ENVIRONMENTAL AND ECONOMIC OUTLOOK OF CONSTRUCTION AND DEMOLITION WASTE MANAGEMENT PRACTICES IN A MID-SIZED CITY

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Environmental and economic outlook of construction and demolition waste management practices in a mid-sized city

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ABSTRACT

Construction and demolition waste (CDW) left at landfill sites increases the burden on landfills, which are increasingly becoming scarce and costly to operate. In North Dakota, CDW generated is disposed of at the Fargo landfill. This practice may hamper the realization of value from construction and demolition waste.

Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) was used to evaluate the benefits of two CDW management scenarios.

The study found that 75% reduction in CDW sent to the landfill can reduce environmental burden by 35%. Furthermore, replacing raw materials with recycled materials creates net environmental savings. This practice can reduce the environmental burden by 25% while generating an income of $61/ton for the city.

The results of this study provide information on the value of recycling CDW and serve as a basis for decision-makers to rethink CDW waste management practices in North Dakota.

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DEDICATION

To God and my Family.

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LIST OF ABBREVIATIONS

CDW	Construction and Demolition Waste
EPA	Environmental Protection Agency
EU	European Union
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
US	United States
RoI	Return on Investment
MSW	Municipal Solid Waste
CE	Circular Economy
USGBC	United States Green Building Council
3Rs	Recover Reuse Recycle
ND	North Dakota
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
ISO	International Organization for Standardization
FU	Functional Unit
TRACI	Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts
LCCA	Life Cycle Cost Analysis
SA	Sensitivity Analysis
SR	Sensitivity Ratio

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CHAPTER 1. INTRODUCTION

1.1. Background

The construction industry is instrumental in the economic and societal progress of countries (Fernando et al. 2022) including the USA. This industry develops products like buildings, roads, bridges, railways, dams, airports, tunnels, and others, which greatly contribute to economic growth and improve the living conditions of humanity. The process of construction involves activities such as clearing of the site, demolition of existing obstacles, excavation, and earthworks, and others. These activities often generate different types of waste which is collectively called construction and demolition waste (CDW). CDW negatively affects the environment and leads to economic losses (Menegaki and Damigos 2018).

Waste are unwanted or unusable materials (Jaseem et al. 2017). These could be solid, liquid and gaseous substances. CDW comprise of undesirable material generated directly or accidentally by construction activities (Huang et al. 2018). Most CDW occur as a result of demolition projects, which is a part of a construction process. On the report of the Environmental Protection Agency (EPA), more than 90% of CDW comes from demolition projects (US EPA 2018). Materials such as bricks, concrete, steel, wood, cardboard, plastic and others are components of construction and demolition waste (Kumbhar et al. 2013). This unutilized waste materials are deleterious to the ecological community and requires substantial financial capital for recycling, reusing and disposal of the waste (Akhund et al. 2019).

CDW is a major challenge for construction stakeholders due to the increasing volumes of its production as the years go by. Furthermore, there may be associated environmental impacts and potential economic losses through the missed opportunities to replace raw materials with recycled materials. The continuous development in the built environment over the world results in the continuous increase in production of CDW. For example, CDW production rate is close to 40% in the European Union (EU) and over 60% in the United States (Ruiz et al. 2020)

There have been studies conducted on the types of construction waste (Akhund et al. 2019), the impact of construction waste (Simion et al. 2013 and Liu, 2018), and the treatment of these waste (Yang 2014). These studies provided considerable knowledge on construction waste types, impact and treatment. However, the authors of this paper could not identify a study that established a linkage between the types, impact and treatment of construction waste in a single study. Hence, there is the need to analyze the interdependence of the types, impact and treatment of construction waste.

Modernization has increased construction activities (Han et al. 2013). Since it has been established that construction waste produces waste, an increase in these activities could increase the waste generated. Over the years, using publications available as evidence, it is obvious that the subject of construction waste has attracted the attention of academia and the industry professionals. A study discussed how the magnitude of waste within the construction industry ought to be decreased for environmental and economic purposes (Liu 2020). This clearly suggests that construction waste generation has direct impact on the environment and the economy. Hence it is important to assess the current levels of research conducted in dealing with construction waste.

There may be a couple of factors why CDW is not recycled. The generalization of CDW as inert waste renders the waste as “safe” to be kept at landfill sites. Furthermore, the potential contamination of CDW constituent materials could render recycled materials unwholesome for reuse. The potential low strength properties of some recycled materials may not render the materials adequate to be reused. These reasons could be cause of low recycling since the reuse of recycled materials is a significant incentive to encourage increased recycling practices.

1.2. Statement of the Problem

The mismanagement of construction and demolition waste (CDW) negatively impact the environment (Cook et al. 2020). Generally, CDW materials contain chemicals that could contribute to water, land, and air pollution, increasing emissions and affecting human life (Vergara and Tchobanoglous, 2012) . Furthermore, materials like gypsum drywall when biodegraded, could produce concentrations of hydrogen sulfide (H_2S). Controlling the smell of H_2S at landfills can be difficult as odor accelerates with the presence of water. Exposure to high concentrations of the gas could be deadly (Jiang et al. 2021).

Traditionally, landfills have been the destination for these CDW in many countries (Madi and Srour 2019). However, previous studies have highlighted the dangers and the missed opportunities when CDW are disposed of at landfills (Marzouk et al. 2014; Spångberg et al. 2014; Xiao et al. 2016). Materials like concrete, wood, steel, drywall, and asphalt concrete found in mixed CDW, could be salvaged and reused. Recycling these materials reduces the burden on the use of virgin materials (Chloe et al. 2015; Doan and Chinda 2016).

Although the CDW generation rate is constantly increasing, the recycling rate of CDW is generally low in many parts of the world (European Commission 2013). This could be due to the classification of CDW as inert in nature (Ahmed and Zhang 2021) and therefore believed to not harm the environment when kept at landfills. Additionally, the belief that recycling requires sophisticated technology (Neto et al. 2017) and does not yield a good return on investment (Gaines 2019). The lack of recycling has imposed an excess burden on landfill spaces that have been reported as increasingly becoming scarce (Song et al. 2015). According to the US EPA, out of the 169 million tons of mixed CDW generated in 2014, only about 38% of it was recycled (US EPA 2015a). A more recent US EPA 2018 data stated that 24% of generated CDW were recycled , which was a significant progress from previous reports. However, according to the North Dakota Department of Environmental Quality, all generated CDW in North Dakota end up at landfill sites. As a result, cities such as Fargo could face environmental challenges of keeping CDW at a landfill. Consequently, the economic potential of recycling CDW may not be fully realized. Furthermore, due to the substantial variabilities in recycling practices, generation rates, market demands, etc., some of the theoretical and practical CDW management options reported in existing literature may not be realized in certain mid-sized cities.

1.3. Statement of Purpose

Existing research undertaken in the area of CDW management have provided benefits that can be derived from adopting recycling as the method of managing CDW. However, in some mid-sized cities the conventional practice of landfilling has been the preferred CDW management approach. This is a major concern since keeping CDW at landfill has been reported to pose certain environmental threats.

This study performs a thorough assessment of the CDW management situation in Fargo, North Dakota and the neighboring State of Minnesota. Interviews will be conducted with representatives at locations that have adopted recycling as their means of managing CDW. The study seeks to investigate the opportunities associated with recycling. Furthermore, this study will find out why landfilling has been the preferred CDW management approach in Fargo, North Dakota (ND). The ultimate purpose is to quantify numerically, the missed opportunities and threats of adopting landfilling as a CDW management approach. Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) will be employed to quantify the environmental and economic implications of both landfilling and recycling CDW. Beyond this, the study seeks to propose a practical strategy to ensure that will ensure a profitable implementation of recycling CDW in Fargo, ND.

1.4. Research Questions

1. How much CDW is generated in Fargo, North Dakota?
2. How is the generated waste managed at the landfill site?
3. What impact does the existing landfill operations have on the environment?
4. What steps are taken by the landfill operators to minimize environmental impacts of the CDW kept at the landfill?
5. How is recycling CDW a better waste management alternative to landfilling?
6. What are the environmental impacts of both landfilling and recycling CDW?
7. What are the economic impacts of both landfilling and recycling CDW?
8. How can recycling be made a profitable venture to attract investors?
9. Are the economic gains of recycling worth the huge initial capital investment required?
10. Are certain cities better choosing landfilling over recycling due to location specific conditions?

1.5. Aim and Objectives of the Study

The aim of the study is to evaluate the environmental and economic benefits of two CDW waste management practices. Thus, this study aims to estimate the environmental and economic benefits of adopting landfill and/or recycling as a CDW waste management alternative.

The outlined research objectives were formulated to achieve the aims of the research:

1. To assess current CDW management practices in Fargo, North Dakota.

2. To investigate the factors influencing the City’s decision to opt for a particular method of CDW management.
3. To investigate CDW management practices in other jurisdictions that share boundaries with North Dakota.
4. To investigate the environmental impacts of landfilling and recycling in the context of Fargo, North Dakota.
5. To investigate the economic impact of landfilling and recycling in the context of Fargo, North Dakota.

1.6. Significance of the Study

The adoption of landfilling as the conventional means of CDW management can result in natural resource depletion, increase in carbon footprint as well as economic losses. However, CDW could be diverted, recycled and reused to protect the environment and make some economic gains. Achieving the aims and objectives of this study will reveal the potential environmental and economic benefits that are been missed with the current practice of landfilling CDW in Fargo, ND. Furthermore, this study reveals to the private sector strategies that could make recycling a viable venture and the resulting return on investment (RoI).

1.7. Organization of the Study

The thesis is arranged in six chapters which have been detailed below:

1.7.1. Chapter 1 – Introduction

This chapter provides details on the background and setting of the research. It establishes the fundamental principles behind the problem statement in addition to the objectives of this research. The research questions adopted for this study has also been outlined in chapter 1.

1.7.2. Chapter 2 – Literature Review

This chapter focuses on review of existing journals, reports, articles, conference proceedings and books written on the subject of CDW. The chapter details CDW management practices around the world and in the USA. Furthermore, studies on LCA and LCC for CDW management have been reviewed. The subject of circular economy and how it intersects with CDW management has also been discussed.

1.7.3. Chapter 3 – Methodology

This chapter presents the methods and materials adopted to achieve the objectives of the study. In this chapter, the study location has been described as well as the LCA and LCC methodology adopted to quantify the environmental and economic benefits of CDW management practices.

1.7.4. Chapter 4 – Data Analysis and Interpretation

The fourth chapter provides the input data used for the LCA and LCC study. The statistical results were also presented in this chapter. Sensitivity analysis was also carried out to justify the LCA and LCC results due to the assumptions which had to be made during the development of the study’s parameters.

1.7.5. Chapter 5 - Conclusions and Recommendations

The last chapter of the thesis presents information on how the aim of the study have been achieved and the questions answered. Additionally, inference made from the findings have been outlined and practical recommendations which can inform policy decisions and future research have been provided.

CHAPTER 2. LITERATURE REVIEW

2.1. Introduction

This chapter introduce the exploration of literature related to CDW management, landfilling, recycling, circular economy, construction material recovery, reuse, LCA, LCC and sensitivity analysis. The intention was to cover all aspects related to the problem statement and the objectives of this study. The review presents information on the extent of existing literature on the subject of CDW management. The CDW management around the world have also been summarized in this section. Finally, the section presents a summary of the basis of the study with specific relevance to findings from existing literature.

2.2. Definition of Terms

Several parameters that are relevant to this study have been defined using existing literature, institutional reports and conference proceedings. It is imperative that these terminologies, practices and methodologies are described due to their adoption as scientific basis for the present study.

2.2.1. Waste

Waste can be defined as unwanted or unused materials that results from any activity (Hoornweg and Bhada-Tata 2012). In fact, waste is not only relevant to materials since time can also be wasted (Buxton et al. 2021). The US EPA describes waste to be of different kinds which includes, municipal solids waste (MSW), hazardous waste, industrial non-hazardous waste, agricultural and animal waste, medical waste, radioactive waste, construction and demolition waste, extraction and mining waste, oil and gas production waste, fossil fuel combustion waste and sewage sludge (US EPA 2022). However, the scope of this study focuses on construction and demolition waste. CDW is categorized as inert waste because it fails to develop into contaminated leachate or act as food for vectors (Ache 2019). However, it is important not to allow the inert nature of CDW dissuade us from giving the treatment of the waste the attention it deserves. Certain CDW contains chemicals that are harmful to the environment when left at the landfill site. For example, materials like gypsum, which is a component of CDW, could contribute to the formation of hydrogen sulphide formation in landfills (Rubright 2017). Hence stringent but practical measures must always be in place to reduce the harmful CDW materials that end up in the landfills.

2.2.2. Waste Management

This is the process of putting measures in place to control, monitor and regulate the production, collection, transport, treatment and disposal of waste (Sharma and Reddy 2004). Adopting sustainable waste management methods have been challenging due to increased production rate and the dynamic socio-economic conditions (Singh et al. 2014). Adopting effective waste management practices is imperative to protecting natural resources (Ispas et al. 2019). The best means of managing waste is controlling generation and ensuring generated waste is stored or treated appropriately (Jebaranjitham et al. 2022). Like any other waste, CDW management can be challenging especially due to its increased volume as more construction activities occur (Iacoboaea 2019). Hence, it is essential to undertake critical view into the existing CDW management practices.

2.2.3. Construction and Demolition Waste (CDW)

Various definitions have been coined for construction and demolition waste (CDW) by different authors. In fact, some definitions are region specific and based on constituent materials found within the CDW. Furthermore, some definitions of CDW have been based on quantity, descriptive and on economic parameters (Papastamoulis 2021). A quantitative definition of

CDW is the excess between the materials ordered, delivered and accepted and those accurately used for the execution of a construction project (Menegaki and Damigos 2018). In instances where authors want to define CDW based on the components, it's been described as the waste material obtained from the construction of all types of buildings but excluding excavated soil (Zheng et al. 2017). An example of an economic definition of CDW is materials resulting from errors in designs, design changes and unused materials (Muhwezi et al. 2012).

There are other definitions which are jurisdictional, institutional, legislative or country related. For instance, the EU defines CDW as waste from activities of companies that belong to the construction sector (Osmani and Villoria-Saez 2019). This definition may be inadequate since it may not include waste generated by private individuals who generate certain construction waste. For example, owners involved in constructing or renovating their homes is a common practice in countries like the US. Hence, the EU definition might leave out waste materials from such activities. Incomplete definitions may omit the more principal CDW materials which could have a significant potential impact if not captured within the waste stream and managed.

In Asia, countries like China and India have related definitions where CDW have been described as waste consisting of building materials or waste resulting from construction activities like remodeling, expansion, demolition and renovation (Huang et al. 2018; Ponnada and Kameswari 2015). This definition is quite elaborate and captures waste from every form of construction activity whether from construction companies or activities of private individuals.

The US EPA defines CDW as the waste generated from the construction, renovation, repair and demolition of commercial and residential buildings as well as roads and bridges. This CDW definition is quite similar to the Asian definitions and indeed broadens the scope of materials that can be classified as CDW materials. Since many of these definitions take into consideration the activities which produce the CDW, it is necessary to recognize what materials form CDW. The component materials of CDW are also another important factor in determining the waste management method to adopt. For instance, if a significantly large percentage of CDW is made of wood, steel and concrete, implementing site sorting strategies could be enough to prevent a greater amount of the waste from ending up in landfills. Unfortunately, some of the CDW components are hazardous in nature and have to be diverted from ending up at the landfills.

2.2.4. Generation of Construction and Demolition Waste

The generated amount of CDW in 40 countries was approximately 3 billion tons annually (Akhtar and Sarmah 2018). This estimation is a cause to worry due to the potential threat associated with CDW production and sending to the landfills (Huang et al. 2018). Knowing the amount of construction waste generated within a particular region is an important step in the CDW management process. The increase in the generation of CDW is unavoidable due to the continuous increase in construction activities.

Existing literature have recounted the quantities of CDW generated in Europe, Asia, US and other countries. The generation of CDW per capita is 720kg/person/year for Germany and 325kg/person/year in Portugal (Coelho and De Brito 2011). Parts of Asia reports an estimated generation of approximately 13.71 million tons in 2012 (Ding and Xiao 2014). The US EPA estimated a CDW generation of 600 million tons in 2018 (US EPA 2020). The constant increase in CDW generation rates around the world signifies the need for the implementation of robust management practices to curb the potential negative impacts (Galvez-Martos 2018). However, gaining insight into the components of CDW generated within a particular region is another step in the waste management process (Taboada 2020).

2.2.5. Construction and Demolition Waste Composition

Another step in ensuring proper CDW management practices is the awareness of the material components within a particular CDW quantity (Spišáková et al. 2021). CDW materials can comprise of hazardous and non-hazardous materials (Borghi et al. 2018). The different waste management methods for hazardous and non-hazardous materials require that CDW materials are properly separated into its constituent materials during the management of the waste (Ruiz et al. 2020).

Several authors have conducted studies on the component materials of CDW. Furthermore, more research has conducted investigations into some of the material components of CDW. Arisha et al. (2018) investigated the performance of aggregates contained in CDW and concluded that the material was better for pavement construction than virgin materials. Kvočka et al. (2020) conducted studies in geopolymeric façade cladding panels. Furthermore, materials like concrete aggregates, wood, steel, asphalt pavement and drywalls have been reported as materials found in CDW (Borghi 2018; Estanqueiro et al. 2018; Zhang et al. 2020; Hossain and Poon 2018). The US EPA CDW materials include steel, wood products, drywall and plaster, brick and clay tile, asphalt shingles, concrete and asphalt concrete (US EPA 2015). Since this study was conducted in the US, the material composition outlined by the US EPA will be adopted for this study.

2.2.6. Construction and Demolition Waste Management

Construction industries worldwide produce more than 450 million tons of CDW per year (European Commission 2000). The prudent management of this waste can help save a substantial amount of energy (Akhtar 2018). Landfilling has been the widely adopted CDW management approach in many countries (Danthurebandara 2012). However, keeping CDW in landfills has negatively impacted the environment regarding natural resource depletion and carbon dioxide emissions (Zhao 2010). The recycling of constituent materials like concrete, steel, and wood, has contributed to saving natural resources, avoiding landfill disposal, and reducing carbon dioxide emissions (Zhao 2010). In economic terms, recycling has been a profitable venture partly due to capital savings made by avoiding high transportation costs and charges involved in the disposal of CDW at landfills (Akhtar 2018; Srour et al. 2012). These studies have employed different means to assess the impact of the different CDW waste management alternatives.

2.2.7. Landfilling

Landfilling has been the conventional CDW management practice in many countries (Di Maria 2018). The effect of landfills on the environment rests in the emissions of gases into the atmosphere (Gallego 2014). There are arguments that CDW have less impact to the environment when kept on landfill due to its characterization as inert waste (Borghi et al. 2018). However, CDW kept at landfill sites also take up landfill spaces which are gradually becoming scarce (Wildeboer and Savini 2022). Landfilling also contributes to subsurface flow which could contaminate ground water which eventually end up in homes for domestic use (Abiriga et al. 2021). Recycling as a CDW management alternative offer more environmental savings and economic gains (Coelho and De Brito 2013).

2.2.8. Recycling

Recycling has been reported as a better waste management alternative to landfilling (Cucchiella, 2017). Recycling is the practice of diverting waste from ending up at the landfill and converting this waste into materials which are reusable (Lockrey et al. 2016). Recycling has the potential to reduce the need for landfill sites, which can result in saving land space for other development projects (Yeheyis et al. 2013). However, there are several factors that affects the success of recycling practices (Kattoua et al. 2019). Recycling is not always profitable due to the sophisticated means required to make certain recycling methods possible (Gaines 2014). Certain measures must be in place to ensure diverted materials can be reused (Ajayi and Oyedele 2017).

The product materials from some recycling activities reduces the strength of the recovered materials (Asmatulu et al. 2013). As a result, some of these materials are not able to be reused. For instance, recycled steel may not be used to replace steel for construction but rather used as input into steel production. This substitution process is referred to as downcycling (Di Maria et al. 2018)

2.2.9. Downcycling

As mentioned by Di Maria et al. (2018), when materials are not used to replace their exact use, they are termed as being downcycled. For example, when waste concrete products cannot be used to replace freshly mixed concrete, that process of recovery and reuse is not recycling but rather downcycling. Di Maria et al. (2018) maintained that existing CDW management practices have been downcycling and not recycling. In fact, due to the comingled nature of certain CDW materials, sophisticated technology is required to recover its constituent materials in the forms that allows them to be replaced for virgin materials (Coelho and De Brito 2013).

2.2.10. Recovery

This phenomenon is often confused with recycling by many, however, the two are different and involved different practices (Cimpan et al. 2015). Recovery is any procedure or method where waste is used to serve a useful purpose by placing other materials which otherwise would have ended up at a landfill or disposed of (Richard 2011). Recovery methods are often practiced on construction sites to recover certain materials which may be seen as reusable

(Galvez-Martos 2018). In some instances, construction site material sorting is established in project contracts to allow project owner recover materials that are reusable (Napier 2012). On-site recovery reduces the effort required to recycle CDW (Hao et al. 2020). Material recovery permits the practice of circular economy where recovered materials are reused rather than ending up at landfills (Ginga et al. 2020).

2.2.11. Circular Economy (CE)

Since becoming a phenomenon within the waste management industry, circular economy (CE) has had various authors provide various definitions to this system. In fact, CE means different things to different people resulting in critics referring to the phenomenon as ambiguous (Kirchherr et al. 2017). Kirchherr et al. (2017) after analyzing 114 definitions been described CE as an economic system that is premised on business scenarios that replaces end-of-life (EoL) phase of products. This essentially means that circular economic principle provides a cyclical system where waste is prevented through the continuous use of a product. This therefore helps to reduce the overall influx of waste produced as a result of raw materials manufacturing and processing (Luttenberger 2020). Furthermore, other authors believe the concept of CE suggest a mindset adjustment which examines waste as a potentially essential resource and not a challenge to manage and dispose (Ghisellini et al. 2018).

CE and recycling intersect at the point where the two methods seek to reduce disposal of waste which could eventually harm the environment (Ghisellini et al. 2016). Essentially, CE does not eliminate recycling. The principle rather strengthens the importance of recycling. Recycling has been introduced within the linear economy (Singh and Ordonez 2016). However, CE reinforces the concept of recycling in a more cyclical perspective. The two phenomena work together to reduce the impact of CDW on the environment (Oliveira et al. 2021).

2.2.12. Life Cycle Assessment (LCA)

Life cycle assessment (LCA) is a powerful tool that has been developed to help quantify the environmental impact associated with a particular product or service. The ISO 14040 defines LCA as the consideration of the environmental aspects and the potential impacts of a product or a service system throughout is its period of life – from raw materials acquisition through production, use and disposal (which is also known as “cradle to grave”). This standard method shows that LCA studies can be conducted in four main stages which are: goal and scope definition, inventory analysis, Impact assessment and improvement assessment. Several authors have adopted these methods to perform several studies. For example, Dixit et al. (2013) adopted LCA methods to propose a model to quantify embodied energy of the life cycle of a building. Additionally, LCA has been used to propose a conceptual framework for CDW management to minimize the disposal of CDW. Furthermore, LCA methods have been applied to recycling CDW where authors reported that recycling was a better alternative to landfilling in terms of environmental savings (Marzouk and Azab 2014; Di Maria et al. 2018).

Another layer of environmental impact studies is the availability of economic data to quantify the impact of environmental burden. Quantifying environmental losses in financial terms seem more comprehensible and the gravity of the environmental burden is well appreciated when expressed in monetary terms (Costantini and Mazzanti 2012). Hence, it is always imperative that LCA studies are integrated with life cycle costing (LCC) to enable the representation of the impact of a product or service in monetary terms.

2.2.13. Life Cycle Costing (LCC)

Life cycle costing is a systematic approach that helps with the evaluation of how a product or service is going to cost over time (Galar et al. 2017). This often involves the cost of owning, operating, maintaining and disposing of a product or service over a period of time. LCC has been adopted by various authors to conduct different kinds of research. The numerous research ranges from LCC of sanitary ware (Jingxiang et al. 2019), mass-timber (Liang et al. 2019), residential buildings (Islam et al. 2015) to saffron production (Abolhassani et al. 2020). In terms of CDW, LCC have been used to perform several analyses. Generally, in these studies, LCC has been used to compare the benefits of CDW management practices (Coelho and De Brito 2013; Di Maria et al. 2018; Iodice et al. 2021). The LCC technique allows authors to predict what CDW management alternative will be beneficial to a particular geographic region.

2.2.14. Sensitivity Analysis

Sensitivity analysis methods have been adopted across wide range of disciplines (Razavi et al. 2021). It aids in identifying vital control point and verifying or validating research models (Wu et al. 2013). In simple terms, sensitivity analysis can be described as the system used to identify how independent variable data affects a particular dependent variable under a particular set of assumptions (Antoniadis 2021).

Due to the use of assumptions in LCA and LCC studies, it is important to perform sensitivity analysis to validate some of the assumptions adopted during the studies (Toosi et al. 2020). Sensitivity analysis is a decision-making tool utilized at the institutional level to help provide strong validations behind certain outcomes (Huang et al. 2013). There are two types of sensitivity analysis methods which are local sensitivity analysis and global sensitivity analysis (Razavi et al. 2021). In this study, sensitivity analysis was used to identify how certain parameters reacted to changes to the initial assumptions used in both the LCA and LCC.

2.3. CDW Management Practices in the United States

The US EPA reports a continuous yearly increase in generation rates of CDW (Hauschild 2015). This annual increase necessitates the importance of implementing effective methods in managing CDW to reduce the burden on the environment while making economic gains. Landfilling and recycling are the two common CDW management methods in the US (US EPA 2015a). In some parts of the US, CDW materials like concrete and asphalt are reused as recycled aggregates (RA) whereas same materials are disposed of at landfills in most parts of the country.

Most of the landfill sites receive the waste and store them in cells. These cells are 10 – 20 feet deep channels dug at the landfill sites. The digging operation in itself harms the environment due to the excessive use of diesel-powered equipment. CDW kept in these cells are left over periods of time with no treatment. This practice is due to the general classification of CDW as inert waste materials. However, CDW may contain certain chemicals like lead which left untreated can contaminate the soil. The US EPA and the United States Green Building Council (USGBC) are targeting reduction of CDW at landfill and incineration facilities through waste prevention and 3Rs (recover, reuse and recycle). However, best CDW management practices are linked to core circular economy principles (Danthurebandara et al. 2012).

2.4. Intersection of CDW Management and Circular Economy

The concept of circular economy (CE) is generally believed to solve challenges such as waste generation, resource scarcity, and sustaining economic benefits (Lieder 2016). Adopting sustainable CDW management could curb the challenge of resource scarcity and render economic benefits. However, it is important that CE principles are operational and not just theoretical. Some of the operational CE principles are maintaining the value of resources within the system, reducing the system's size, designing for CE and educating for CE (Suárez-Eiroa

2019). The output of this study helps with achieving educating for CE principle by highlighting the benefits of adopting an effective CDW management alternative. The intersection of CDW management and CE is when the present study provides compelling evidence revealing how adopting certain CDW management practices could help reduce resource scarcity and provide economic benefits.

2.5. Comparing Two Methods of CDW Management (Landfilling vs. Recycling)

Landfilling and recycling are the two predominant CDW management practices (Crawford 2017) . LCA and LCC have been widely used to identify the impacts of CDW management practices. While LCA primarily evaluates the environmental impacts, LCC assesses the economic impact of a facility or product.

Several authors from Europe, South America, and Asia have adopted LCA for construction and demolition waste management. For example, in Denmark, LCA was used to compare CDW materials like concrete and masonry debris utilization in road construction and landfilling (Vieira and Pereira 2015). The results showed that utilization of CDW on the road was better than landfilling. However, landfilling proved a better alternative than road utilization in some impact categories. Hence, it was important for the author to point out a more compelling impact to further place road utilization over landfilling. For example, the study could have discussed the economic comparisons between landfilling and the utilization of CDW, which could have distinguished road utilization and landfilling based on the economic viabilities.

Kvocka et al. (2020) investigated the environmental performance of prefabricated geopolymeric façade cladding panels made from large fractions of CDW. Although this study reported a reduction in CO_2 resulting in environmental benefits, no economic viability analysis was performed on these products made from recycled CDW. Borghi et al. (2018) investigated the critical aspects and possible CDW management improving actions. This study reported that although recycling is better than landfilling, restricting quarrying activities by setting higher taxes could make recycling economically competitive. This study further recommended that different geographical contexts could report different results. Imposing higher taxes may not work in every jurisdiction since recycling is primarily a private venture. The government may not be compelled to impose taxes to encourage recycling because the non-profitability of recycling may not necessarily be a challenge to the government.

Two studies in Portugal conducted a thorough economic analysis of recycling CDW (Coelho and De Brito 2013a, 2013b). Although these studies reported economic gains for recycling, most of the parameters adopted for their analysis were tied to the geographical location of the studies. Parameters like tipping fees, equipment maintenance, transportation, and labor costs may differ by location. Hence, it is necessary to perform a geographic-based, environmental and economic analysis of recycling CDW and compare the results to existing findings.

Furthermore, after assessing the CDW management of thirteen municipalities in Brazil, Rosado et al. (2019) found that specific environmental impacts are avoided when CDW is recycled. They reported environmental savings associated with steel recycling. However, this study noted that subsequent studies should not only focus on mineral fractions. Thus, it is essential to conduct an analysis that includes CDW materials like asphalt, bricks, and cement concrete.

In India, Jain et al. (2020) compared different alternatives to CDW management. They concluded that recycling CDW could help reduce carbon emissions. Although this study reported recycling as a better approach than landfilling, the parameters and study assumptions were based on practices in India. Many CDW recycling studies are region-based and usually focuses on specific localities due to the different construction and demolition waste management methods adopted across the globe (Vergara and Tchobanoglous 2012). In China, Liu et al. (2020) investigated the cost of carbon emissions from CDW using LCA and LCC. The study reported net environmental savings and the potential for profit in recycling. However, this study did not consider the cost components in the various recycling process in terms of LCC. The focus was more on demolition and the equipment needed for that operation. Recycling CDW requires enormous investment capital. There requires an analysis of every financial detail involved in recycling to accurately project the profitability of such a business venture.

In the United States, LCA has been applied to buildings (Jin and Qian 2015), construction materials (Arulrajah et al 2013; Barbudo et al 2012), and end-of-life management options for CDW (Carpenter et al. 2013). However, combining LCA and LCC to evaluate the benefits of CDW recycling have not been thoroughly explored. It is difficult to ascertain which of the theoretical and practical CDW management practices reported in existing literature can be applied in the United States waste management scenario.

For example, Coelho and de Brito (2013a; 2013b) sought to quantify the potential benefits of recycling CDW. This study proposed using an advanced recycling method where the facility operated on a 350 tonnes/h installed capacity. Using an 8-hour per day, 240 days per year work period, this facility will be required to recycle 672 thousand tonnes of CDW every year. Although this technique was applicable per the generation rate of the study location, it is impossible to implement in an area with a much lower CDW generation rate. The sustainability of an option must be evaluated using site-specific conditions related to generation rate and costs, raw material requirements and costs, transportation distances, energy sources, etc. Therefore, it is vital to carry out the study for a set scenario in a mid-sized city.

A good amount of research has been conducted in CDW management. However, due to region-specific conditions and policies affecting the success of implementing circular economic principles, it is essential to pursue continued studies to unravel regionalized challenges and associated solutions. For example, Meglin et al. (2022) stated the impact of different regional constraints on the successful implementation of circular economy principles. Since sustainable CDW management directly links to the circular economy principle, it is vital to conduct research that accounts for practices, strategies, and conditions distinct to geographic locations. Hence, the results of this study are critical to the successful implementation of sustainable CDW management policies in the study region and regions with similar conditions and practices.

CHAPTER 3. METHODOLOGY

This study was conducted in two stages which were: i) assessing the current CDW management practices in Fargo, North Dakota, ii) applying LCA and LCC to highlight the environmental and economic impacts of the current and a proposed CDW management practice.

3.1. Description of the Study Location

Fargo is the largest city in North Dakota with almost 17% of the state's population. The population of the city is rapidly increasing (with a growth rate of 18% between 2010 and 2019). According to the US 2018 census data, the average household income witnessed a 5.44% increase. This means development and standards of living are expected to continuously increase in Fargo. These developments generate more deconstruction, renovation and construction activities. Hence, it is important to identify how the waste generated from these activities impact the environment and economy of Fargo, ND. The Figure shows the map of the study location.

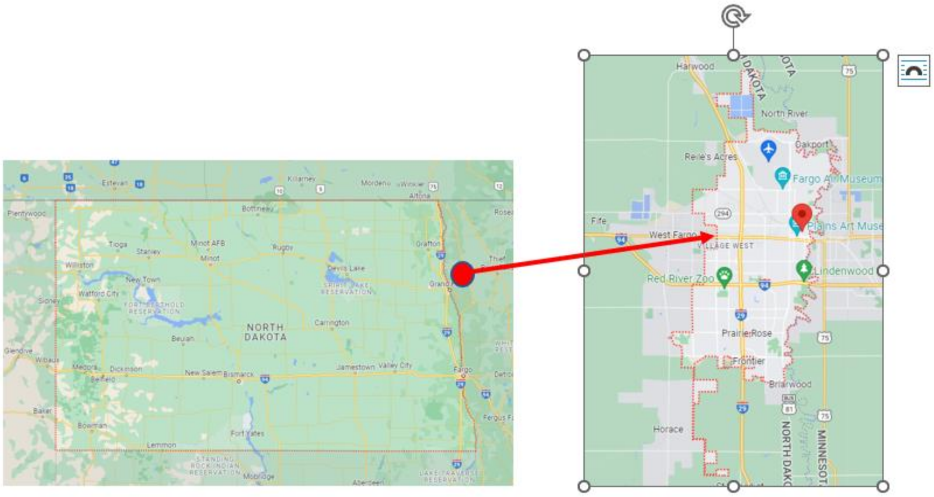


Figure 1. Map of North Dakota showing the city of Fargo (Source: Google Maps)

3.2. Assessing Current CDW Management Practices in Fargo, North Dakota

To evaluate the prevailing CDW management practices, the authors interviewed the city’s waste management sectorial representatives. The goal of this approach was to ascertain the existing CDW management practices. Additionally, construction companies were also interviewed to understand the prevailing demolition methods. This interview was necessary because the method or choice of demolition directly impacts the present study's analysis.

Furthermore, CDW recyclers in Minneapolis, a city in the state of Minnesota, were interviewed to understand their CDW recycling methods and principles. This information was essential to inform the practical recycling method proposed in the current study. Information derived from these CDW recyclers was also essential to inform practical financial considerations for the present study. Findings from these interviews influenced the second stage of this study.

The interviews revealed that: the annual amount of CDW generated in the city was 20,000 tons. The prevailing CDW management practice is sending all generated waste to the landfill. The City of Fargo has no CDW recycling procedures as an alternative to landfilling. One reported method of reducing the quantity of CDW directly transported to the landfill is on-site sorting after controlled or selective demolition. However, contractors in the city do not conduct selective demolition unless the project contract demands it. As a result, controlled or selective demolition is not typical within the study location, making it difficult to accurately characterize the types of construction materials in a mixed CDW.

In the study location, generated CDW is classified into seven material categories: (a) concrete (b) asphalt pavement (c) metals (d) wood (e) bricks (f) drywall (g) plastics. The city’s waste management sector adopts the US EPA CDW classification methods and characterization. The US EPA provides the percentage composition of the various material constituents found in the generated mass CDW (US EPA 2017 and 2018), shown in Table 1. This waste characterization was adopted to quantify the amount of each material category found in the mixed CDW generated in Fargo.

Table 1. Percentage composition of construction materials in mixed CDW

Material Category	Percent Composition (%)
Concrete	69.70
Asphalt Pavement	15
Wood	7.10
Metals	3.3
Bricks	2.10
Drywall	2.70
Plastics	0.1

3.3. Current Practice of Landfilling CDW (Scenario 1)

Keeping CDW at the landfill, referred to as scenario 1 for the present study analysis, is the prevailing CDW management practice in the study location. The annual estimated amount of CDW generated in the city ends up at the landfill site. The landfill site has three staff (1 manager and three laborers/operators) supervising operations at the landfill. CDW generators owe the responsibility to haul the waste from the various sites to the landfill.

The average transportation distance from the farthest point of the city to the landfill location is 22 miles. The CDW is first inspected at the landfill gate to ascertain whether it meets the inert waste criteria before it is received at the landfill. A tipping fee of $46/ton is charged at the landfill gate, and the waste truck is directed to dump the waste at a specified location. The mass CDW are kept in cells of 43,560 square feet and 10 feet deep, dug with excavators and dozers. It takes 24 workdays (10-hour work periods per day) to complete the excavation of one cell. After dumping the waste in these cells, clay and black dirt are used to cover it. This practice means: (i) the opportunity to reuse some of the materials contained in CDW is lost, (ii) landfill spaces are not conserved, and (iii) an increase in emissions and a possible natural resource depletion. Hence, this study proposed establishing a recycling facility as a better alternative to the current CDW management practice.

3.4. Recycling of CDW (Scenario 2)

Recycling the CDW generated in the study location is referred to as scenario 2 in this study. The application of technology and the mechanized nature of recycling demands the construction of a facility where these activities can take place. Buildings generate high environmental impacts during their life cycle phases (Gardner 2020), mainly construction, use/operation, and demolition. Some studies have applied LCA methods for the construction phase of buildings (Banawi 2014; Bilec et al. 2010) and have concluded that the impact on the environment (0.4 – 11%) is lower than the impact of the use/operation phase. Hence, this research will focus on the environmental impact of the recycling operations, which has a more significant environmental burden but will quantify the cost component of building the recycling facility. The building footprint, operational hours, and human resource needs were determined based on provisions in the US EPA manual and the annual generation rate of CDW.

The proposed facility will cover 17,500 square feet and operate on a 4-hour day, 240 days per year. The operation hours were derived based on the annual quantity of waste generated. The facility will charge a $110/ton fee for collecting and hauling of waste. In Fargo, it costs between $200 and $400 to rent a 3-ton dump truck. Adding this cost to landfill gate fees makes the proposed rate a more cost-effective option for waste generators, giving the recycling facility a competitive advantage over the landfill. Operations at the facility will require a manager, two nonskilled workers, and two truck drivers. It is essential to establish the various recycling stages or processes to accurately evaluate the impacts of each process.

The waste collection model for the proposed facility will be to provide dumpsters at project sites, at the request of waste generators, which receives the CDW and then hauled to the recycling facility. The targeted recycling rate is 75%. The remaining 25% of non-recovered materials will be transported to the landfill as inert waste. Achieving the desired recycling rates depends mainly on the recycling procedure adopted. A highly advanced recycling method increases the recycling rate of materials that can be recovered (Di Maria et al. 2018).

The proposed CDW recycling process can be divided into four main stages: hauling from the source of waste to the centralized facility, separating mixed CDW, processing (crushing, grinding, and screening), and hauling recovered materials to the end markets.

The mixed CDW hauled to the facility is first dumped at a tipping floor where water is first applied to the waste. An excavator is used to break down substantial concrete materials into medium sizes. It then picks the mixed CDW and dumps it into the main feeder of the recycling equipment for the separation process to begin.

After dumping it into the main feeder, a taper slot screen vibrates the waste. Light materials like dust and very small-sized unwanted waste go through the taper slot screen under sieves. The materials are then transferred to a magnetic screen which sorts all ferrous metals from the waste unto a conveyor, which dumps the ferrous metals into a container. The remaining materials are carried to a <4" and >4" trommels which sort the <4" and >4" aggregates. The medium-sized fractions are transmitted to a conveyor, which goes to a manual sorting platform or screen. Here, wood chips and plastics are sorted manually from a conveyor, which carries the remaining waste into a dense-out separator. This separator sorts the medium-sized heavy concrete and bricks from the materials. It is then carried to another manual sorting conveyor where massive concrete, brick, and wood are manually sorted into different containers. The residue is then conveyed to a residue end compactor which compacts all the residue for disposal. This residue is the 25% of rejected fragments directly transported to the landfill. A schematic representation of the recycling process is shown in Figure 2.

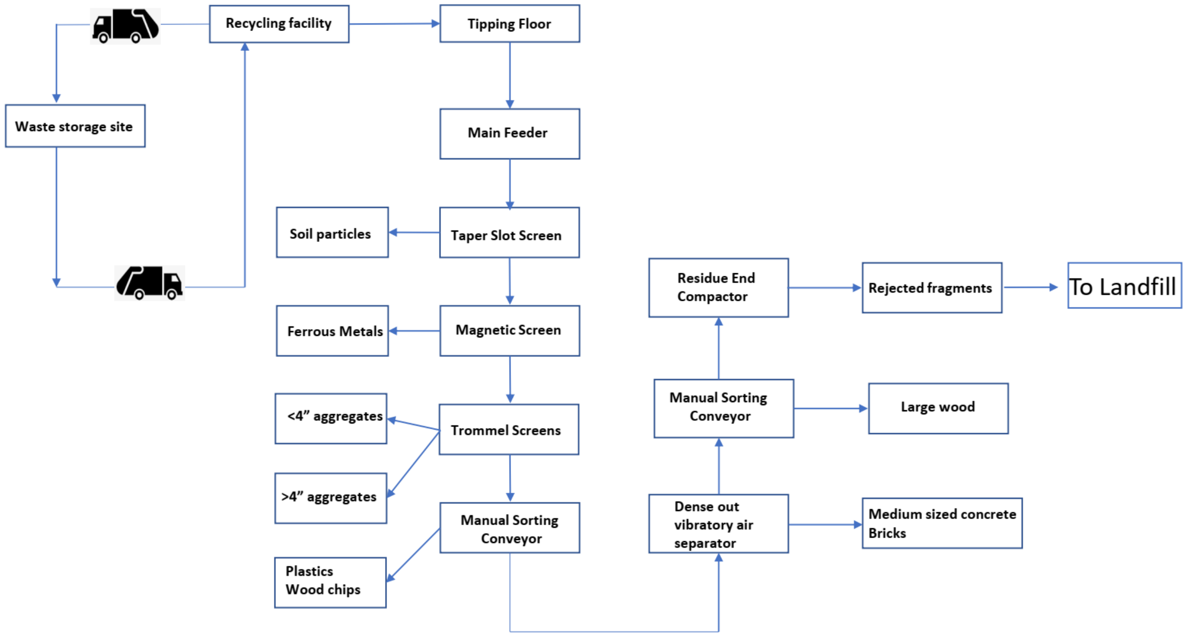


Figure 2. Process flow for recycling mixed CDW

Recovered materials undergo further processing (screening, grinding, and crushing) before they are transported to the end markets, where these materials are reused or substituted. The recovered materials are aggregates, wood products, metals, plastics, drywall, and bricks. With a substitution rate of 1:1, these materials are used to replace virgin materials or used for energy recovery, for example, in the case of wood products. Aggregates replace natural aggregates (NA) in concrete and asphalt production, avoiding natural aggregate production and its associated costs and environmental impacts. Metals are used to replace iron ore needed for the manufacturing of steel.

Materials that are obtained through controlled demolition could be reused. For instance, bricks obtained from controlled demolition could be cleaned and reused. Additionally, wood and nails could be reused if obtained under controlled demolition.

Since controlled demolition is usually not a common practice, materials like broken bricks are ground and used as filling materials, saving sand and gravel production. Wood that cannot be reused is sent for energy recovery. Plastics are melted and used to produce new plastics saving the use of new polymers for plastics. Lastly, drywall is grinded into its raw form (gypsum), which can be used to produce new drywalls.

Although the reuse options described above are more of downcycling, it is safer for the environment when recovered materials are being reused in one way or another. The demolition practices in the city reduces the strength properties of recovered materials, making it difficult for these materials to be reused as new construction materials. For example, recovered wood cannot be reused as rafters and purlins for another construction. Hence, there is low confidence in recycled materials, which results in relatively lower market prices. This lower market price makes decision-makers argue that recycling may not be worth the time and capital investment. Especially when the initial investment involved in establishing a recycling facility is not commensurate with the return on investment (RoI). To provide evidence of a better waste management approach, LCA and LCC are needed to quantify the benefits of landfilling and recycling.

3.5. LCA/LCC Structure for the Study

LCA and LCC are primarily combined in several studies due to their complementary characteristics of aiding decision-making and policy formulation. As a result, LCA/LCC must be complementary to provide a robust analysis from which policy decisions can be made.

The present study utilizes an LCA and LCC results to analyze the current CDW management (Landfilling) and proposed alternative management practices (Recycling). The LCA helps us look at the qualitative inventory to produce flow diagrams within the CDW management scenarios considered for this study. The LCA helps understand which components have the highest relative environmental impact within the two scenarios.

The LCC analysis will summarize all costs associated with the system boundary of the present study. The cost will relate to actual cash flows. These costs will include establishing a facility where recycling will take place. Furthermore, the LCC analysis will consider initial capital and operational costs (including labor, utility, equipment maintenance, transportation, and administrative costs).

Per the ISO 14040 (Bare 2002; Hunkeler et al. 2008), LCA and LCC consist of four phases, namely: goal and scope definition, life cycle inventory (LCI), and life cycle impact assessment (LCIA), and life cycle interpretation.

3.5.1. Goal and Scope of the Adopted LCA/LCC Method

This LCA study aims to assess the environmental impacts associated with landfilling and recycling of CDW in Fargo, ND. Equally, the goal of the LCC is to highlight the economic inputs and the corresponding financial benefits associated with the two CDW management practices. The primary data utilized for this study were based on local data from Fargo, ND. Where applicable, data were acquired from institutions like the US EPA, commercial CDW recyclers, local contractors, and existing literature to aid in the analysis of the present study. The LCA and LCC analysis was performed with the same system boundary and functional unit.

3.5.2. Functional Unit and System Boundaries

LCA and LCC need to share a standard functional unit (FU) to ensure the validity of both analyses. As a result, both LCA and LCC share a standard FU of managing 1 ton of generated CDW. The system boundary for the LCA focuses on the two scenarios considered in this study. Scenario 1 involved the situation where generated CDW are sent to the landfill. In contrast, scenario 2 was the option where the generated waste undergoes recycling. The input and output processes involved in the two waste management scenarios have been considered for the LCA study and shown in Figure 3.

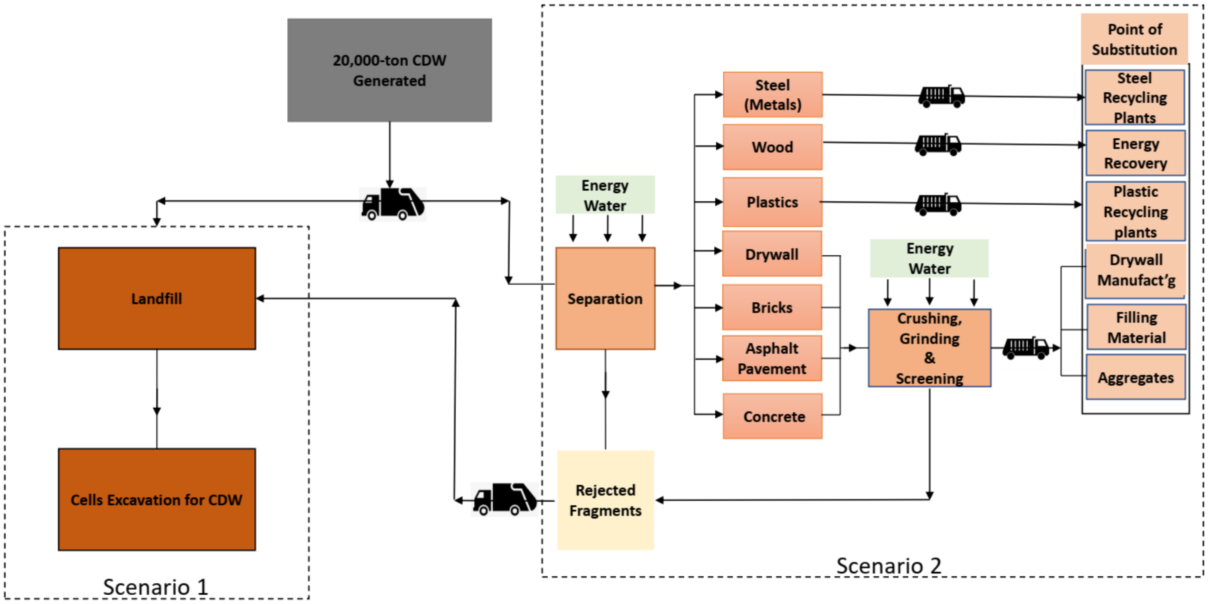


Figure 3. LCA system boundary, process, and material flow for scenarios 1&2

Similarly, the system boundary and cost parameters considered in the LCC have been shown in Figure 4.

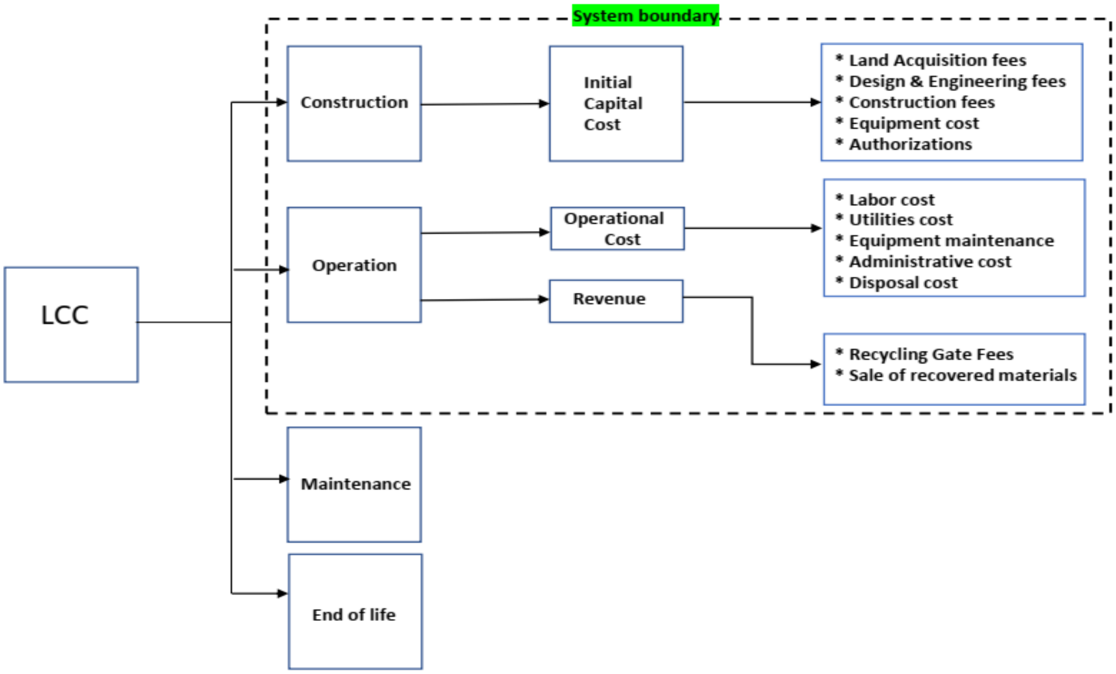


Figure 4. LCC system boundary for scenario 2

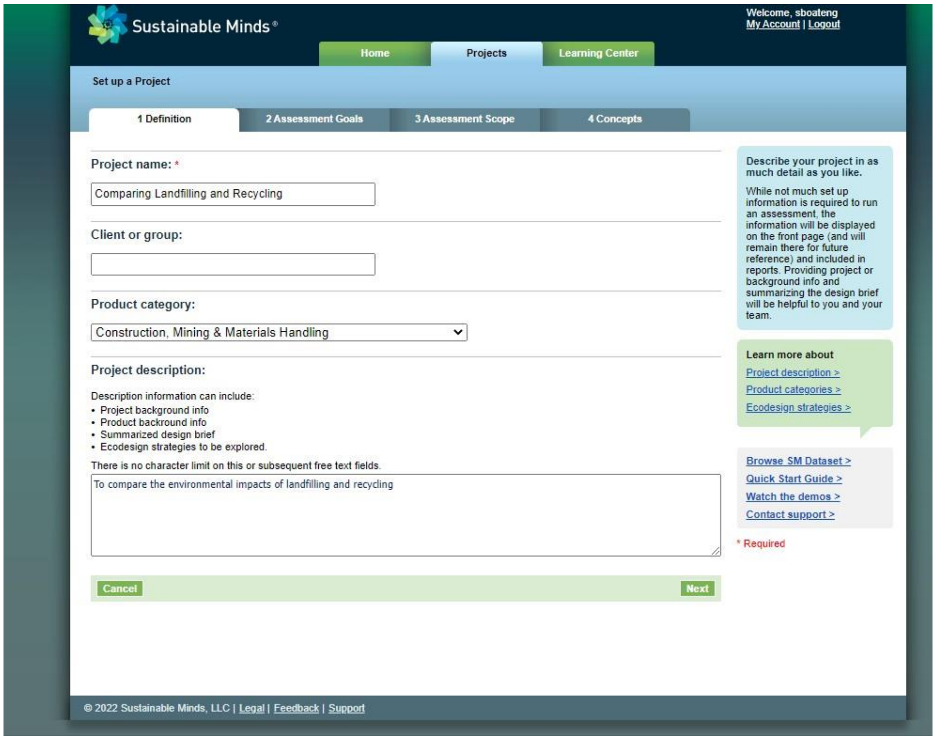
3.5.3. Life Cycle Inventory for the LCA and LCC

Primary data was gathered for each unit process within the system boundary at the life cycle inventory (LCI) phase. This data consists of all the LCA's material and energy inputs and outputs. The LCC gathered all costs associated with the various unit processes.

Due to regional and time variabilities in costs, it was essential to use local specific data relative to Fargo, ND, whenever possible. Costs of design, construction, statutory permits/authorizations, equipment, labor, utilities, and transportation were gathered from local data. Financial data which could not be collected locally were obtained through direct interviews and sectorial reports from the neighboring state for the LCC analysis. Furthermore, data that could not be found from both local and neighboring state sources were collected from existing literature related to the present study.

The LCI data for both the LCA and LCC and their respective references have been outlined in Table 2. The LCI model was developed with the Sustainable Minds LCA software, using Ecoinvent database v3.8 as a reference to model the process flows.

The Sustainable Minds LCA software works with the ISO LCA methodology. The first interface allows the user to define the LCA project. There is another tab that allows the user to specify the assessment goals. Furthermore, the assessment scope tab allows the user to specify the system boundary of the LCA model. The concept tab is where the user selects what LCA parameters is going to be used. For example, the user is able to select the version of Ecoinvent database to be used for the analysis. The next interface allows the user to input the LCI data with the various calculated input amounts. After feeding the model with these inputs, the user then clicks on results. The environmental impact results are then shown on a scorecard with the various impact categories. An interface of the LCA software is shown in the Figures 5, 6, 7, 8 & 9.



Project name: *

Comparing Landfilling and Recycling

Client or group:

Product category:

Construction, Mining & Materials Handling

Project description:

Description information can include:
- Project background info
- Product backround info
- Summarized design brief
- Ecodesign strategies to be explored.

There is no character limit on this or subsequent free text fields.

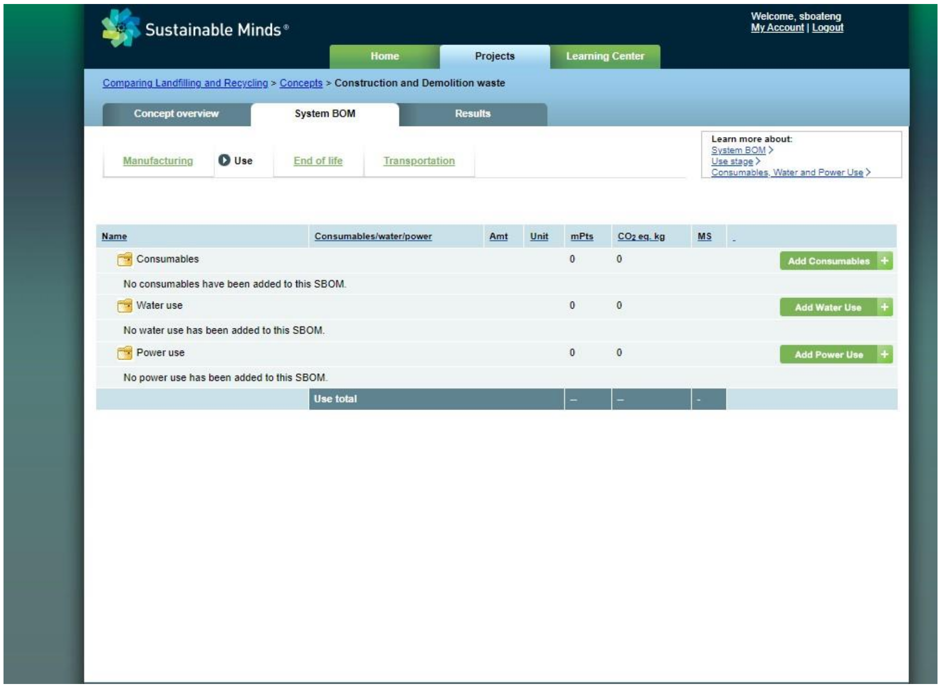
To compare the environmental impacts of landfilling and recycling

Describe your project in as much detail as you like.

While not much set up information is required to run an assessment, the information will be displayed on the front page (and will remain there for future reference) and included in reports. Providing project or background info and summarizing the design brief will be helpful to you and your team.

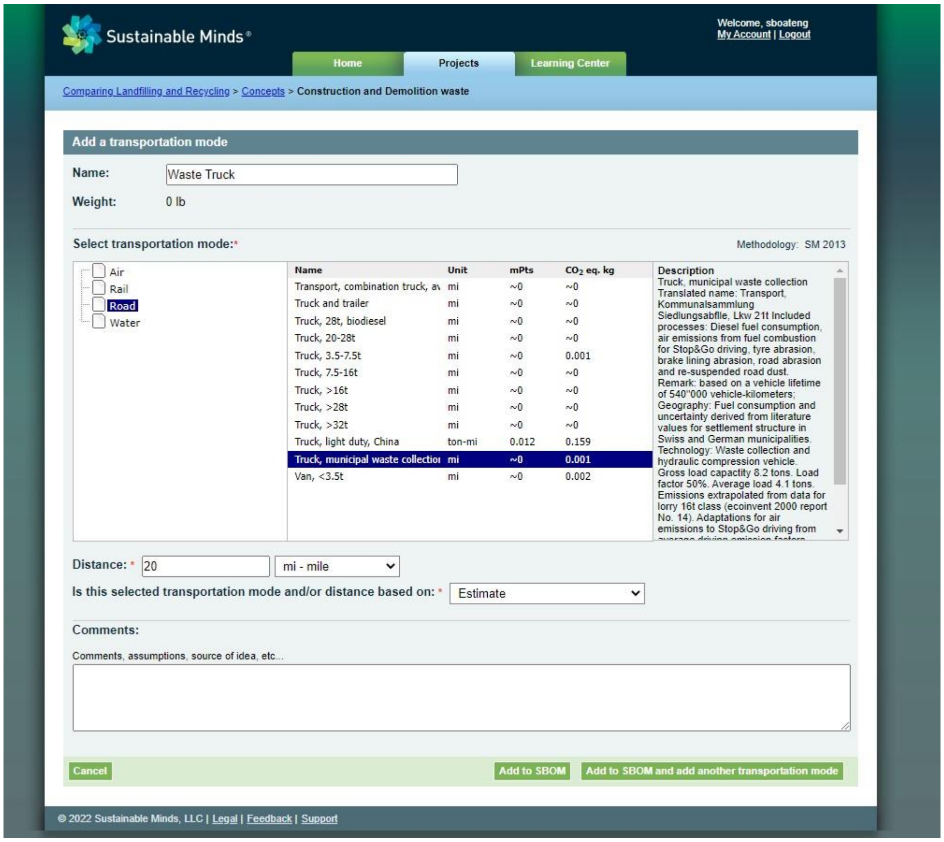
* Required

Figure 5. Interface of the LCA software, project scope tab



Name	Consumables/water/power	Amt	Unit	mPts	CO_2 eq. kg	MS
Consumables				0	0	
No consumables have been added to this SBOM.						
Water use				0	0	
No water use has been added to this SBOM.						
Power use				0	0	
No power use has been added to this SBOM.						
	Use total			–	–	-

Figure 6. Interface of the LCA software, inventory tab



Add a transportation mode

Name: Waste Truck

Weight: 0 lb

Select transportation mode:* Methodology: SM 2013

- ☐ Air
- ☐ Rail
- ☐ Road
- ☐ Water

Name	Unit	mPts	CO_2 eq. kg
Transport, combination truck, av	mi	~0	~0
Truck and trailer	mi	~0	~0
Truck, 28t, biodiesel	mi	~0	~0
Truck, 20-28t	mi	~0	~0
Truck, 3.5-7.5t	mi	~0	0.001
Truck, 7.5-16t	mi	~0	~0
Truck, >16t	mi	~0	~0
Truck, >28t	mi	~0	~0
Truck, >32t	mi	~0	~0
Truck, light duty, China	ton-mi	0.012	0.159
Truck, municipal waste collectio	mi	~0	0.001
Van, <3.5t	mi	~0	0.002

Description
Truck, municipal waste collection Translated name: Transport, Kommunalsammlung Siedlungsabflle, Lkw 21t Included processes: Diesel fuel consumption, air emissions from fuel combustion for Stop&Go driving, tyre abrasion, brake lining abrasion, road abrasion and re-suspended road dust. Remark: based on a vehicle lifetime of 540"000 vehicle-kilometers; Geography: Fuel consumption and uncertainty derived from literature values for settlement structure in Swiss and German municipalities. Technology: Waste collection and hydraulic compression vehicle. Gross load capacity 8.2 tons. Load factor 50%. Average load 4.1 tons. Emissions extrapolated from data for lorry 16t class (ecoinvent 2000 report No. 14). Adaptations for air emissions to Stop&Go driving from

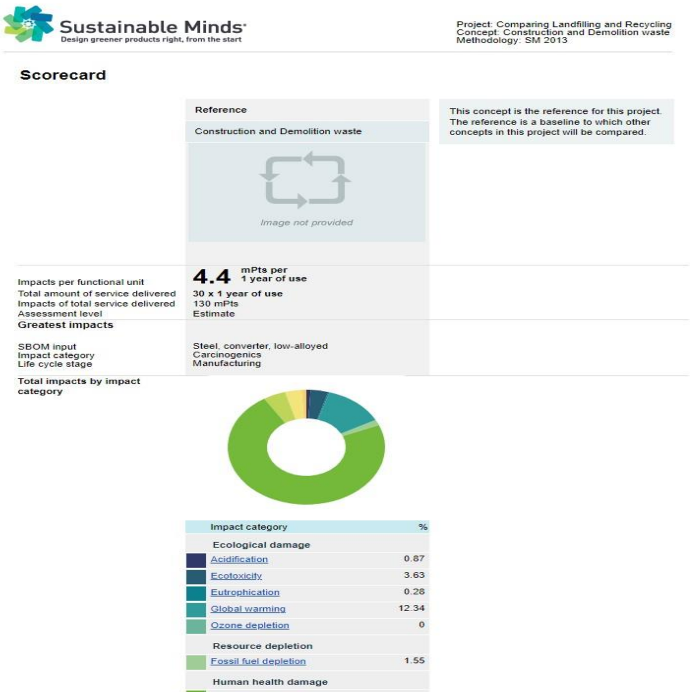
Distance:* 20 mi - mile

Is this selected transportation mode and/or distance based on:* Estimate

Comments:

Comments, assumptions, source of idea, etc...

Figure 7. LCA software showing LCI input options



Project: Comparing Landfilling and Recycling
Concept: Construction and Demolition waste
Methodology: SM 2013

Scorecard

Reference

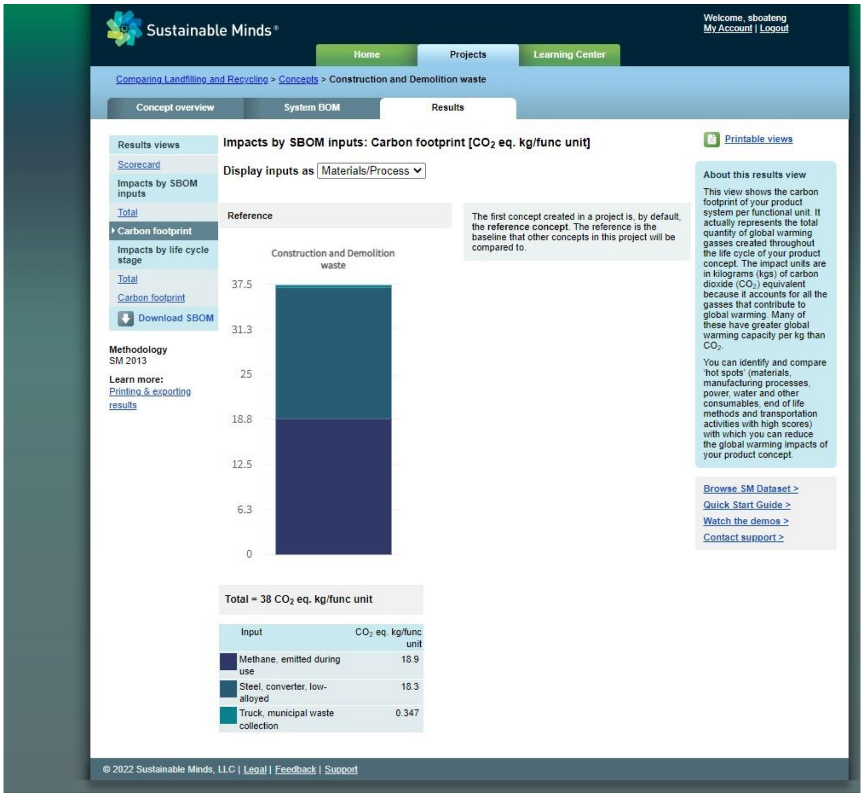
Construction and Demolition waste

This concept is the reference for this project. The reference is a baseline to which other concepts in this project will be compared.

Impacts per functional unit	4.4 mPts per 1 year of use
Total amount of service delivered	30 x 1 year of use
Impacts of total service delivered	130 mPts
Assessment level	Estimate
Greatest impacts	
SBOM input	Steel, converter, low-alloyed
Impact category	Carcinogenics
Life cycle stage	Manufacturing
Total impacts by impact category	

Impact category	%
Ecological damage	
Acidification	0.87
Ecotoxicity	3.63
Eutrophication	0.28
Global warming	12.34
Ozone depletion	0
Resource depletion	
Fossil fuel depletion	1.55
Human health damage	

Figure 8. LCA software showing environmental results



Impacts by SBOM inputs: Carbon footprint [CO_2 eq. kg/func unit]

Display inputs as: Materials/Process

The first concept created in a project is, by default, the **reference concept**. The reference is the baseline that other concepts in this project will be compared to.

About this results view

This view shows the carbon footprint of your product system per functional unit. It actually represents the total quantity of global warming gasses created throughout the life cycle of your product concept. The impact units are in kilograms (kgs) of carbon dioxide (CO_2) equivalent because it accounts for all the gasses that contribute to global warming. Many of these have greater global warming capacity per kg than CO_2.

You can identify and compare 'hot spots' (materials, manufacturing processes, power, water and other consumables, end of life methods and transportation activities with high scores) with which you can reduce the global warming impacts of your product concept.

Total = 38 CO_2 eq. kg/func unit

	Input	CO_2 eq. kg/func unit
■	Methane, emitted during use	18.9
■	Steel, converter, low-alloyed	18.3
■	Truck, municipal waste collection	0.347

Figure 9. LCA software showing unit processes impact contribution

3.5.3.1 Transport Distances

Transport distance for scenario 1 was calculated using the average distances of the farthest points in the city to the location of the landfill site. The same theory was used to develop transport distance to the proposed recycling facility. The average distances from the farthest points of the city to the industrial area were calculated. Transport distances for the hauling of recovered materials were assumed equal. Since the proposed facility is in the city's industrial area, the processing plants where recovered materials will be sent may be in close range. The impact of the transport distance assumptions will be assessed using sensitivity analysis.

3.5.4. Life Cycle Impact Assessment (LCIA)

This phase of the LCA involved evaluating the relevance of the potential environmental impacts associated with the two scenarios adopted for this study. Life cycle impact assessment

(LCIA) helps interpret LCA studies by translating these emissions and resource extractions into a limited number of environmental impact scores (Hauschild 2015).

The environmental impacts of this study were evaluated using the TRACI 2.1 method (Bare 2002). TRACI is one of the widely used LCIA methods for LCA studies in the USA. The impact categories reported in this method are region-specific and applicable to the study location. Normalization factors were also generated for all the impact categories. These factors were essential to accurately assess the weight of the various impact categories on the environment. A summary of the environmental input data used for the LCIA has been shown in Table 2.

Table 2. Summary of environmental input data

		Quantity	Unit	Notes	Source
Scenario 1					
Transportation to landfill		22	mi	Average distance from farthest point of the city to landfill site was used as assumption	Measurement
Digging of cell to keep CDW	Diesel (Dozer)	6.56	gal/ton	Fuel consumption for landfill equipment	City of Fargo landfill
Digging of cell to keep CDW	Diesel (Dozer)	6.56	gal/ton	Fuel consumption for landfill equipment	City of Fargo landfill
Scenario 2					
Transportation for recycling process		15	mi	The total transportation distance from facility to waste storage and back to the facility	Measurement
Sorting/Separation	Electricity	8.8	MJ/ton		Coelho and De Brito (2013a)
	Diesel	2	gal/ton		Di Maria et al. (2018)
	Water	12	gal/ton		Personal Communication with CDW Recycling Facilities
Crushing, Grinding & Screening	Electricity	2.2	MJ/ton		Coelho and De Brito (2013a)
	Water	5	gal/ton		
Transportation of rejected fragments to landfill		7	mi	Average distance from landfill to industrial area was calculated	Measurement
Avoided Natural Aggregates production	Concrete recycling	12,705	ton	Impact modelled with Ecoinvent database	
Transportation to site		5.2	mi	Assumption	

Table 2. Summary of environmental input data (continued)

		Quantity	Unit	Notes	Source
Scenario 2					
Avoided raw iron-ores mining	Waste metal recycling	495	ton	Impact modelled with Ecoinvent database	
Transportation to utilization site	Scrap iron	5.2	mi	Assumption	
Avoided virgin wood production	Waste wood recycling	1,065	ton	Impact modelled with Ecoinvent database	
Transportation to utilization site		5.2	mi	Assumption	
Avoided plastic production	Plastics	15	ton	Impact modelled with Ecoinvent database	
Transportation to utilization site		5.2	mi	Assumption	
Avoided gypsum production	Drywall	405	ton	Impact modelled with Ecoinvent database	
Transportation to utilization site		5.2	mi	Assumption	
Avoided production of gravel/sand	Bricks	315	ton	Impact modelled with Ecoinvent database	
Transportation to utilization site		5.2	mi	Assumption	

The environmental analysis results for recycling and landfilling are shown in Figure 10. The avoided impact is the environmental impact of producing materials recovered from recycling the CDW. Subtracting the recycling impact from the avoided impact will produce a negative environmental impact representing an environmental gain. Hence, recycling proved a better alternative in all the impact categories considered in the LCIA.

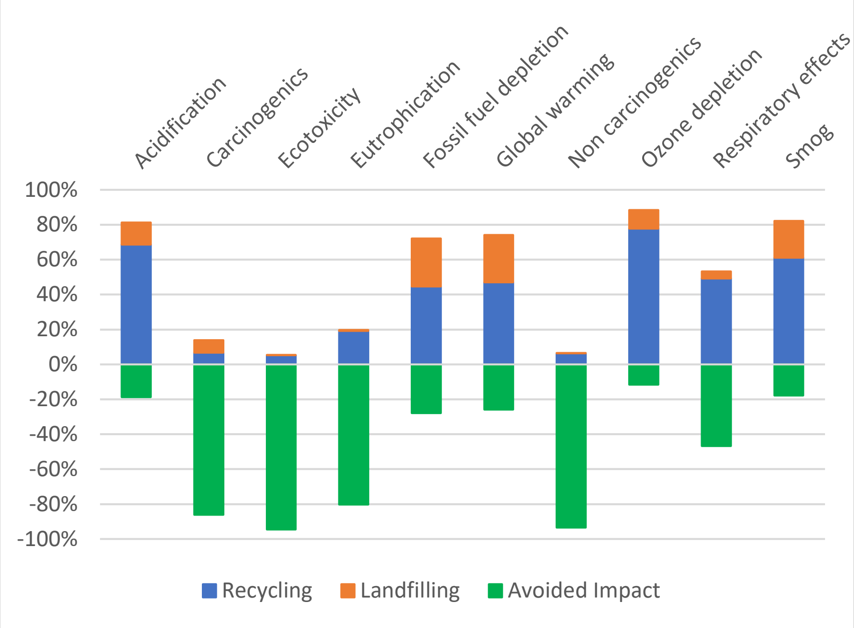


Figure 10. Environmental LCIA results

Figure 11 shows the normalized results for recycling and landfilling. Recycling showed substantial environmental impacts when the LCIA results were normalized. However, due to the gains made from recovering materials that otherwise would have been reproduced as raw materials, recycling presented higher net environmental gains than landfilling.

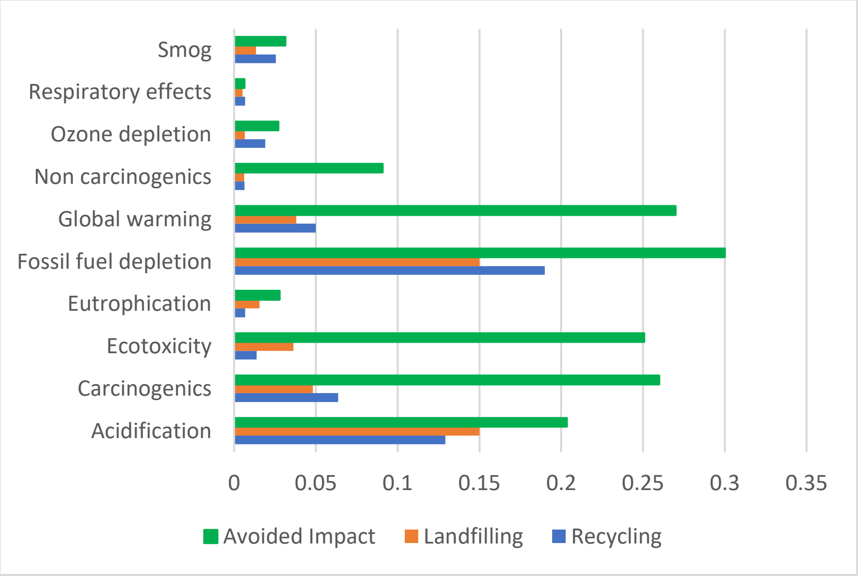


Figure 11. Normalized environmental LCIA results

The transportation results presented a higher environmental impact for recycling, which was due to the inclusion of transport distances involved in taking recovered materials to the points of substitution, where these materials are reused. Hence, strategic considerations must be made to reduce transportation distances as much as possible because of the high environmental impact involved. Figure 12 shows the normalized transportation impacts for both scenarios.

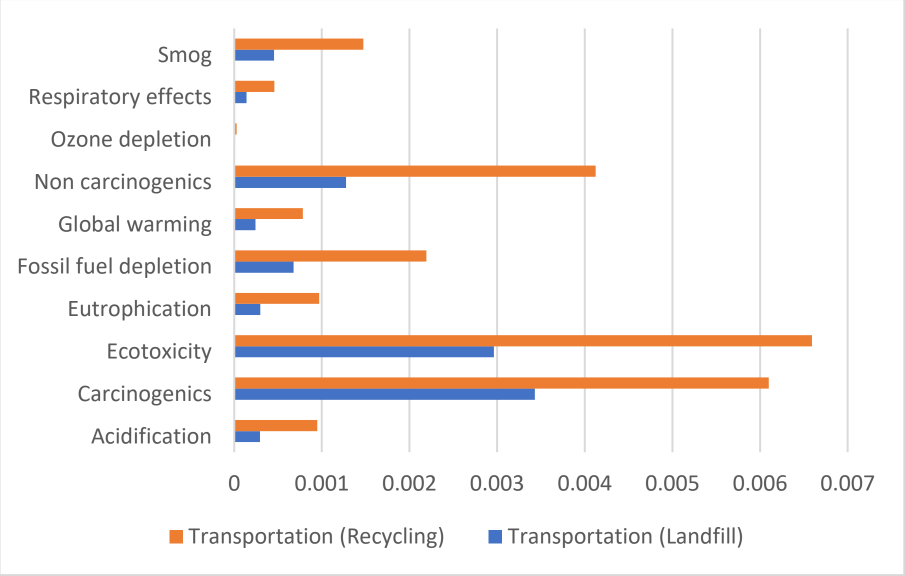


Figure 12. Normalized transportation impacts for scenarios 1&2

3.6. Life Cycle Cost Analysis (LCCA)

The LCC analysis involved the calculation of revenues and operational costs for both scenarios. For scenario 1, revenue is generated from gate fees collected before CDW is received at the landfill. Additionally, operational costs involve labor, purchase, and maintenance costs for excavators and dozers used for landfill operations. The cost of the dump truck and its maintenance was not considered in the analysis for scenario one since CDW generators bear that cost.

For scenario 2, calculations were made for the capital and operational expenditure required to set up and operate the facility. Revenue is generated from charging waste handling fees which are lower compared to what CDW generators will spend if they are to collect and haul the waste themselves. Furthermore, revenue is generated when the recovered materials are sold to the end market. A detailed calculation was done for the various cost components contained in the capital and operational costs (see Figure 4). Cost values were generated relying on local data from RS Means, CDW recyclers, the city’s waste management authorities, local equipment suppliers, etc. The summary of the economic input data has been shown in Table 3.

Table 3. Summary of economic input data

	Quantity	Unit	Notes	Source
Scenario 1				
Landfill Gate Fee	46	$/ton	Landfill disposal cost (2022)	City of Fargo landfill
Cost per hour of labor	30	$/hr	Hourly wage for a landfill supervisor in Fargo	City of Fargo landfill
Cost per hour for landfill manager	34	$/hr	Hourly wage for landfill manager at the Fargo landfill	City of Fargo landfill
Cost per hour for excavator/dozer operator	30	$/hr	Hourly wage for excavator operator at the Fargo landfill	City of Fargo landfill
Cost of excavator	200,000	$/unit		Local equipment suppliers
Cost of a Dozer	175,000	$/unit		Local equipment suppliers
Diesel cost	3.90	$/gal		Local data on fuel
Excavator maintenance cost (incl. insurance)	23.46	$/hr		Local equipment suppliers
Scenario 2				
Cost of design and construction (incl. equipment installation)	6,953,771.00	$/facility	Fees for design and construction of the 17,500 sq. ft recycling facility	City of Fargo RS Means Data US EPA
Work hours per year (240d/4h)	960	hr/yr	Assumption	
No. of workers	5	personnel		Coelho and De Brito (2013a)
Utilities cost	46,724.74	$/yr		Fargo electricity rate
Labor cost	125,904.00	$/yr		Bureau of labor statistics (BLS)
Disposal cost	230,000.00	$/yr		Fargo landfill
Equipment maintenance cost	276,106.96	$/yr		Local data from equipment suppliers
Administrative cost	10,472.39	$/yr		Bureau of labor statistics (BLS)

Table 3. Summary of economic input data (continued)

	Quantity	Unit	Notes	Source
Scenario 2				
Recycling fee at facility	110	$/ton	Fees charged by facility to collect and handle waste	Data obtained from direct communication with commercial recyclers
Price of recycled aggregates	2.40	$/ton	Selling price of recycled aggregates	
Price of recycled metals	120	$/ton	Selling price of mixed scrap metals	Direct communication with commercial recyclers
Price of recycled wood	25	$/ton	Selling price of recycled wood	
Price of recycled plastics	12	$/ton	Selling price of recycled plastic	
Price of recycled drywall (gypsum)	5	$/ton	Selling price of gypsum powder	
Price of recycled bricks	9	$/ton	Selling price of filling material	

The equations below were used for the LCC analysis as defined by Martinez-Sanchez et al. (2015).

$$\text{LCC} = \text{capital cost} + \text{operational cost} \tag{1}$$

$$\text{Profit}_n = \text{operational cost}_n - \text{revenue}_n \tag{2}$$

n = the particular year under review. For example, n =1 for year 1 analysis

Initial investment capital is required to cover the construction and equipment installation costs. Per the initial capital cost calculations, a loan facility of $8 million will be required to set up the recycling facility. The payback period for the initial capital investment was calculated using the methodology outlined by Di Maria et al. (2018). The interest rate used was 6%, the average bank loan prevailing interest rate in the study location. This rate was obtained through direct communication with local banks. The payback calculation formula is shown in equation 3.

$$\text{Payback period} = \frac{Initial\ Investment}{Cash\ Flow\ per\ year} \tag{3}$$

Figure 13 shows the LCC results for recycling and landfilling. It is seen that recycling requires more expenditure for its operations compared to landfilling. However, the revenue is double that of recycling, resulting in profits that are more than thrice what can be gained in landfilling. In the economic analysis, the profits generated from recycling was used to offset the loan facility.

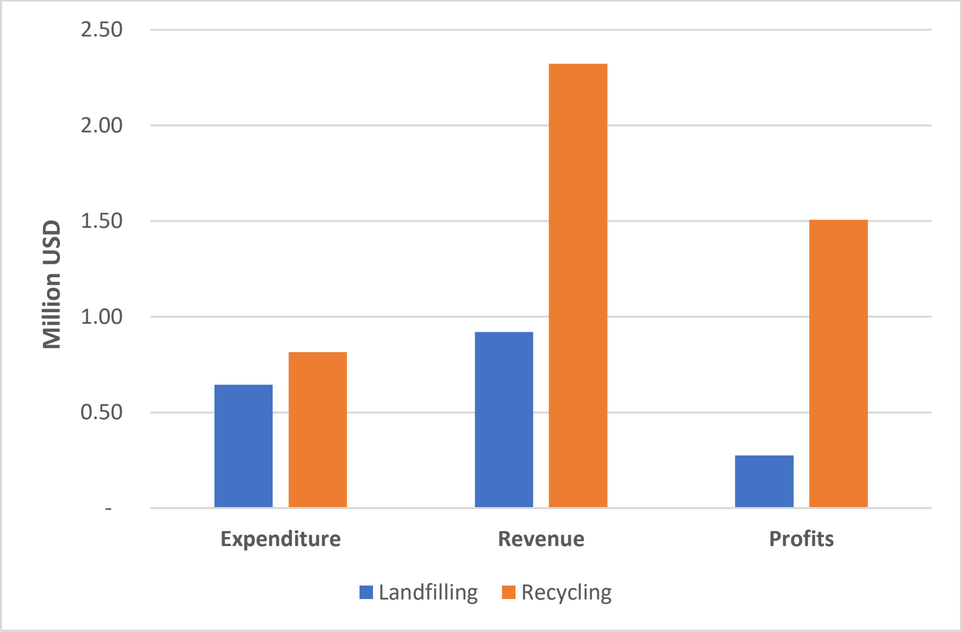


Figure 13. LCC results for scenarios 1 & 2

3.7. LCA and LCC Sensitivity Analysis

It is likely that both the LCA and LCC, due to the assumptions applied, are affected by uncertainties. These uncertainties are mostly related to the data input differences in building the

LCI. Furthermore, specific regional data may not reflect exact scenarios relative to the study location. It is essential to know how altering an assumption affects interpretation or conclusion.

One way to ensure the accuracy and validity of the LCA and LCC results is to conduct a sensitivity analysis. Sensitivity analysis (SA) is a methodology to assess the influence of input changes on the model's results (Di Maria et al. 2018). Sensitivity analysis is performed for LCA and LCC to assess the impact of distinct input parameters on the LCA and LCC results.

This study adopted perturbation analysis for the SA as described by Clavreul et al. (2012). Initially, the impact of the random change in one parameter is analyzed while maintaining all other parameters. The sensitivity ratios (SR) were calculated for both scenarios. The SR is defined as the ratio between the two relative changes:

$$\text{SR} = \frac{\frac{change\ in\ result}{initial\ result}}{\frac{Change\ in\ parameter}{initial\ parameter}} \tag{4}$$

Three simplified SA are performed for both scenarios. Different transport distances, gate fees, recycling rates, and the cost of recycled materials are modeled to analyze how these will affect the results. Analysis of gate fees, recycling rate, and cost of recycled materials are performed to ascertain how these can impact the return on investment (RoI) of establishing the recycling facility.

CHAPTER 4. DATA ANALYSIS AND INTERPRETATION

4.1. Environmental Impacts

The environmental LCIA results are reported based on both scenarios' potential impacts on ten impact categories as recognized by the US EPA. The processes contributing to the total impact in both scenarios have been outlined as the costs associated with diesel consumption, electricity consumption, and transportation. The impact of recovered materials was calculated as avoided burden since these materials are used to replace raw materials production. The breakdown of the contribution of the various unit processes to the LCA results is shown in Table 4.

Table 4. Unit process contribution to LCA results

Process	Description	Scenario 1	Scenario 2
Digging of cells for waste storage	Diesel used to power equipment	47.3%	
Sorting/Separation	Electricity consumption		10.40%
	Diesel consumption		5.90%
Crushing/Grinding	Electricity Consumption		7.70%
Transportation			
CDW to landfill	Haulage of waste to landfill	52.7%	
CDW to recycling	Haulage of waste from storage to facility		57.1%
Recovered materials to market	Haulage of recovered materials to recycling market		18.9%
Total		100%	100%

The LCIA results presented scenario 2 (recycling) as the waste management practice with the higher environmental burden, based on the overall environmental burden released by both waste management practices. It is seen from the results that recycling has a substantial environmental impact in most of the impact categories due to the nature of the recycling activity. Ideally, the environmental burden of landfilling results from the inability to reuse materials.

However, in this study landfilling showed some slightly high environmental impacts in some of the impact categories and this was due to the landfill practice at the City of Fargo landfill. The avoided impact shown in the LCA results is the impact of virgin material production that is avoided by the use of recycled material. What it means is that when recycling is the adopted CDW management practice, the “avoided impact” is an environmental gain but when landfilling is adopted, the “avoided impact” becomes an environmental burden. This phenomenon explains the substantial environmental benefits of recycling over landfilling.

4.1.1. Environmental Sensitivity Results

The environmental sensitivity analysis was performed using perturbation analysis. A random variation of ±20% was generated for the relevant parameters. The results of this analysis have been presented in Table 5. For scenario 1, the variation of 20% of transport resulted in a 10.5% on the total results.

Table 5. Perturbation analysis for variation ±20%

Process	Description	Scenario 1	Scenario 2
Digging of cells for waste storage	Diesel used to power equipment	±9.5%	
Sorting/Separation	Electricity consumption		±2.1%
	Diesel consumption		±1.2%
Crushing/Grinding	Electricity Consumption		±1.5%
Transportation			
CDW to landfill	Haulage of waste to landfill	±10.5%	
CDW to recycling	Haulage of waste from storage to facility		±11.4%
Recovered materials to market	Haulage of recovered materials to recycling market		±3.8%

For scenario 2, the transportation of waste to the facility has a higher effect on the result giving 7.6% more than the impact of transporting recovered materials. Even with the higher effect of the variations on transport for scenario 2, diesel consumption in scenario 1 has a relatively high impact on the result in scenario 1. The impacts of the variations are represented in Figure 14 for each unit process, where assumptions were made for the presented LCA study.

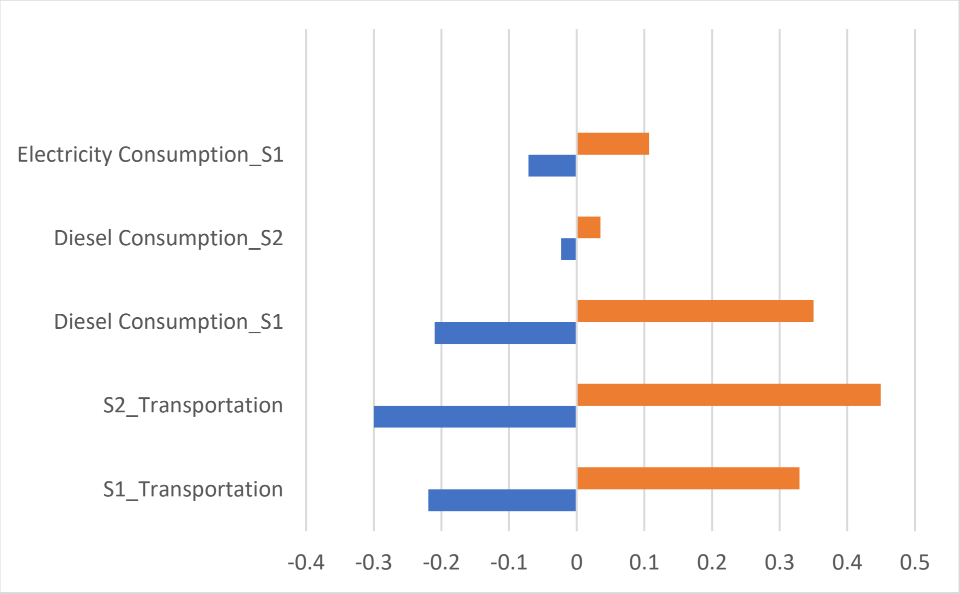


Figure 14. LCA sensitivity analysis (±20%)

It can be noted how variations in transport have the highest impact on all the unit processes, followed by the variation in diesel consumption. For example, the SR value observed for the transport distance in scenario 2 was 0.450. A variation of 15% in recycling transport distance changes the scenario result by 6.75%. Hence, it can be concluded that the environmental impact results are more sensitive to the variation of transport distances. Therefore, the optimum location of the recycling facility is essential to guarantee an increase in environmental savings.

4.2. Economic Results

The LCC results showed the operational expenditure, revenue, and profit for one year of operation in both scenarios. Scenario 2 showed a revenue generation that was 43% higher than scenario 1. Scenario 1 presents a profit of $13.74/ton of CDW, while scenario 2 was $75.32/ton. A significant amount of the profit in scenario 2 is due to the fees charged by the facility to collect and haul waste and the fees charged for selling recovered materials. The only source of revenue generation for scenario 1 was the gate fees charged at the landfill. Looking at the operational expenditure and revenue generated, scenario 2 presented a profit margin that is 500% greater than scenario 1. Therefore, reducing revenue in scenario 2 by half still presents recycling as a better option than landfilling.

The profit from recycling is used to offset the initial capital investment. Figure 15 presents a payback analysis showing how the profits are used to offset the capital investment required for setting up the recycling facility. Figure 15 shows that the loan of $8 million, assuming a consistent revenue generation, can be paid off at the end of year 8.

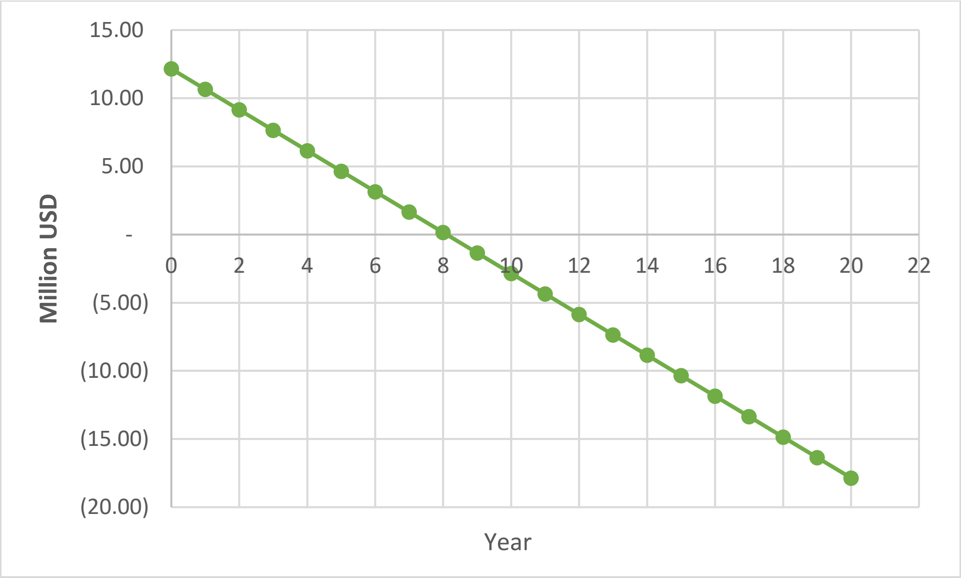


Figure 15. Payback analysis of capital investment for scenario 2

4.2.1. Economic Sensitivity Analysis

The economic sensitivity analysis focuses on three main aspects: (i) identifying how the variation of waste handling fees and recycling rate affect the profit margins of the recycling facility, (ii) identifying how operational expenditure affects profit margins, and (iii) to identify how the revenue generation parameters can change the payback time of the capital investment. The initial capital investment was not considered for the sensitivity analysis since most cost parameters are fixed and would not change over time. For instance, a change in design or construction fees does not affect the required capital investment once the facility is built.

Since the recycling and waste handling module is a new phenomenon in the study location, it could be unpredictable to consumer acceptance. Therefore, it is essential to iterate situations where fees charged are less than $110/ton, the base fee used for the LCC analysis. Furthermore, the 75% recycling rate impacts the number of materials recovered and how much gate fees will be paid to dispose of rejected fragments. Sensitivity analysis was only performed for scenario 2 since all parameters and information used for the LCC in scenario 1 reflected the current practices at the city’s landfill.

Perturbation analysis is used to evaluate how the gate fees, recycling rate, and operational expenditure affect the economic viability of CDW recycling. This analysis can provide helpful information for investors and policymakers. A variation of ±20% was generated for the parameters to evaluate the impact of varying gate fees, recycling rate, and operational expenditure on the profitability of the recycling plant. The results of the perturbation analysis were used to calculate the various payback times associated with both variations (±20%), as shown in Figure 16 and Figure 17.

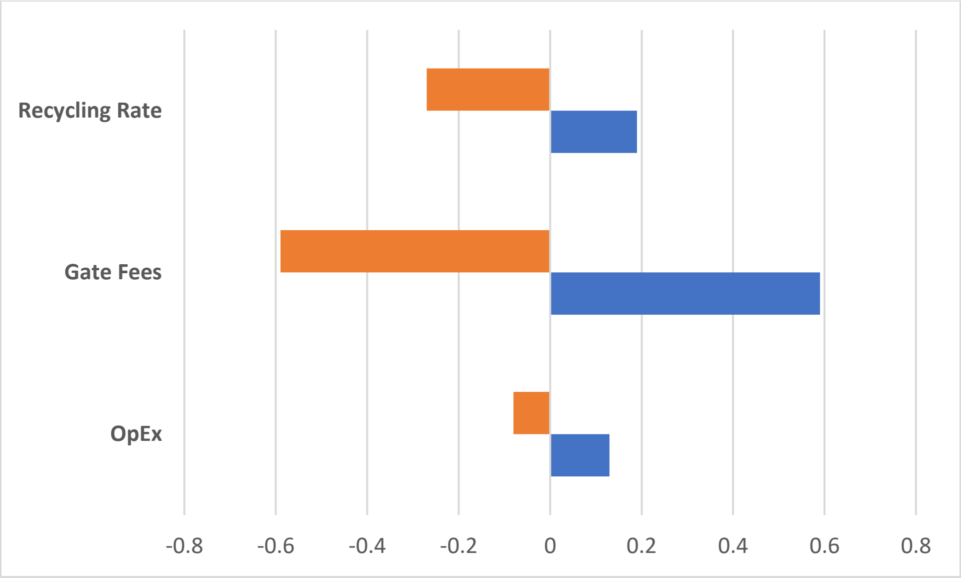


Figure 16. LCC sensitivity analysis (±20%)

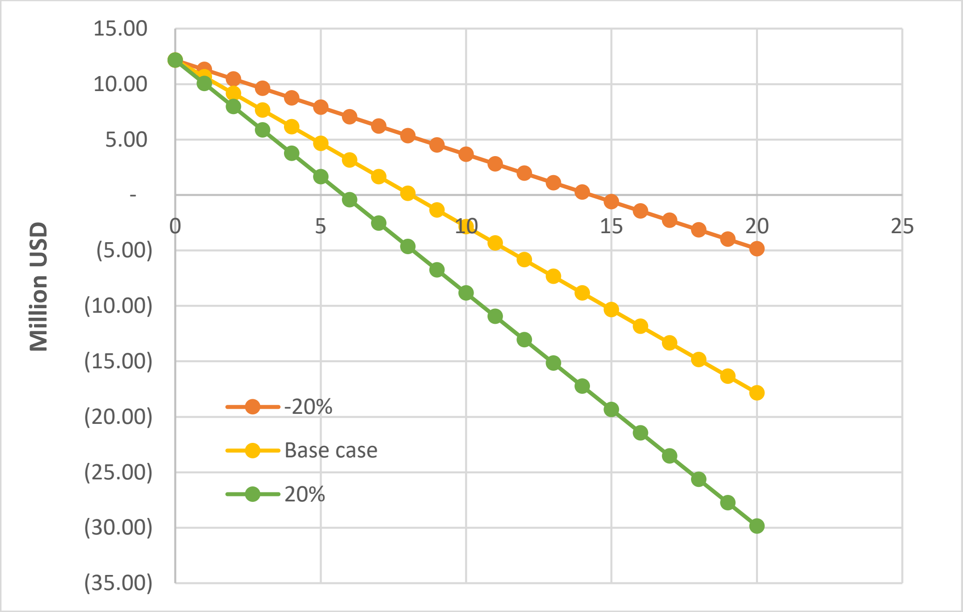


Figure 17. Payback time in response to ±20% variation

The sensitivity analysis showed that the gate fees were the most sensitive parameter to the viability of the recycling plant, almost double the ratio of recycling rate and operational expenditure. It can be noted from Figure 16 that the sensitivity ratio for gate fees was 0.590. By that, a 10% variation of the fees collected to handle the recycling rate can affect the profitability of recycling CDW.

4.3. Discussions

The combination of LCA and LCC helps policymakers to make informed decisions. The LCA results provide information on the impact of landfilling and recycling on a mid-sized city. Several studies (Zhao et al. 2010; Coelho and De Brito 2013a; Rosado et al. 2019; Di Maria et al. 2018) have looked at LCA/LCC for landfilling and recycling CDW. However, generation rates of CDW used for these studies are usually higher than those of a mid-sized city. Therefore, it was essential to ascertain how these methodologies can be used for mid-sized cities with low generation rates.

The LCA showed that regardless of the generation rate of CDW in a mid-sized city, recycling still proves a better option for landfilling. The study also showed that current landfill practices at the study location produce an excessive burden on the environment through the high usage of diesel for landfill operations. Recycling releases specific environmental impacts due to the process of separating comingled CDW. However, the recovery of materials that replaces raw materials showed a high environmental gain (avoided impact).

Again, the LCA results showed that encouraging selective demolition, can produce a low environmental impact by reducing energy consumption involved in separating the comingled CDW. Furthermore, materials obtained from selective demolition can be used for other construction purposes rather than downcycled, as Di Maria et al. (2018) indicated. Additionally, as Rigamonti et al. (2009) mentioned, it is almost impossible to have a 1:1 substitution rate for recycled materials, mainly when the CDW are obtained through uncontrolled demolition. Therefore, mid-size cities must encourage selective demolition at the various construction sites.

The LCA results were more sensitive to transportation distance variations. However, considering the net environmental gains generated from reusing recovered materials, a substantial environmental benefit is still achieved. Furthermore, the sensitivity of the LCA results to lower electricity consumption variations shows the need to encourage recycling in mid-sized cities, where generation rates are low. Low generation rates mean fewer operation hours at the recycling facility, thereby reducing the environmental impact of excessive energy consumption.

The LCC reveals the importance of collecting CDW directly from waste generators. Previous studies (Coelho and De Brito 2013a; Di Maria et al. 2018) recommend increasing landfill taxes to encourage recycling. However, this study revealed that taking the responsibility to collect, haul and handle CDW directly from generators has vast economic benefits. While gate fees were the primary revenue source for the recycling plant, care must be taken to ensure these fees are competitive with fees charged at the landfill.

For the presented study, the analysis was based on setting a lower fee than the anticipated cost borne by CDW generators in terms of labor and equipment to collect and haul waste to the landfill. Variation of the gate fees at the recycling plant had a significant impact on the profitability of the recycling facility, as it increased the payback period of the initial investment required to establish the facility. Therefore, a recycling facility in the study location cannot charge gate fees lower than \$100/ton, reducing the viability of recycling. Charging \$100/ton is lower than the cost CDW generators bear to dispose of waste, making the rate utilized in this study a competitive option for recycling facilities in mid-sized cities. Reusing recovered materials was not crucial in the LCC as was in the LCA due to how minimally sensitive variation of recovered materials sale was to the revenue generation. Therefore, without achieving a substitution rate of 1:1, recycling still proved profitable.

This study aligns with existing LCA and LCC studies on the benefits of recycling CDW. The LCA results are consistent with previous studies (Zhao et al. 2010; Coelho and De Brito 2013; Rosado et al. 2019; Di Maria et al. 2018). Although the present study is distinct in terms of the amount of CDW generation rate, transportation distances affected the LCA results as in the case of the previous LCA studies.

This study presents a strategy that encourages recycling without the need to increase landfill taxes, as mentioned by similar studies. In economic terms, the recycling of CDW is still viable. However, the payback time calculated for this study differs from that of existing studies. The payback time for this study was eight years. Previous studies reported two years (Coelho and De Brito 2013) and 11.5 years (Di Maria et al. 2018). This could be due to the economic variabilities existing in different geographic locations. The findings show how LCA and LCC studies can depend on local and regional conditions, markets and data. This phenomenon should encourage more region or locally based studies using locally acquired data and practices peculiar to those locations.

It is essential to mention the limitation of the current study. Most of the data used for this study was locally acquired and dependent on local practices and market conditions, which may not necessarily reflect those in other mid-sized cities. There is a significant lack of data on the composition of CDW materials in many areas in the United States. This study relied on information provided by US EPA, waste sector managers, CDW recycling companies, construction companies, and existing literature. Therefore, implementation of portions of this study must be carefully considered due to the differences in practices and principles.

CHAPTER 5. CONCLUSION AND RECOMMENDATIONS

5.1. Introduction

This study evaluated the environmental and economic benefits of two CDW management scenarios in Fargo, ND. In this chapter, the conclusions and recommendations of the study have been presented and discussed. This has been done taking into consideration the study's objectives. The specific objectives for the study have been outlined below.

i. To assess current CDW management practices in Fargo, North Dakota.
ii. To investigate the factors influencing the City's decision to opt for a particular method of CDW management.
iii. To investigate CDW management practices in other jurisdictions that share boundaries with North Dakota.
iv. To investigate the environmental impacts of landfilling and recycling in the context of Fargo, North Dakota.
v. To investigate the economic impact of landfilling and recycling in the context of Fargo, North Dakota.

5.2. Conclusions

The conclusions drawn from this study is based on the empirical and theoretical findings of every objective outlined. Hence, the conclusion has been explained below and is indicative of achieving the objectives.

5.2.1. Objective 1

The first objective targeted to understand the prevailing CDW management practices in Fargo, ND. It was concluded that the city generates 20,000 tons of CDW per year. All generated

CDW ends up at the landfill site. The waste that ends up in the landfill is not recycled. Cells are dug in which these wastes are kept.

5.2.2. Objective 2

The second research objective was to identify factors influencing the City’s decision to opt for a particular method of CDW management. The study found that the City’s decision to opt for landfilling practice is due to the availability of low-cost land space to keep CDW. Furthermore, the city landfill managers consider CDW as inert and do not believe it is harmful to the environment. In fact, the interviews revealed that municipal solid waste is hauled to neighboring cities to be recycled but same is not done for CDW.

5.2.3. Objective 3

The third objective was targeted at investigating CDW management practices in other jurisdictions that share boundaries with North Dakota. It was concluded that recycling CDW are at its advanced stages in jurisdictions sharing boundary with Fargo, ND. In fact, there are several private entities that have established recycling facilities. As a result, there are minimal amount of CDW that ends up at landfill sites.

5.2.4. Objective 4

The fourth objective was to investigate the environmental impacts of landfilling and recycling in the context of Fargo, North Dakota. The study concluded that when CDW is recycled, there are many environmental gains rather than ending at a landfill. Different recycling strategies based on site-specific conditions and data are required to make recycling CDW viable. Policymakers need to know the monetary and environmental losses associated with the traditional practices of landfilling CDW. This study combined LCA and LCC to compare two CDW management scenarios: (i) landfilling CDW and (ii) recycling CDW.

Recycling offers higher environmental benefits than landfilling. The current landfill practices at the study location present an excessive environmental burden. The burden can be reduced if the size of CDW sent to the landfill can be reduced. A 75% reduction in the CDW sent to the landfill can reduce the environmental burden by 35%. Furthermore, replacing raw materials with recycled materials creates net environmental savings by preventing the production of raw or virgin materials. This practice can reduce the environmental burden by 25%.

5.2.5. Objective 5

The last objective was to investigate the economic impact of landfilling and recycling in the context of Fargo, North Dakota. The study concluded that the economic return on recycling is remarkable if the right strategies that suit the peculiarity of the location are employed. Recycling CDW provided a profit margin of $61 higher than landfilling for every ton of CDW managed. Therefore, every ton of CDW landfilled is $61, equivalent to a $61 loss. Gate fees charged at the recycling facility are critical to the recycling facility's viability. Without imposing high landfill taxes, recycling can still be encouraged by charging competitive fees relative to the cost borne by CDW generators to dispose of the waste at the landfill. The present study analysis presented a payback period of 8 years for the initial investment cost.

The sensitivity analysis showed how transport distances and gate fees charged at recycling facilities directly influence environmental and economic benefits. Siting of recycling facilities must be strategic to reduce transport distances. The facility should be sited close to an existing landfill or close to locations in high demand for recycled materials. A reduction in each instance goes a long way to reduce the environmental burden presented by transportation distances. The recycling gate fee is the highest source of revenue generation. It must be competitive with the cost incurred by CDW generators to dispose of the waste themselves.

Finally, this study demonstrated that regardless of the generation rate of CDW, practical strategies can be implemented. These strategies can help achieve the economic benefits of recycling while reducing the excessive environmental burden presented by landfill activities.

5.3. General Conclusions

The main aim of the study was to evaluate the environmental and economic benefits of two CDW management practices. The present study achieved its objectives through interviews and applying LCA and LCC to compare the benefits of landfilling and recycling. The following conclusions have been drawn from the study.

i. There is a pressing need for Fargo, ND to adopt recycling as the main CDW management practice due to the environmental and economic losses the current practice is posing to the city.
ii. The city needs to adopt the strategy of collecting, hauling and handling CDW. This will provide substantial financial gains to the city.

5.4. Limitations of the Study

This study was limited by the non-availability of site specific CDW material data. The study relied on generic data from US EPA. In LCA studies, site specific data is necessary to build region specific LCI data.

5.5. Recommendations

The findings of this study pointed out that there are potential environmental and economic gains from adopting recycling as the main CDW management practice. As a result, the following recommendations have been made to the city's waste management representatives.

i. Increase landfill fees to encourage on site CDW sorting by waste generators.

5.6. Recommendations for Future Studies

The outlined recommendations are made for future research:

i. Further studies can set out to build site specific data on CDW material composition.

ii. Further studies can be conducted to assess CDW generators willingness to pay (WTP) for waste generated to be collected and hauled by the city.

iii. Further studies can be conducted into how to improve the strength properties of recycled CDW materials. The demand for recycled CDW materials is one major factor that will make the practice accepted. Therefore, if recycled CDW materials show similar or better strength properties than raw materials, it will increase demand thereby enhancing the profitability of recycling.

iv. Further studies can be conducted to assess the chemical content of soil at the landfill site to determine the amount of hazardous waste been sent to the landfill site. This provides a strong basis for the city to continue with landfilling or review its CDW management practices.

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APPENDIX A. SUPPLEMENTARY TABLES FOR LCA ANALYSIS

Process in the study	Ecoinvent module
Scenario 1	
Landfill	Treatment of inert waste, inert material landfill
Diesel for landfill equipment	Diesel, burned in building machine
Transport	Truck, municipal waste collection
Scenario 2	
Energy in CDW for recycling plant	Market for electricity, high voltage (BE)
Water use at recycling plant	Tap water, at user
Diesel for recycling equipment	Diesel, burned in building machine
Diesel for landfilling equipment	Diesel, burned in building machine
Recovered Metals (avoided)	Iron ore beneficiation to 65% Fe
Recovered wood	Hardwood forestry, mixed species, sustainable forest management
Recovered plastics	Plastics manufacturing
Recovered gypsum	Gypsum plasterboard, at plant
Recovered bricks	Sand, at mine
Recovered concrete aggregates	Gravel production, crushed
Transport	Truck, municipal waste collection

APPENDIX B. SUPPLEMENTARY TABLES FOR LCC ANALYSIS

Table B.1. Capital cost for the recycling facility

Initial Capital Cost	Cost per unit	Amount ($)
Land acquisition	N/A	319,248.00
Design fees	$8.04/sf	140,700.00
Building cost	$91.88/sf	1,607,900.00
Construction fees	$22.97/sf	401,975.00
Equipment cost	N/A	4,601,783.00
Authorizations	N/A	44,963.00

Table B.2. Equipment selected for the recycling operation

Equipment	Quantity	Cost per unit ($)	Amount ($)
Excavator	1	160,000	160,000
Roll off truck	3	169,000	507,000
Dumpster	6	460	2,760
Scales	1	22,600	22,600
Conveyor belt 5m	1	40,520	134,205
Conveyor belt 10m	1	81,050	81,050
Conveyor belt 15m	1	121,550	121,550
Vibrating feeder	1	134,205	134,205
Manual separation cabinet	1	8,550	8,550
Crusher	1	153,050	153,050
Magnet	1	55,950	55,950
Air sifters	2	117,723	235,446
Eddy current generator	1	115,500	115,500
Spirals	3	59,100	177,300
Horizontal screens	2	96,810	193,620
Air jig	3	810,330	2,430,990

Table B.3. Cost projections for utilities

Utility	Quantity of use per month	Rate (USD)	Amount per Month ($)	Amount for 1 year of operation ($)
Electricity	6740 kWh	$0.0802/kWh	540.55	6,486.6
Fuel (Diesel)	862 gallons	$3.89/gallon	3,353.18	40,238.16

Table B.4. Labor costs

Personnel	Wages ($/hr)	Annual Salary ($)	No. of workers	Total Amount ($)
Plant manager	n/a	90,000.00	1	90,000.00
Non-Skilled Workers	18.7	43084.80	2	17,952.00
Drivers	18.7	43084.80	2	17,952.00