *J. Environ. Eng.*, vol. 139, no. 5, pp. 703–711, 2013.

[28] Y. Luo, A. Alaghbandrad, T. K. Genger, and A. Hammad, "History and recent development of multi-purpose utility tunnels," *Tunn. Undergr. Sp. Technol.*, vol. 103, p. 103511, 2020.

[29] K. Altshuler, S. Horst, N. Malin, G. Norris, and Y. Nishioka, "Assessment of the technical basis for a PVC-related materials credit for LEED," *US Green Build. Counc. Febr.*, 2007.

[30] A. Abolmaali, A. Motahari, J. Hutcheson, and T. Le, "Evaluation of HDPE Pipelines Structural Performance," 2010.

[31] E. N. Allouche, "Condition assessment and management of municipal sewers in Canada: State-of-the-practice," 2002.

[32] M. Wang, Y. Deng, J. Won, and J. C. P. P. Cheng, "An integrated underground utility management and decision support based on BIM and GIS," *Autom. Constr.*, vol. 107, no. November 2018, p. 102931, 2019, doi: https://doi.org/10.1016/j.autcon.2019.102931.

[33] R. H. Mahmoud, “Integration of Municipal Infrastructure Asset Management Processes: Challenges and Solutions,” *J. Comput. Civ. Eng.*, vol. 22, no. 3, 2008, doi: 10.1061/(ASCE)0887-3801(2008)22:3(216).

[34] C. Ellul, G. Boyes, C. Thomson, and D. Backes, “Towards Integrating BIM and GIS—An End-to-End Example from Point Cloud to Analysis,” A. Abdul-Rahman, Ed. Cham: Springer International Publishing, 2017.

[35] L. Sabol, “BIM Technology for FM,” *BIM Facil. Manag.*, vol. 1, pp. 17–45, 2013, doi: 10.1002/9781119572633.ch2.

[36] L. Wastiels and R. Decuypere, “Identification and comparison of LCA-BIM integration strategies,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 323, p. 12101, 2019, doi: 10.1088/1755-1315/323/1/012101.

[37] Commission of the European Communities, “Green Paper on the Urban Environment,” 1990. Accessed: Mar. 30, 2021. [Online]. Available: http://aei.pitt.edu/1205/1/urban_environment_gp_COM_90_218.pdf.

[38] S. A. I. C. (SAIC) and M. A. Curran, “Life-cycle assessment: principles and practice.” National Risk Management Research Laboratory, Office of Research and …, 2006.

[39] M. Reiner and D. Rouse, “Dependency model: Reliable infrastructure and the resilient, sustainable, and livable city,” *Sustain. Resilient Infrastruct.*, vol. 3, no. 3, pp. 103–108, 2018.

[40] D. G. Abreu, I. Jefferson, N. Metje, and C. D. F. Rogers, “Embedding sustainability into utilities projects,” 2017, doi: 10.1061/9780784481202.012.

[41] M. Al Hattab, “The dynamic evolution of synergies between BIM and sustainability: A text mining and network theory approach,” *J. Build. Eng.*, vol. 37, p. 102159, 2021, doi: https://doi.org/10.1016/j.jobe.2021.102159.

[42] T. O. Olawumi and D. W. M. Chan, “Identifying and prioritizing the benefits of integrating BIM and sustainability practices in construction projects: A Delphi survey of international experts,” *Sustain. Cities Soc.*, vol. 40, pp. 16–27, 2018, doi: https://doi.org/10.1016/j.scs.2018.03.033.

[43] R. Charef, H. Alaka, and S. Emmitt, “Beyond the third dimension of BIM: A systematic review of literature and assessment of professional views,” *J. Build. Eng.*,

vol. 19, 2018.

[44] S. A. Jones and D. Laquidara-Carr, *The Business Value of BIM for Water Projects*. 2018.

[45] R. Ruparathna, K. Hewage, and R. Sadiq, “Improving the energy efficiency of the existing building stock: A critical review of commercial and institutional buildings,” *Renew. Sustain. Energy Rev.*, vol. 53, pp. 1032–1045, 2016, doi: 10.1016/j.rser.2015.09.084.

[46] H. Karunathilake, K. Hewage, and R. Sadiq, “Opportunities and challenges in energy demand reduction for Canadian residential sector: A review,” *Renewable and Sustainable Energy Reviews*, vol. 82, no. February 2017. Elsevier Ltd, pp. 2005–2016, 2018, doi: 10.1016/j.rser.2017.07.021.

[47] C. of Kelowna, “Open Kelowna.” https://opendata.kelowna.ca/ (accessed Apr. 01, 2021).

[48] Federation of Canadian Municipalities and N. Research Council, “Best Practices for Utility-based Data A Best Practice by the National Guide to Sustainable Municipal Infrastructure,” 2003. Accessed: Apr. 12, 2021. [Online]. Available: https://fcm.ca/sites/default/files/documents/resources/guide/infraguide-best-practices-utility-based-data-mamp.pdf.

[49] B. G. M. and C. David, “State Required Water Asset Management Plans: Lessons Learned from Hundreds of AMPs from Michigan,” *Pipelines 2019*. pp. 8–18, Oct. 05, 2020, doi: doi:10.1061/9780784482483.002.

[50] M. M. R. Halfawy, L. A. Newton, and D. J. Vanier, “Review of commercial municipal infrastructure asset management systems,” *J. Inf. Technol. Constr.*, vol. 11, no. 16, 2006.

[51] J. Nikolic, “Building ‘with the Systems’ vs. Building ‘in the System’ of IMS Open Technology of Prefabricated Construction: Challenges for New ‘Infill’ Industry for Massive Housing Retrofitting,” *Energies*, vol. 11, p. 1128, May 2018, doi: 10.3390/en11051128.

[52] S.-L. Fan, C.-H. Wu, and C.-C. Hun, “Integration of Cost and Schedule Using BIM,” *J. Appl. Sci. Eng.*, vol. 18, no. 3, pp. 223–232, 2015, doi: 10.6180/jase.2015.18.3.02.

[53] S. Althobaiti, “An Integrated Database Management System and Building

Information Modeling for Sustainable Design," 2009.

[54] M. Wyszomirski and D. Gotlib, "A Unified Database Solution to Process BIM and GIS Data," *Appl. Sci.*, vol. 10, no. 23, p. 8518, 2020.

[55] Y. Wang, V. K. Thangasamy, Z. Hou, R. L. K. Tiong, and L. Zhang, "Collaborative relationship discovery in BIM project delivery: A social network analysis approach," *Autom. Constr.*, vol. 114, p. 103147, 2020, doi: https://doi.org/10.1016/j.autcon.2020.103147.

[56] B. Rajani and Y. Kleiner, "Non-destructive inspection techniques to determine structural distress indicators in water mains," *Eval. Control Water Loss Urban Water Networks*, 2004.

[57] T. Hao *et al.*, "Condition assessment of the buried utility service infrastructure," *Tunn. Undergr. Sp. Technol.*, vol. 28, 2012, doi: https://doi.org/10.1016/j.tust.2011.10.011.

[58] K. M. Ram, M. S. Abdullahi, L. Yue, and Y. Xiong, "Performance Evaluation of Water Distribution Systems and Asset Management," *J. Infrastruct. Syst.*, vol. 24, no. 3, 2018, doi: 10.1061/(ASCE)IS.1943-555X.0000426.

[59] C. D. F. Rogers *et al.*, "Condition assessment of the surface and buried infrastructure – A proposal for integration," *Tunn. Undergr. Sp. Technol.*, vol. 28, 2012, doi: https://doi.org/10.1016/j.tust.2011.10.012.

[60] City of Toronto, "Pavement Design and Rehabilitation Guideline." 2019.

[61] V. E. Uz, M. Saltan, and İ. G. Ökalp, "Comparison of DCP , CBR , and RLT Test Results for Granular Pavement Materials and Subgrade with Structural Perspective," *Int. Symp. Non-Destructive Test. Civ. Eng.*, no. September, 2015.

[62] J. Chen, M. Hossain, and T. M. Latorella, "Use of falling weight deflectometer and dynamic cone penetrometer in pavement evaluation," *Transp. Res. Rec.*, vol. 1655, no. 1, 1999.

[63] J. Hussain, D. J. Wilson, T. F. P. Henning, and D. Alabaster, "Comparing results between the repeated load triaxial test and accelerated pavement test on unbound aggregate," *J. Mater. Civ. Eng.*, vol. 26, no. 3, 2014.

[64] Y.-C. Suh and N.-H. Cho, "Development of a rutting performance model for asphalt concrete pavement based on test road and accelerated pavement test data," *KSCE J.*

Civ. Eng., vol. 18, no. 1, 2014.

[65] J.-S. Lee, S. Y. Kim, W.-T. Hong, and Y.-H. Byun, "Assessing subgrade strength using an instrumented dynamic cone penetrometer," *Soils Found.*, vol. 59, no. 4, 2019.

[66] B. Hua, R. Sadiq, H. Najjaran, and B. Rajani, "Translation of pipe inspection results into condition rating using theory of evidence," *Proc.Water Manag. Challenges Glob. Chang. CCWI2007 SUWM2007, Leicester, Engl.*, 2007.

[67] B. Rajani, Y. Kleiner, and R. Sadiq, "Translation of pipe inspection results into condition ratings using the fuzzy synthetic evaluation technique," *J. Water Supply Res. Technol.*, vol. 55, no. 1, 2006.

[68] K. Suprabhas and H. N. Dib, "Integration of BIM and utility sensor data for facilities management," in *Computing in Civil Engineering 2017*, 2017, pp. 26–33.

[69] R. Attar, E. Hailemariam, M. Glueck, A. Tessier, J. McCrae, and A. Khan, "BIM-based Building Performance Monitor," *SimAUD 2010*, no. August, p. 2010, 2010, [Online]. Available: http://www.autodeskresearch.com/publications/bimdashboardvideo.

[70] J. H. Woo, C. Diggelman, and B. Abushakra, "BIM-based energy monitoring with XML parsing engine," *Proceeding 28th ISARC, Seoul, Korea*, pp. 544–545, 2011.

[71] B. Cahill, K. Menzel, and D. Flynn, "BIM as a centre piece for optimised building operation," 2012.

[72] L. Xuesong and A. Burcu, "Requirements and Evaluation of Standards for Integration of Sensor Data with Building Information Models," *Computing in Civil Engineering (2009)*. pp. 95–104, doi: 10.1061/41052(346)10.

[73] J. S. Miller and W. Y. Bellinger, "Distress Identification Manual for the Long-Term Pavement Performance Program (Fourth Revised Edition)." [Online]. Available: https://rosap.ntl.bts.gov/view/dot/40882.

[74] R. Sadiq, M. J. Rodríguez, and S. Tesfamariam, "Integrating indicators for performance assessment of small water utilities using ordered weighted averaging (OWA) operators," *Expert Syst. Appl.*, vol. 37, no. 7, 2010.

[75] S. Tesfamariam, G. Kabir, and R. Sadiq, "Risk and life cycle cost based asset management framework for aging water supply system," *Routledge Handb. Sustain.*

Resilient Infrastruct., 2018.

[76] S. Boudreau, "National guide to sustainable municipal infrastructure; Record identifier / Identificateur de l'enregistrement : 0fda9c0a-b047-45a1-b121-7248ea29aadb," *NO-DIG 2005 Proceedings]*. 2005.

[77] H. Haider, R. Sadiq, and S. Tesfamariam, "Multilevel performance management framework for small to medium sized water utilities in Canada," *Can. J. Civ. Eng.*, vol. 42, no. 11, 2015.

[78] G. Morcous and Z. Lounis, "Maintenance optimization of infrastructure networks using genetic algorithms," *Autom. Constr.*, vol. 14, no. 1, 2005.

[79] D. J. "Dana" Vanier, "Why Industry Needs Asset Management Tools," *J. Comput. Civ. Eng.*, vol. 15, no. 1, 2001, doi: 10.1061/(ASCE)0887-3801(2001)15:1(35).

[80] N. Gu and K. London, "Understanding and facilitating BIM adoption in the AEC industry," *Autom. Constr.*, vol. 19, no. 8, 2010, doi: https://doi.org/10.1016/j.autcon.2010.09.002.

[81] M. Venugopal, C. M. Eastman, R. Sacks, and J. Teizer, "Semantics of model views for information exchanges using the industry foundation class schema," *Adv. Eng. Informatics*, vol. 26, no. 2, 2012, doi: https://doi.org/10.1016/j.aei.2012.01.005.

[82] R. Sacks, C. Eastman, G. Lee, and P. Teicholz, *BIM handbook: a guide to building information modeling for owners, designers, engineers, contractors, and facility managers*. John Wiley & Sons, 2018.

[83] K. Barlish and K. Sullivan, "How to measure the benefits of BIM — A case study approach," *Autom. Constr.*, vol. 24, pp. 149–159, 2012, doi: https://doi.org/10.1016/j.autcon.2012.02.008.

[84] J. C. P. Cheng and Y. Deng, "An integrated BIM-GIS framework for utility information management and analyses," 2015.

[85] P.-C. Lee, Y. Wang, T.-P. Lo, and D. Long, "An integrated system framework of building information modelling and geographical information system for utility tunnel maintenance management," *Tunn. Undergr. Sp. Technol.*, vol. 79, 2018.

[86] Y. Bishr, "Overcoming the semantic and other barriers to GIS interoperability," *Int. J. Geogr. Inf. Sci.*, vol. 12, no. 4, pp. 299–314, 1998, doi: 10.1080/136588198241806.

[87] M. F. Worboys and M. Duckham, *GIS: a computing perspective*. CRC press, 2004.

[88] P. Yung and X. Wang, “A 6D CAD model for the automatic assessment of building sustainability,” *Int. J. Adv. Robot. Syst.*, vol. 11, no. 8, 2014, doi: https://doi.org/10.5772%2F58446.

[89] J. Chen, “A case study of embedding real-time infrastructure sensor data to BIM,” 2014.

[90] J. C. P. Cheng, W. Chen, Y. Tan, and M. Wang, “A BIM-based decision support system framework for predictive maintenance management of building facilities,” 2016.

[91] P. Teicholz, “Owner BIM for FM Guidelines,” in *BIM for Facility Managers*, John Wiley & Sons, Ltd, 2018, pp. 47–83.

[92] M. Al-Kasasbeh, O. Abudayyeh, and H. Liu, “An integrated decision support system for building asset management based on BIM and Work Breakdown Structure,” *J. Build. Eng.*, vol. 34, p. 101959, 2021, doi: https://doi.org/10.1016/j.jobe.2020.101959.

[93] A. Porwal and K. N. Hewage, “Building Information Modeling (BIM) partnering framework for public construction projects,” *Autom. Constr.*, vol. 31, pp. 204–214, 2013, doi: https://doi.org/10.1016/j.autcon.2012.12.004.

[94] A. Bradley, H. Li, R. Lark, and S. Dunn, “BIM for infrastructure: An overall review and constructor perspective,” *Autom. Constr.*, vol. 71, 2016, doi: https://doi.org/10.1016/j.autcon.2016.08.019.

[95] T. Catlin, J.-T. Lorenz, B. Sternfels, and P. Willmott, “A roadmap for a digital transformation The CEO cannot simply sanction a digital transformation ; communicate a vision,” *McKinsey Q.*, vol. 3, pp. 1–11, 2017, [Online]. Available: https://www.mckinsey.com/~/media/McKinsey/Industries/Financial Services/Our Insights/A roadmap for a digital transformation/A-roadmap-for-a-digital-transformation.ashx.

[96] Qiuchen Lu, X. Xie, Heaton James, J. Schooling, and A. K. Parlikad, “From BIM Towards Digital Twin: Strategy and Future Development for Smart Asset Management,” *Springer, Cham*, vol. 853, no. October 2019, pp. 392–404, 2019, doi: https://doi.org/10.1007/978-3-030-27477-1_30.

[97] Y. Song *et al.*, "Trends and Opportunities of BIM-GIS Integration in the Architecture, Engineering and Construction Industry: A Review from a Spatio-Temporal Statistical Perspective," *ISPRS International Journal of Geo-Information*, vol. 6, no. 12. 2017, doi: 10.3390/ijgi6120397.

[98] M. El-Mekawy, A. Östman, and I. Hijazi, "A Unified Building Model for 3D Urban GIS," *ISPRS Int. J. Geo-Information*, vol. 1, no. 2, pp. 120–145, 2012, doi: 10.3390/ijgi1020120.

[99] U. Isikdag and S. Zlatanova, "Towards Defining a Framework for Automatic Generation of Buildings in CityGML Using Building Information Models," J. Lee and S. Zlatanova, Eds. Berlin, Heidelberg: Springer Berlin Heidelberg, 2009, pp. 79–96.

[100] Y. Deng, J. C. P. Cheng, and C. Anumba, "Mapping between BIM and 3D GIS in different levels of detail using schema mediation and instance comparison," *Autom. Constr.*, vol. 67, 2016, doi: https://doi.org/10.1016/j.autcon.2016.03.006.

[101] K. C. CLARKE and L. J. GAYDOS, "Loose-coupling a cellular automaton model and GIS: long-term urban growth prediction for San Francisco and Washington/Baltimore," *Int. J. Geogr. Inf. Sci.*, vol. 12, no. 7, 1998, doi: 10.1080/136588198241617.

[102] A. Stadler and T. H. Kolbe, "Spatio-semantic coherence in the integration of 3D city models," 2007.

[103] X. Liu, X. Wang, G. Wright, J. C. P. Cheng, X. Li, and R. Liu, "A State-of-the-Art Review on the Integration of Building Information Modeling (BIM) and Geographic Information System (GIS)," *ISPRS Int. J. Geo-Information*, vol. 6, no. 2, 2017, doi: 10.3390/ijgi6020053.

[104] M. Marzouk and A. Othman, "Planning utility infrastructure requirements for smart cities using the integration between BIM and GIS," *Sustain. Cities Soc.*, vol. 57, p. 102120, 2020, doi: https://doi.org/10.1016/j.scs.2020.102120.

[105] Y. Deng, J. C. P. Cheng, and C. Anumba, "A framework for 3D traffic noise mapping using data from BIM and GIS integration," *Struct. Infrastruct. Eng.*, vol. 12, no. 10, 2016, doi: 10.1080/15732479.2015.1110603.

[106] L. Barazzetti, M. Previtali, and M. Scaioni, "Roads detection and parametrization in

integrated BIM-GIS using LiDAR," *Infrastructures*, vol. 5, no. 7, 2020, doi: 10.3390/infrastructures5070055.

[107] E. F. Codd, "A Relational Model of Data for Large Shared Data Banks," *Commun.ACM*, vol. 26, no. 1, Jan. 1983, doi: 10.1145/357980.358007.

[108] H. T. T. Le, V. Likhitruangsilp, and N. Yabuki, "A BIM-Integrated Relational Database Management System for Evaluating Building Life-Cycle Costs," *Eng. J.*, vol. 24, no. 2, 2020, doi: https://doi.org/10.4186/ej.2020.24.2.75.

[109] D. Kehily and J. Underwood, "Embedding life cycle costing in 5D BIM," *J. Inf. Technol. Constr.*, vol. 22, pp. 145–167, 2017.

[110] M. Finkbeiner, A. Inaba, R. Tan, K. Christiansen, and H.-J. Klüppel, "The new international standards for life cycle assessment: ISO 14040 and ISO 14044," *Int. J. life cycle Assess.*, vol. 11, no. 2, pp. 80–85, 2006.

[111] M. Goedkoop, R. Heijungs, M. Huijbregts, A. De Schryver, J. Struijs, and R. Van Zelm, "ReCiPe 2008," *A life cycle impact Assess. method which comprises Harmon. Categ. Indic. midpoint endpoint Lev.*, vol. 1, pp. 1–126, 2009.

[112] S. Rahman and D. J. Vanier, "Life cycle cost analysis as a decision support tool for managing municipal infrastructure," in *CIB 2004 triennial congress*, 2004, vol. 2.

[113] K. Shahata and T. Zayed, "Simulation as a tool for life cycle cost analysis," 2008.

[114] H. S. Matthews, C. T. Hendrickson, and D. H. Matthews, "Life cycle assessment: Quantitative approaches for decisions that matter," *Retrieved June*, vol. 1, p. 2016, 2015, [Online]. Available: https://www.lcatextbook.com/.

[115] K. P. Yoon and C.-L. Hwang, *Multiple attribute decision making: an introduction*. Sage publications, 1995.

[116] J. J. Wang, Y. Y. Jing, C. F. Zhang, and J. H. Zhao, "Review on multi-criteria decision analysis aid in sustainable energy decision-making," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 9. pp. 2263–2278, 2009, doi: 10.1016/j.rser.2009.06.021.

[117] H. P. Karunathilake, "A life cycle thinking approach for planning renewable energy systems : net-zero transformation strategies for communities," 2019.

[118] A. Petrillo, F. De Felice, E. Jannelli, C. Autorino, M. Minutillo, and A. L. Lavadera,

"Life cycle assessment (LCA) and life cycle cost (LCC) analysis model for a stand-alone hybrid renewable energy system," *Renew. Energy*, vol. 95, pp. 337–355, Sep. 2016, doi: 10.1016/j.renene.2016.04.027.

[119] J. C. Rojas-Zerpa and J. M. Yusta, "Application of multicriteria decision methods for electric supply planning in rural and remote areas," *Renew. Sustain. Energy Rev.*, vol. 52, pp. 557–571, 2015, doi: 10.1016/j.rser.2015.07.139.

[120] Y. Tang and F. You, "Life cycle environmental and economic analysis of pulverized coal oxy-fuel combustion combining with calcium looping process or chemical looping air separation," *J. Clean. Prod.*, vol. 181, pp. 271–292, 2018, doi: 10.1016/j.jclepro.2018.01.265.

[121] Z. Wang and G. P. Rangaiah, "Application and Analysis of Methods for Selecting an Optimal Solution from the Pareto-Optimal Front obtained by Multiobjective Optimization," *Ind. Eng. Chem. Res.*, vol. 56, no. 2, pp. 560–574, 2017, doi: 10.1021/acs.iecr.6b03453.

[122] J. R. San Cristóbal, "Multi-criteria decision-making in the selection of a renewable energy project in spain: The Vikor method," *Renew. Energy*, vol. 36, no. 2, pp. 498–502, Feb. 2011, doi: 10.1016/j.renene.2010.07.031.

[123] C. Davenport and I. Voiculescu, *Mastering AutoCAD Civil 3D 2016: Autodesk Official Press*. John Wiley & Sons, 2015.

[124] City of Kelowna, "SCHEDULE 4 OF BYLAW 7900 CITY OF KELOWNA DESIGN STANDARDS 0. GENERAL DESIGN CONSIDERATIONS." Accessed: Mar. 31, 2021. [Online]. Available: https://apps.kelowna.ca/CityPage/Docs/PDFs/Bylaws/Subdivision, Development and Servicing Bylaw No. 7900/Schedule 4 - Design Standards.pdf.

[125] Creative Commons Attribution-ShareAlike 3.0 licence (CC BY-SA), "Welcome to the QGIS project!" https://qgis.org/en/site/ (accessed Apr. 18, 2021).

[126] City of Kelowna, "Contour 1m 2019 | Open Kelowna." https://opendata.kelowna.ca/datasets/contour-1m-2019?geometry=-120.384%2C49.745%2C-118.531%2C50.054 (accessed Apr. 18, 2021).

[127] A. Sharafat, M. S. Khan, K. Latif, and J. Seo, "BIM-Based Tunnel Information Modeling Framework for Visualization, Management, and Simulation of Drill-and-

Blast Tunneling Projects," *J. Comput. Civ. Eng.*, vol. 35, no. 2, p. 4020068, 2021.

[128] M. Hajibabaei, S. Nazif, and F. Tavanaei Sereshgi, "Life cycle assessment of pipes and piping process in drinking water distribution networks to reduce environmental impact," *Sustain. Cities Soc.*, vol. 43, pp. 538–549, 2018, doi: https://doi.org/10.1016/j.scs.2018.09.014.

[129] G. Chhipi-Shrestha, K. Hewage, and R. Sadiq, "Water–energy–carbon nexus modeling for urban water systems: system dynamics approach," *J. Water Resour. Plan. Manag.*, vol. 143, no. 6, p. 4017016, 2017.

[130] H. Slagstad and H. Brattebø, "Life cycle assessment of the water and wastewater system in Trondheim, Norway–A case study: Case Study," *Urban water J.*, vol. 11, no. 4, pp. 323–334, 2014.

[131] M. J. Amores, M. Meneses, J. Pasqualino, A. Antón, and F. Castells, "Environmental assessment of urban water cycle on Mediterranean conditions by LCA approach," *J. Clean. Prod.*, vol. 43, pp. 84–92, 2013, doi: https://doi.org/10.1016/j.jclepro.2012.12.033.

[132] G. Barjoveanu, I. M. Comandaru, G. Rodriguez-Garcia, A. Hospido, and C. Teodosiu, "Evaluation of water services system through LCA. A case study for Iasi City, Romania," *Int. J. Life Cycle Assess.*, vol. 19, no. 2, pp. 449–462, 2014, doi: 10.1007/s11367-013-0635-8.

[133] C. Remy and M. Jekel, "Energy analysis of conventional and source-separation systems for urban wastewater management using Life Cycle Assessment," *Water Sci. Technol.*, vol. 65, no. 1, pp. 22–29, 2012.

[134] O. Jolliet *et al.*, "IMPACT 2002+: A new life cycle impact assessment methodology," *Int. J. Life Cycle Assess.*, vol. 8, no. 6, p. 324, 2003, doi: 10.1007/BF02978505.

[135] D. Sanjuan-Delmás *et al.*, "Environmental assessment of different pipelines for drinking water transport and distribution network in small to medium cities: a case from Betanzos, Spain," *J. Clean. Prod.*, vol. 66, pp. 588–598, 2014, doi: https://doi.org/10.1016/j.jclepro.2013.10.055.

[136] M. D. Ambrose, G. D. Salomonsson, and S. Burn, "Piping systems embodied energy analysis," *C. Doc*, vol. 2, p. 302, 2002.

[137] M. L. Marceau, M. A. Nisbet, and M. G. Vangeem, “Life cycle inventory of Portland cement concrete (No. SN2011),” *Portl. Cem. Assoc. Skokie, Illinois*, 2007.

[138] A. Howard, “The Five Types of Pipeline Trenches,” in *ICPTT 2011: Sustainable Solutions For Water, Sewer, Gas, And Oil Pipelines*, 2011, pp. 1104–1114.

[139] IUOE, “Slope Calculator Tool | Excavations 101.” http://excavations101.iuoe-hazmat.com/slope-calculator.html (accessed Apr. 02, 2021).

[140] R. Morrison and L. Wang, “State of technology report for force main rehabilitation,” 2010.

[141] A. B. Paradkar, “An Evaluation of Failure Modes for Cast Iron and Ductile Iron Water Pipes,” 2013.

[142] M. Najafi, *Trenchless technology: Pipeline and utility design, construction, and renewal*. McGraw-Hill Education, 2005.

[143] V. Kaushal, M. Najafi, R. Serajiantehrani, and M. Malek Mohammadi, “Social Cost Comparison of CIPP with Open-cut,” *Proc. ASCE Pipelines*, 2020.

[144] R. Mundy, “Why Should I Use Ductile Iron Pipe? Four Key Considerations | McWane Ductile,” 2019. https://www.mcwaneductile.com/blog/why-should-i-use-ductile-iron-pipe-four-key-considerations/ (accessed Jun. 10, 2021).

[145] H. Ahmed, M. Tiznobaik, S. B. Huda, M. S. Islam, and M. S. Alam, “Recycled aggregate concrete from large-scale production to sustainable field application,” *Constr. Build. Mater.*, vol. 262, p. 119979, 2020, doi: https://doi.org/10.1016/j.conbuildmat.2020.119979.

[146] R. Geyer, J. R. Jambeck, and K. L. Law, “Production, use, and fate of all plastics ever made,” *Sci. Adv.*, vol. 3, no. 7, p. e1700782, 2017.

[147] H. H. Khoo, “LCA of plastic waste recovery into recycled materials, energy and fuels in Singapore,” *Resour. Conserv. Recycl.*, vol. 145, pp. 67–77, 2019.

[148] Government of Canada, “Canada one-step closer to zero plastic waste by 2030 - Canada.ca,” 2020. https://www.canada.ca/en/environment-climate-change/news/2020/10/canada-one-step-closer-to-zero-plastic-waste-by-2030.html (accessed Feb. 22, 2021).

[149] E. Vahidi, E. Jin, M. Das, M. Singh, and F. Zhao, “Environmental life cycle analysis

of pipe materials for sewer systems," *Sustain. cities Soc.*, vol. 27, pp. 167–174, 2016.

[150] G. E. Williams and K. Von Aspern, "Asbestos cement pipe: what if it needs to be replaced," 2008.

[151] D. Berglund, "Life cycle assessment comparison of CIPP lining and traditional pipe replacement." 2015.

[152] S. S. Corporation, "Life Cycle Assessment of PVC Water and Sewer Pipe and Comparative Sustainability Analysis of Pipe Materials," 2017.

[153] "Canada Pipe | Manufacturers of Quality Waterworks Products." https://www.canadapipe.com/ (accessed Apr. 29, 2021).

[154] "Home | IPEX." https://www.ipexna.com/ (accessed Apr. 29, 2021).

[155] "Vitrified Clay Pipe Products | Logan Clay Products LLC." https://www.loganclaypipe.com/index.html (accessed Apr. 29, 2021).

[156] "Lafarge Canada - Cement, concrete, aggregates and construction." https://www.lafarge.ca/en (accessed Apr. 29, 2021).

[157] A. Choate and H. Ferland, "Waste Management and Energy Savings: Benefits by the Numbers. US EPA." 2004.

[158] M. Goedkoop, M. Oele, J. Leijting, T. Ponsioen, and E. Meijer, "Introduction to LCA with SimaPro," San Francisco, 2016.

[159] Treasury Board of Canada Secretariat, *Canadian Cost-Benefit Analysis Guide Regulatory Proposals Interim*. 2007.

[160] H. Karunathilake *et al.*, "Renewable energy selection for net-zero energy communities : Life cycle based decision making under uncertainty," *Renew. Energy*, vol. 130, pp. 558–573, 2019, doi: 10.1016/j.renene.2018.06.086.

[161] F. R. Cecconi, N. Moretti, S. Maltese, and L. C. Tagliabue, "A BIM-Based Decision Support System for Building Maintenance," in *Advances in Informatics and Computing in Civil and Construction*, 2019.

[162] G. Kabir, R. Sadiq, and S. Tesfamariam, "A review of multi-criteria decision-making methods for infrastructure management," *Struct. Infrastruct. Eng.*, vol. 10, no. 9, 2014, doi: 10.1080/15732479.2013.795978.

[163] V. Sharma, M. Al-Hussein, H. Safouhi, and A. Bouferguène, "Municipal

infrastructure asset levels of service assessment for investment decisions using analytic hierarchy process," *J. Infrastruct. Syst.*, vol. 14, no. 3, pp. 193–200, 2008.

[164] M. T. M. Lakshmi, A. J. Anand, K. Vetriselvi, and V. P. Venkatesan, "A Study on Different Types of Normalization Methods in Adaptive Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)."

[165] P. P. Kalbar, M. Birkved, S. E. Nygaard, and M. Hauschild, "Weighting and aggregation in life cycle assessment: do present aggregated single scores provide correct decision support?," *J. Ind. Ecol.*, vol. 21, no. 6, pp. 1591–1600, 2017.

[166] E. Meijer, "Weighting: applying a value judgment to LCA results - PRé Sustainability," 2014. https://pre-sustainability.com/articles/weighting-applying-a-value-judgement-to-lca-results/ (accessed May 19, 2021).

[167] M. Pizzol, B. Weidema, M. Brandão, and P. Osset, "Monetary valuation in Life Cycle Assessment: a review," *J. Clean. Prod.*, vol. 86, pp. 170–179, 2015, doi: https://doi.org/10.1016/j.jclepro.2014.08.007.

[168] S. Sala, A. K. Cerutti, and R. Pant, "Development of a weighting approach for the Environmental Footprint," *Publ. Off. Eur. Union Luxemb.*, 2018.

[169] H. Karunathilake, P. Perera, R. Ruparathna, K. Hewage, and R. Sadiq, "Renewable energy integration into community energy systems: A case study of new urban residential development," *J. Clean. Prod.*, vol. 173, pp. 292–307, 2018, doi: 10.1016/j.jclepro.2016.10.067.

[170] J. Terrados, G. Almonacid, and P. Pérez-Higueras, "Proposal for a combined methodology for renewable energy planning. Application to a Spanish region," *Renew. Sustain. Energy Rev.*, vol. 13, no. 8, pp. 2022–2030, 2009, doi: https://doi.org/10.1016/j.rser.2009.01.025.

[171] S. Khan, "Design improvement in water distribution systems: a life cycle thinking approach." University of British Columbia, 2019.

[172] Xirtec PVC, "PVC Schedule 80 Grey Plain End Pressure Pipe," *IPEX*, 2020. https://www.ipexna.com/media/12218/cdn-xirtec-pvc-sch-80-pipe-eastern-pdf-march-1-2021.pdf (accessed Mar. 21, 2021).

[173] US Pipe Fabrication, "US Pipe Frabrication Protecto 401 Price List," 2020. https://www.uspipe.com/wp-content/uploads/2020/12/USPF-FAB-401-2020-01-

120120-For-Website.pdf (accessed Mar. 21, 2021).

[174] Wavin, “Hepworth Clay Price List 1st March 2021.” https://www.wavin.com/en-gb/searchresult#e=0&q=price clay (accessed Mar. 21, 2021).

[175] “Mississauga Scrap Metal Pricing - Premier Recycling Mississauga Ltd.” http://www.premierrecycling.ca/contact/premier-recycling-mississauga-ltd/pricing/ (accessed Feb. 23, 2021).

[176] Y. Kleiner and B. Rajani, “Comprehensive review of structural deterioration of water mains: statistical models,” *Urban Water*, vol. 3, no. 3, 2001, doi: https://doi.org/10.1016/S1462-0758(01)00033-4.

[177] Canadian Network of Asset Managers, “Canadian Infrastructure Report Card - Asset Management Primer,” 2014. [Online]. Available: https://www.cnam.ca/wp-content/uploads/2015/05/CIRC-Asset-Management_EN_LR.pdf.

[178] D. Veshosky, C. R. Beidleman, G. W. Buetow, and M. Demir, “Comparative analysis of bridge superstructure deterioration,” *J. Struct. Eng.*, vol. 120, no. 7, 1994.

[179] D. Mizutani, N. Lethanh, B. T. Adey, and K. Kaito, “Improving the estimation of Markov transition probabilities using mechanistic-empirical models,” *Front. Built Environ.*, vol. 3, p. 58, 2017.

[180] R. B. Kulkarni, “Dynamic decision model for a pavement management system,” *Transp. Res. Rec.*, vol. 997, pp. 11–18, 1984.

[181] A. A. Butt, M. Y. Shahin, K. J. Feighan, and S. H. Carpenter, *Pavement performance prediction model using the Markov process*, no. 1123. 1987.

[182] Y. Jiang, M. Saito, and K. C. Sinha, *Bridge performance prediction model using the Markov chain*, no. 1180. 1988.

[183] Y. Kleiner, R. Sadiq, and B. Rajani, “Modelling the deterioration of buried infrastructure as a fuzzy Markov process,” *J. Water Supply Res. Technol.*, vol. 55, no. 2, 2006.

[184] S. Madanat, R. Mishalani, and W. H. W. Ibrahim, “Estimation of infrastructure transition probabilities from condition rating data,” *J. Infrastruct. Syst.*, vol. 1, no. 2, pp. 120–125, 1995.

[185] S. Madanat and W. H. W. Ibrahim, “Poisson regression models of infrastructure

transition probabilities," *J. Transp. Eng.*, vol. 121, no. 3, pp. 267–272, 1995.

[186] S. Bulusu and K. C. Sinha, "Comparison of methodologies to predict bridge deterioration," *Transp. Res. Rec.*, vol. 1597, no. 1, pp. 34–42, 1997.

[187] E. Parzen, *Stochastic processes*. SIAM, 1999.

[188] G. Morcous, Z. Lounis, and M. S. Mirza, "Identification of environmental categories for Markovian deterioration models of bridge decks," *J. Bridg. Eng.*, vol. 8, no. 6, pp. 353–361, 2003.

[189] Z. Lounis and M. S. Mirza, "Reliability-based service life prediction of deteriorating concrete structures," in *Proc. 3rd Int. Conf. on Concrete under Severe Conditions*, 2001, vol. 1, pp. 965–972.

[190] "MMULT function - Office Support." https://support.microsoft.com/en-us/office/mmult-function-40593ed7-a3cd-4b6b-b9a3-e4ad3c7245eb (accessed May 10, 2021).

[191] WSSC, "SECTION II-MISCELLANEOUS DETAILS," 2005. Accessed: Mar. 31, 2021. [Online]. Available: https://www.wsscwater.com/sites/default/files/sites/wssc/files/Engg_and_Cons/specs/details_2005/m_view_all_2005.pdf.

[192] Federation of Canadian Municipalities and National Research Council, "DETERIORATION AND INSPECTION OF WATER DISTRIBUTION SYSTEMS A BEST PRACTICE BY THE NATIONAL GUIDE TO SUSTAINABLE MUNICIPAL INFRASTRUCTURE," 2003. Accessed: May 31, 2021. [Online]. Available: https://fcm.ca/sites/default/files/documents/resources/guide/infraguide-deterioration-inspection-water-distribution-systems-mamp.pdf.

[193] D. V. Renwick, A. Heinrich, R. Weisman, H. Arvanaghi, and K. Rotert, "Potential Public Health Impacts of Deteriorating Distribution System Infrastructure," *J. Am. Water Works Assoc.*, vol. 111, no. 2, pp. 42–53, Feb. 2019, doi: 10.1002/awwa.1235.

[194] I. American Water Works Service Co., "Deteriorating Buried Infrastructure Management Challenges and Strategies," 2002. Accessed: May 31, 2021. [Online]. Available: https://www.epa.gov/sites/production/files/2015-09/documents/2007_09_04_disinfection_tcr_whitepaper_tcr_infrastructure.pdf.

Appendices

Appendix A Condition rating

A.1 Condition vectors for water system in severe environment

Scale / Year	6	5	4	3	2	1	Condition Rating: Rehabilitate	Condition Rating: Do Nothing
0	1.00	0.00	0.00	0.00	0.00	0.00	6.00	6.00
1	0.77	0.23	0.00	0.00	0.00	0.00	5.77	6.00
2	0.59	0.36	0.04	0.00	0.00	0.00	5.55	6.00
3	0.46	0.43	0.11	0.01	0.00	0.00	5.34	5.99
4	0.35	0.45	0.17	0.02	0.00	0.00	5.14	5.99
5	0.27	0.45	0.24	0.04	0.00	0.00	4.95	5.99
6	0.21	0.43	0.29	0.07	0.00	0.00	4.76	5.98
7	0.16	0.39	0.34	0.10	0.01	0.00	4.59	5.97
8	0.12	0.35	0.37	0.14	0.01	0.00	4.43	5.96
9	0.10	0.32	0.39	0.18	0.02	0.00	4.27	5.95
10	0.07	0.28	0.40	0.21	0.03	0.01	4.13	5.94
11	0.06	0.24	0.40	0.25	0.04	0.01	3.99	5.93
12	0.04	0.21	0.39	0.28	0.06	0.02	3.85	5.91
13	0.03	0.18	0.38	0.32	0.07	0.02	3.73	5.90
14	0.03	0.15	0.37	0.34	0.08	0.03	3.60	5.88
15	0.02	0.13	0.35	0.37	0.10	0.04	3.49	5.87
16	0.15	0.71	0.14	0.00	0.00	0.00	5.01	5.85
..	..	..	..	..	..	..	..	..
100	1.00	0.00	0.00	0.00	0.00	0.00	6.00	0.00

A.2 Condition vectors for sanitary sewer in moderate environment

Scale	**6**	**5**	**4**	**3**	**2**	**1**	**Condition Rating**	
Year							**Rehabilitate**	**Do Nothing**
0	1.00	0.00	0.00	0.00	0.00	0.00	6.00	6.00
1	0.83	0.17	0.00	0.00	0.00	0.00	5.83	6.00
2	0.69	0.29	0.02	0.00	0.00	0.00	5.67	6.00
3	0.57	0.36	0.06	0.00	0.00	0.00	5.51	5.99
4	0.47	0.41	0.11	0.00	0.00	0.00	5.36	5.99
5	0.39	0.43	0.16	0.01	0.00	0.00	5.21	5.99
6	0.33	0.44	0.22	0.02	0.00	0.00	5.07	5.98
7	0.27	0.43	0.27	0.03	0.00	0.00	4.94	5.97
8	0.23	0.42	0.31	0.04	0.00	0.00	4.82	5.96
9	0.19	0.40	0.36	0.05	0.01	0.00	4.71	5.95
10	0.16	0.37	0.39	0.06	0.01	0.00	4.59	5.94
11	0.13	0.35	0.43	0.08	0.01	0.00	4.49	5.93
12	0.11	0.32	0.45	0.09	0.02	0.01	4.39	5.91
13	0.09	0.29	0.48	0.11	0.02	0.01	4.29	5.90
14	0.07	0.27	0.49	0.12	0.03	0.01	4.20	5.88
15	0.06	0.24	0.51	0.13	0.04	0.02	4.11	5.87
16	0.05	0.22	0.52	0.15	0.04	0.02	4.02	5.85
17	0.04	0.20	0.52	0.16	0.05	0.03	3.93	5.83
18	0.03	0.18	0.52	0.17	0.06	0.04	3.85	5.81
19	0.03	0.16	0.52	0.18	0.06	0.05	3.77	5.78
20	0.02	0.14	0.52	0.19	0.07	0.06	3.69	5.76
21	0.02	0.13	0.51	0.20	0.07	0.07	3.61	5.74
22	0.02	0.11	0.50	0.21	0.08	0.08	3.53	5.71
23	0.01	0.10	0.49	0.21	0.09	0.09	3.46	5.68
..	..	..	..	..	..	..	..	..
100	1.00	0.00	0.00	0.00	0.00	0.00	6.00	0.00

A.3 Condition vectors for storm sewer system in low environment

Scale	6	5	4	3	2	1	Condition Rating	
Year							Rehabilitate	Do Nothing
0	1.00	0.00	0.00	0.00	0.00	0.00	6.00	6.00
1	0.93	0.07	0.00	0.00	0.00	0.00	5.93	6.00
2	0.86	0.13	0.00	0.00	0.00	0.00	5.86	6.00
3	0.80	0.18	0.01	0.00	0.00	0.00	5.79	5.99
4	0.75	0.23	0.03	0.00	0.00	0.00	5.72	5.99
5	0.70	0.26	0.04	0.00	0.00	0.00	5.65	5.99
6	0.65	0.29	0.06	0.00	0.00	0.00	5.58	5.98
7	0.60	0.32	0.07	0.01	0.00	0.00	5.51	5.97
8	0.56	0.34	0.09	0.01	0.00	0.00	5.44	5.96
9	0.52	0.35	0.11	0.02	0.00	0.00	5.37	5.95
10	0.48	0.36	0.13	0.02	0.00	0.00	5.30	5.94
11	0.45	0.37	0.14	0.03	0.00	0.00	5.24	5.93
12	0.42	0.38	0.16	0.04	0.00	0.00	5.17	5.91
13	0.39	0.38	0.18	0.04	0.01	0.00	5.10	5.90
14	0.36	0.38	0.19	0.05	0.01	0.00	5.03	5.88
15	0.34	0.38	0.21	0.06	0.01	0.00	4.96	5.87
16	0.31	0.38	0.22	0.07	0.01	0.00	4.90	5.85
17	0.29	0.37	0.24	0.08	0.02	0.01	4.83	5.83
18	0.27	0.37	0.25	0.09	0.02	0.01	4.76	5.81
19	0.25	0.36	0.26	0.10	0.02	0.01	4.70	5.78

Scale	6	5	4	3	2	1	Condition Rating	
Year							**Rehabilitate**	**Do Nothing**
20	0.23	0.35	0.27	0.11	0.03	0.01	4.63	5.76
21	0.22	0.34	0.28	0.12	0.03	0.01	4.56	5.74
22	0.20	0.34	0.29	0.13	0.03	0.02	4.50	5.71
23	0.19	0.33	0.29	0.14	0.04	0.02	4.43	5.68
24	0.18	0.32	0.30	0.15	0.04	0.02	4.37	5.65
25	0.16	0.31	0.30	0.15	0.05	0.03	4.30	5.63
26	0.15	0.30	0.30	0.16	0.05	0.03	4.24	5.59
27	0.14	0.29	0.31	0.17	0.06	0.04	4.17	5.56
28	0.13	0.28	0.31	0.18	0.06	0.04	4.11	5.53
29	0.12	0.27	0.31	0.19	0.07	0.05	4.04	5.50
30	0.11	0.26	0.31	0.19	0.07	0.06	3.98	5.46
31	0.11	0.25	0.31	0.20	0.07	0.06	3.92	5.42
32	0.10	0.24	0.31	0.21	0.08	0.07	3.85	5.39
33	0.09	0.23	0.31	0.21	0.08	0.08	3.79	5.35
34	0.08	0.22	0.30	0.22	0.09	0.09	3.73	5.31
35	0.08	0.21	0.30	0.22	0.09	0.10	3.67	5.27
36	0.07	0.20	0.30	0.23	0.10	0.11	3.61	5.22
37	0.07	0.19	0.29	0.23	0.10	0.11	3.55	5.18
38	0.06	0.18	0.29	0.24	0.10	0.12	3.49	5.13
..	..	..	..	..	..	..	..	..
100	1.00	0.00	0.00	0.00	0.00	0.00	6.00	0.00

Appendix B : Life Cycle Inventory

B.1 LCI of AC pipe, 200 mm dia, 43.5 mm thick, 1-meter length

Input (Process/Materials)	**Ecoinvent (Process/Materials)**	**Unit**	**Qty.**
Asbestos	Asbestos, crysotile type {GLO}| market for | Alloc Def, U	kg	3.55
Portland Cement	Cement, Portland {US}| market for | Alloc Def, U	kg	22.50
Sand	Sand {GLO}| market for | Alloc Def, U	kg	3.55
Cement mortar (interior coating)	Cement mortar {RoW}| market for cement mortar | Alloc Def, U	kg	3.00
Embodied Energy	Electricity, high voltage {CA-BC}| electricity production, hydro, run-of-river | Alloc Def, U	MJ	39.57
Crushed gravel for Bedding	Gravel, crushed {CA-QC}| production | Alloc Def, U	kg	97.58
Flowable Fill for Haunch	Concrete, normal {RoW}| market for | Alloc Def, U	m^3	0.0343
Imported Sand for Backfill	Sand {GLO}| market for | Alloc Def, U	kg	478.56
Transportation of pipes from Manufacturing Plant to Construction Site	Transport, freight, lorry >32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	tkm	134.68
Transportation of Crushed gravel for Bedding	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	tkm	2.44

Input (Process/Materials)	**Ecoinvent (Process/Materials)**	**Unit**	**Qty.**
Transportation of Imported Sand for Backfill	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	tkm	11.96
Transportation of Flowable Fill for Haunch	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	tkm	2.06
Excavator	Excavation, hydraulic digger {GLO}| market for | Alloc Def, U	m^3	4.39
Vibrating compactor	Machine operation, diesel, < 18.64 kW, steady-state {GLO}| market for | Alloc Def, U	hr	1.00
Air compressor	Air compressor, screw-type compressor, 300kW {RER}| production | Alloc Def, U	p	0.0001
Loader	Excavation, skid-steer loader {GLO}| market for | Alloc Def, U	m^3	4.39
Transport of Waste	Electricity, high voltage {CA-BC}| electricity production, hydro, run-of-river | Alloc Def, U	MJ	1.98

B.2 LCI of CONC pipe, 200 mm dia, 43.5 mm thick, 1-meter length

Input (Process/Materials)	**Ecoinvent (Process/Materials)**	**Unit**	**Qty.**
Portland Cement	Cement, Portland {US}| market for | Alloc Def, U	kg	22.50
Sand	Sand {GLO}| market for | Alloc Def, U	kg	3.55
Aggregate	Natural stone plate, cut {RoW}| production | Alloc Def, U	kg	3.55
Cement mortar (interior coating)	Cement mortar {RoW}| market for cement mortar | Alloc Def, U	kg	3.28
Embodied Energy	Electricity, high voltage {CA-BC}| electricity production, hydro, run-of-river | Alloc Def, U	MJ	189.36
Crushed gravel for Bedding	Gravel, crushed {CA-QC}| production | Alloc Def, U	kg	97.58
Flowable Fill for Haunch	Concrete, normal {RoW}| market for | Alloc Def, U	m^3	0.0343
Imported Sand for Backfill	Sand {GLO}| market for | Alloc Def, U	kg	478.56
Transportation of pipes from Manufacturing Plant to Construction Site	Transport, freight, lorry >32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	tkm	134.68
Transportation of Crushed gravel for Bedding	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	tkm	2.44

Input (Process/Materials)	Ecoinvent (Process/Materials)	Unit	Qty.
Transportation of Imported Sand for Backfill	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	tkm	11.96
Transportation of Flowable Fill for Haunch	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	tkm	2.06
Excavator	Excavation, hydraulic digger {GLO}| market for | Alloc Def, U	m^3	4.39
Vibrating compactor	Machine operation, diesel, < 18.64 kW, steady-state {GLO}| market for | Alloc Def, U	hr	1.00
Air compressor	Air compressor, screw-type compressor, 300kW {RER}| production | Alloc Def, U	p	0.0001
Loader	Excavation, skid-steer loader {GLO}| market for | Alloc Def, U	m^3	4.39
Transport of Waste	Electricity, high voltage {CA-BC}| electricity production, hydro, run-of-river | Alloc Def, U	MJ	16.52

B.3 LCI of DI pipe, 200 mm dia, 6.4 mm thick, 1-meter length

Input (Process/Materials)	**Ecoinvent (Process/Materials)**	**Unit**	**Qty.**
Cast iron	Cast iron {GLO}| market for | Alloc Def, U	kg	32.30
Cast iron Production	Cast iron {RoW}| production | Alloc Def, U	kg	32.30
Cement mortar (interior coating)	Cement mortar {RoW}| market for cement mortar | Alloc Def, U	kg	3.53
Bitumen (external coating)	Bitumen adhesive compound, hot {GLO}| market for | Alloc Def, U	kg	0.19
Zinc oxide (external coating)	Zinc {GLO}| market for | Alloc Def, U	kg	0.08
Magnesium	Magnesium {GLO}| market for | Alloc Def, U	kg	1.62
FerroSilicon	Ferrosilicon {GLO}| market for | Alloc Def, U	kg	14.86
Embodied Energy	Electricity, high voltage {CA-BC}| electricity production, hydro, run-of-river | Alloc Def, U	MJ	1,199.48
Crushed gravel for Bedding	Gravel, crushed {CA-QC}| production | Alloc Def, U	kg	97.58
Flowable Fill for Haunch	Concrete, normal {RoW}| market for | Alloc Def, U	m^3	0.03
Imported Sand for Backfill	Sand {GLO}| market for | Alloc Def, U	kg	478.56
Transportation of pipes from Manufacturing Plant to Construction Site	Transport, freight, lorry >32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	tkm	141.30

Input (Process/Materials)	**Ecoinvent (Process/Materials)**	**Unit**	**Qty.**
Transportation of Crushed gravel for Bedding	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	tkm	2.44
Transportation of Imported Sand for Backfill	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	tkm	11.96
Transportation of Flowable Fill for Haunch	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	tkm	2.06
Excavator	Excavation, hydraulic digger {GLO}| market for | Alloc Def, U	m^3	4.39
Vibrating compactor	Machine operation, diesel, < 18.64 kW, steady-state {GLO}| market for | Alloc Def, U	hr	1.00
Air compressor	Air compressor, screw-type compressor, 300kW {RER}| production | Alloc Def, U	p	0.0001
Loader	Excavation, skid-steer loader {GLO}| market for | Alloc Def, U	m^3	4.39
Transport of Waste	Electricity, high voltage {CA-BC}| electricity production, hydro, run-of-river | Alloc Def, U	MJ	18.02

B.4 LCI of PVC pipe, 200 mm dia, 13 mm thick, 1-meter length

Input (Process/Materials)	**Ecoinvent (Process/Materials)**	**Unit**	**Qty.**
Polyvinylchloride	Polyvinylchloride, bulk polymerised {GLO}| market for | Alloc Rec, U	kg	8.08
Limestone	Limestone, crushed, washed {CA-QC}| production | Alloc Def, U	kg	0.43
Production Process	Extrusion, plastic pipes {CA-QC}| production | Alloc Def, U	kg	8.51
Bitumen (external coating)	Bitumen adhesive compound, hot {GLO}| market for | Alloc Def, U	kg	0.02
Embodied Energy	Electricity, high voltage {CA-BC}| electricity production, hydro, run-of-river | Alloc Def, U	MJ	1,292.77
Crushed gravel for Bedding	Gravel, crushed {CA-QC}| production | Alloc Def, U	kg	84.00
Flowable Fill for Haunch	Concrete, normal {RoW}| market for | Alloc Def, U	m^3	0.09
Imported Sand for Backfill	Sand {GLO}| market for | Alloc Def, U	kg	339.84
Transportation of pipes from Manufacturing Plant to Construction Site	Transport, freight, lorry >32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	tkm	18.58
Transportation of Crushed gravel for Bedding	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	tkm	2.10

Input (Process/Materials)	Ecoinvent (Process/Materials)	Unit	Qty.
Transportation of Imported Sand for Backfill	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	tkm	8.50
Transportation of Flowable Fill for Haunch	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	tkm	5.16
Excavator	Excavation, hydraulic digger {GLO}| market for | Alloc Def, U	m^3	4.16
Vibrating compactor	Machine operation, diesel, < 18.64 kW, steady-state {GLO}| market for | Alloc Def, U	hr	1.00
Air compressor	Air compressor, screw-type compressor, 300kW {RER}| production | Alloc Def, U	p	0.0001
Loader	Excavation, skid-steer loader {GLO}| market for | Alloc Def, U	m^3	4.16
Transport of Waste	Electricity, high voltage {CA-BC}| electricity production, hydro, run-of-river | Alloc Def, U	MJ	4.75

B.5 LCI of VIT pipe, 200 mm dia, 27 mm thick, 1-meter length

Input (Process/Materials)	**Ecoinvent (Process/Materials)**	**Unit**	**Qty.**
Clay	Clay plaster {GLO}| market for | Alloc Def, U	kg	94.49
Synthetic Rubber	Synthetic rubber {GLO}| market for | Alloc Def, U	kg	0.08
Embodied Energy	Electricity, high voltage {CA-BC}| electricity production, hydro, run-of-river | Alloc Def, U	MJ	114.55
Crushed gravel for Bedding	Gravel, crushed {CA-QC}| production | Alloc Def, U	kg	97.58
Flowable Fill for Haunch	Concrete, normal {RoW}| market for | Alloc Def, U	m^3	0.03
Imported Sand for Backfill	Sand {GLO}| market for | Alloc Def, U	kg	478.56
Transportation of pipes from Manufacturing Plant to Construction Site	Transport, freight, lorry >32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	tkm	178.80
Transportation of Crushed gravel for Bedding	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	tkm	2.44
Transportation of Imported Sand for Backfill	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	tkm	11.96
Transportation of Flowable Fill for Haunch	Transport, freight, lorry 16-32 metric ton, EURO3 {GLO}| market for | Alloc Def, U	tkm	2.06

Input (Process/Materials)	**Ecoinvent (Process/Materials)**	**Unit**	**Qty.**
Excavator	Excavation, hydraulic digger {GLO}| market for | Alloc Def, U	m^3	4.39
Vibrating compactor	Machine operation, diesel, < 18.64 kW, steady-state {GLO}| market for | Alloc Def, U	hr	1.00
Air compressor	Air compressor, screw-type compressor, 300kW {RER}| production | Alloc Def, U	p	0.0001
Loader	Excavation, skid-steer loader {GLO}| market for | Alloc Def, U	m^3	4.39
Transport of Waste	Electricity, high voltage {CA-BC}| electricity production, hydro, run-of-river | Alloc Def, U	MJ	52.72

B.6 LCI of CIPP, 200 mm dia, 1-meter length

Input (Process/Materials)	**Ecoinvent (Process/Materials)**	**Unit**	**Qty**
Epoxy-Resin	Epoxy resin, liquid {GLO}| market for | Alloc Def, U	kg	2.69
Felt Liner	Polyester resin, unsaturated {GLO}| market for | Alloc Def, U	kg	0.78
Felt Liner - Fibreglass reinforced	Polyurethane, rigid foam {GLO}| market for | Alloc Def, U	kg	0.80
Cure-Polyaminimidazolin	Imidazole {RoW}| production | Alloc Def, U	kg	0.03
Cure-Isoforondiamin	Methylcyclohexane {GLO}| market for | Alloc Def, U	kg	0.01
Cure-Fenalkamin	Formaldehyde {GLO}| market for | Alloc Def, U	kg	0.01
Cure-Benzendimetanamin	Xylene {GLO}| market for | Alloc Def, U	kg	0.01
Cure-4-tert-Butylfenol	Phenol {GLO}| market for | Alloc Def, U	kg	0.01
Cure-2-piperazin-1-yletylamin	Ethylenediamine {GLO}| market for | Alloc Def, U	kg	0.001
Cure-Trietanolamin	Triethanolamine {GLO}| market for | Alloc Def, U	kg	0.002
Embodied Energy	Electricity, high voltage {CA-BC}| electricity production, hydro, run-of-river | Alloc Def, U	MJ	2,171
Embodied Energy	Electricity, high voltage {CA-BC}| electricity production, hydro, run-of-river | Alloc Def, U	MJ	152

Input (Process/Materials)	**Ecoinvent (Process/Materials)**	**Unit**	**Qty**
Jetter Truck	Transport, freight, lorry 3.5-7.5 metric ton, EURO6 {GLO}| market for | Alloc Def, U	tkm	0.11
Air compressor	Air compressor, screw-type compressor, 300kW {RER}| production | Alloc Def, U	p	0.0001
Refrigerated truck	Transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, freezing {GLO}| transport, freight, lorry with refrigeration machine, 7.5-16 ton, EURO6, R134a refrigerant, freezing | Alloc Def, U	tkm	0.11
Utility truck	Transport, freight, lorry 3.5-7.5 metric ton, EURO6 {GLO}| market for | Alloc Def, U	tkm	0.11
Generator set	Machine operation, diesel, < 18.64 kW, generators {GLO}| market for | Alloc Def, U	Hr	3.00
TV Truck	Transport, freight, lorry 3.5-7.5 metric ton, EURO6 {GLO}| market for | Alloc Def, U	tkm	0.11