A BIM-based Object-oriented Data Model to Support Sustainable Demolition Waste Management Decision Making at End-of-Life

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Dissertation submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

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April 29, 2015

Blacksburg, VA

Keywords: End-of-life, Sustainable Demolition Waste Management, BIM, Object-oriented Data Modeling

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ABSTRACT

Sustainable demolition waste management is rarely practiced within the construction industry. This is mainly due to the fact that the decision-making process for sustainable demolition waste management is a very resource-demanding and time-consuming task in terms of *data collection* and *data management*. The decision-making process includes multiple analyses of possible demolition waste management alternatives from *economic, environmental*, and *social perspectives*. Such analyses require waste managers to capture and manage huge amounts of data scattered within fragmented data sources at the end-of-life of a building. The process of capturing and managing this information for the building end-of-life would be time-consuming and costly. Therefore, the waste managers are reluctant to pursue sustainable demolition waste management practices in order to prevent potential delays and incurred costs.

This research identified information that is required to conduct sustainable demolition waste management analyses. The identified information was then classified based on information sources. An object-oriented data model (OODM) was proposed to allow the waste managers to more efficiently store and manage the information at the end-of-life phase. Furthermore, a sustainable demolition waste management prototype application was developed to demonstrate how the required information is captured from different sources of data, stored within OODM classes, and retrieved from the integrated database. Finally, the proposed OODM was verified in terms of its scope, flexibility, and implementability.

The goal of the research is to offer a *method for storing and managing end-of-life information in an efficient and effective manner to support sustainable demolition waste management decision making*. To achieve the goal, this dissertation outlines the objectives of the research, the methodologies used in developing the object-oriented data model, conclusions, limitations, and potential future research work.

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DEFINITIONS OF KEY TERMS

Definitions of relevant terms as each pertains to this research are as follows:

Construction & Demolition (C&D) Waste is defined as the waste generated as the result of building new structures and demolishing or renovating existing structures (EPA, 2009).

Building-related (C&D) Waste is generated when new buildings are built and when existing buildings are demolished or renovated (EPA, 2009).

Waste Manager: In the context of this research, the waste manager is an entity who is responsible to manage the generated C&D waste. The waste manager can be the owner of a given building or a third party who is hired by the owner (e.g., demolition contractor).

Waste Management Scenarios are waste management strategies defined by the U.S. Environmental Protection Agency (EPA). These strategies include waste reduction, reuse, recycling, energy recovery, and disposal (EPA, 2013).

End-of-Life Operations consist of all activities to demolish and renovate existing buildings as well as activities to manage the generated waste.

Sustainable C&D Waste Management is defined as a practice, which considers all three pillars of sustainable development when managing C&D waste. These three pillars include economic analysis, environmental assessment, and social analysis.

Inert Waste Vs Non-inert Waste: The generated waste is defined in two general categories including inert waste and non-inert waste. Inert waste refers to materials that are nonhazardous and are not regulated under the U.S. Environmental Protection Agency (EPA) (e.g., concrete). On the other hand, non-inert waste consists of materials that are either hazardous (e.g., lead-based paint materials) or have the potential to become hazardous once landfilled (e.g., plasterboard).

Waste Diversion is the prevention and reduction of generated waste through various methods defined by EPA. These methods include reduction, recycling, reuse, or composting. Waste diversion generates economic, environmental, and social benefits, including reducing disposal costs, conserving energy, and reducing the burden on landfills (EPA, 2012).

Public Fill vs. Landfill: In the context of this study, public fill facilities refer to a disposal destinations for inert waste (e.g., concrete, asphalt, rock, etc). On the other hand, landfills are disposal destinations for non-inert waste resulting from construction and demolition activities (e.g., wood, insulation, plasterboard, etc).

Building Information Modeling (BIM) is an object-oriented, information rich, intelligent model to support the decision making processes through the facility's lifecycle (Eastman et.al., 2008). In the context of the research BIM is not simply a 3D model, but an information repository to be accessed to waste managers at the end-of-life phase.

Object-oriented Data Model (OODM) is an approach to model the world in objects, before applying the approach to a real-world problem (Zhao and Roberts, 1998). Objects in the context of this research include components (e.g., external sources and standards) and stakeholders involved in end-of-life operations.

1. INTRODUCTION

The Introduction chapter discusses a background on building-related construction and demolition (C&D) waste, the impacts of the C&D waste, sustainable C&D waste management practice, and information management at the end-of-life phase of a building. Furthermore, this chapter lays out the problem statement, the research goal and objectives, the proposed research methods, and the contribution of this work. Finally this chapter provides overview of the next chapters of the document.

1.1. Background

Building-related C&D waste is one of the largest waste streams in the United States (U.S.). According to a report released by the U.S. Environmental Protection Agency (EPA, 2009), the U.S. generates 160 million tons of building-related C&D debris per year. Nationwide, this amount accounts for approximately 26 percent of total non-industrial waste (EPA, 2008). This stream of waste is mainly generated as a result of demolition, renovation, and new construction activities. Demolition projects, as the concern of this study, are responsible for nearly half of building-related C&D waste generation in the U.S. (EPA, 2009).

Considering the fact that waste generation is quickly increasing due to rapid urbanization, it is essential for stakeholders to know the potential resulting impact. In general, C&D waste was initially considered to be environmentally benign (Clark et al., 2006). Therefore, until the early 1990s, the generated waste was mostly sent to landfills, with little attention to more environmentally-friendly options, such as recycling and reuse (Goldstein, 2006). However, the growing awareness of the environmental and social impacts of C&D waste has changed that perception during the last two decades.

Potential Impacts of Demolition Waste Management Activities

The generated waste at the end-of-life of a facility along with waste management activities has various impacts. Generally, these impacts can be classified into three main impact categories including *economic impacts*, *social impacts*, and *environmental impacts*. Various studies have been conducted to evaluate these impacts. Some studies only focused on one individual impact category (Wang et al., 2004; Duran et al., 2006; Begum et al., 2006), while others considered two or more impact categories in their studies (Roussat et al., 2009; Klang et al., 2003; Yuan et al., 2012; Yuan, 2013). A set of examples of the impacts within each impact category are presented in Figure 1. These impacts were selected according to the existing literature on demolition waste management (Wang et al., 2004; Duran et al., 2006; Begum et al., 2006; Roussat et al., 2009; Klang et al., 2003; Yuan et al., 2012; Yuan, 2013).

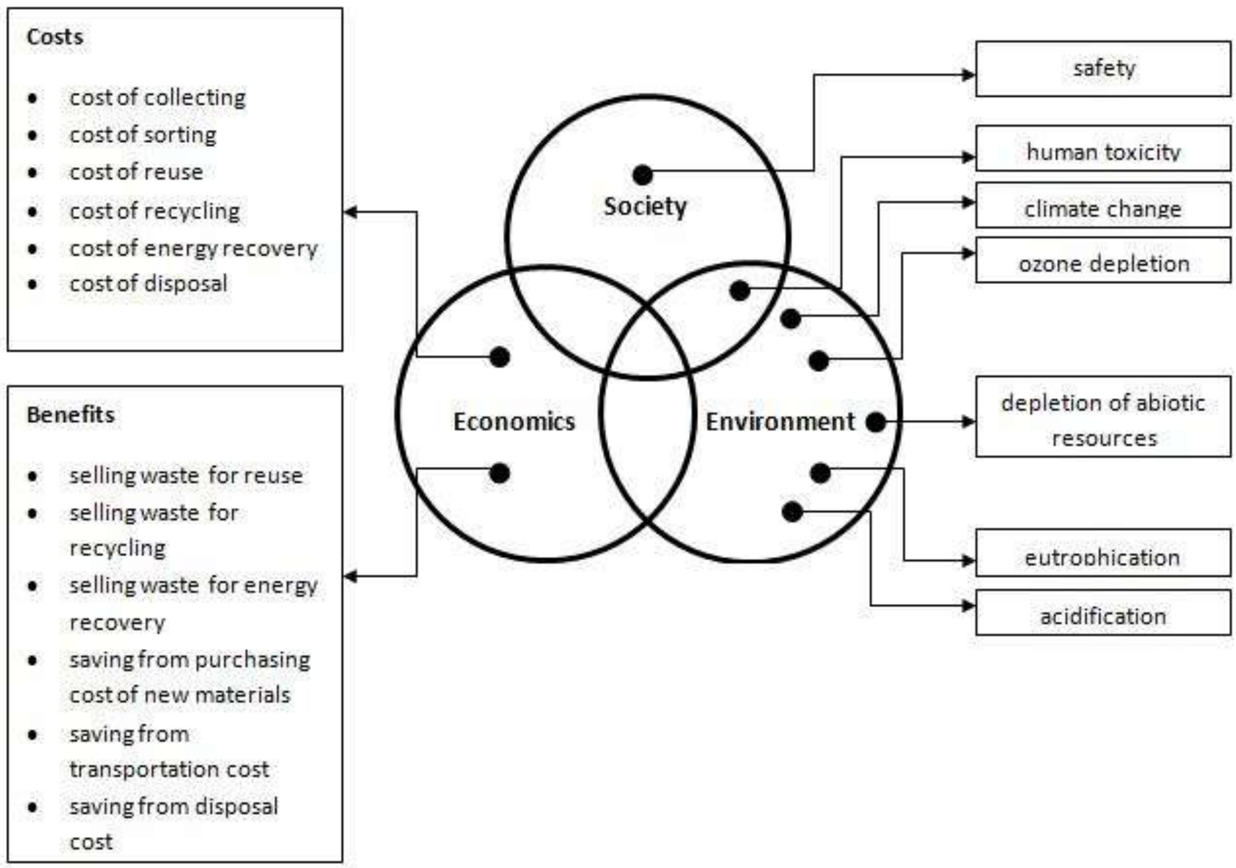

Figure 1: Impacts of Demolition Waste Management

Sustainable Demolition Waste Management

In line with the increasing concern for the diverse impacts of the demolition waste to the environment and resources, proper waste management is an urgent need. However, the literature indicates that the economic performance of demolition, (e.g., cost of recycling) is still the main driver when it comes to managing the C&D waste, while social impacts (e.g., noise pollution) and environmental considerations (e.g., climate change) have a much lower priority (Wang et al., 2010; Yuan, 2012). To address the competing priorities between these three areas, recent studies applied the *principle of sustainable development* to C&D waste management, which requires a balance between environmental development, social development and economic development

(Roussat et al., 2009; Klang et al., 2003; Yuan et al., 2012; Yuan, 2013). These efforts resulted in the development of more comprehensive and multi-faceted decision-making models, methods, and tools aimed to assist the stakeholders in evaluating the environmental, social, and economic impacts of C&D waste.

End-of-Life Information Management

Practicing sustainable demolition waste management demands decision makers (e.g., waste managers) deal with a huge amount of information at the end-of-life of a facility. For instance, waste managers need to collect information from different sources including *on-site surveys, drawings, Life Cycle Inventories (LCI), regulatory codes and standards (e.g., local codes and OSHA standards), and end-of-life information sources (e.g., inquiries from demolition and abatement contractors, salvage and new material markets, and recycling facilities)*. However, the current sources of information are fragmented, which makes data collection and data management a very resource-demanding and time consuming task. That being said, the recent advances in BIM technology and IT solutions aim to streamline data management for the Architecture / Engineering / Construction (AEC) industry by developing open source data models and ontologies for building information such as Industry Foundation Classes (IFC) (buildingSMART, 2013) and Construction-Operations Building Information Exchange (COBie) (East, 2007).

Building Information Modeling (BIM)

BIM is an emerging technology aimed to manage various aspects of a facility during its life cycle. Despite the wide application of BIM technology within the construction industry, no study considered the application of this technology for the purpose of sustainable demolition waste management. This research leverages BIM solutions to manage information at the end-of-life of a facility to support sustainable demolition waste management decision making. That being said, this study identified a gap for the potential application of BIM in the context of sustainable waste management at the end-of-life operations. The next section identifies the current problem existing in the area of sustainable demolition waste management practice.

1.2. Problem Statement

Sustainable demolition waste management is rarely practiced in the construction industry. This is mainly due to the fact that the decision-making process in sustainable demolition waste management is a resource-demanding and time-consuming task in terms of data collection and data management. This process includes analyzing the possible waste management scenarios from economic, environmental, and social perspectives. Such analyses require waste managers to deal with significant amounts of data scattered within fragmented sources at the end-of-life of a building. Therefore, the waste managers are reluctant to conduct sustainable waste management in order to prevent potential delay and incurred costs.

This study defines the following problem as the main obstacle within the current practice of sustainable demolition waste management.

Problem Statement: The information that is needed to support sustainable demolition waste management is fragmented and not properly managed for building end-of-life building operations.

Figure 2 illustrates the problem description. The white circles represent an information set required to support sustainable demolition waste management decision making at the end-of-life phase. Each circle is associated with an example of required information for decision making. The required information scatters within different data sources. For instance, the quantity of the generated waste can be calculated using information protocols embedded within the BIM-based model. On the other hand, information on embodied energy and emissions of materials is required to be collected from life cycle inventory databases. Furthermore, information on safety instructions needs to be acquired from regulatory codes and standards. In addition to these sources of information, inquiries need to be made in order to collect information from different stakeholders involved in waste management processes. The current state of the problem is that, these sources of information are fragmented, which makes data collection and data management a very resource-demanding and time-consuming task for the waste managers. Therefore, lack of proper information management at the end-of-life deters waste managers from managing the generated waste sustainably.

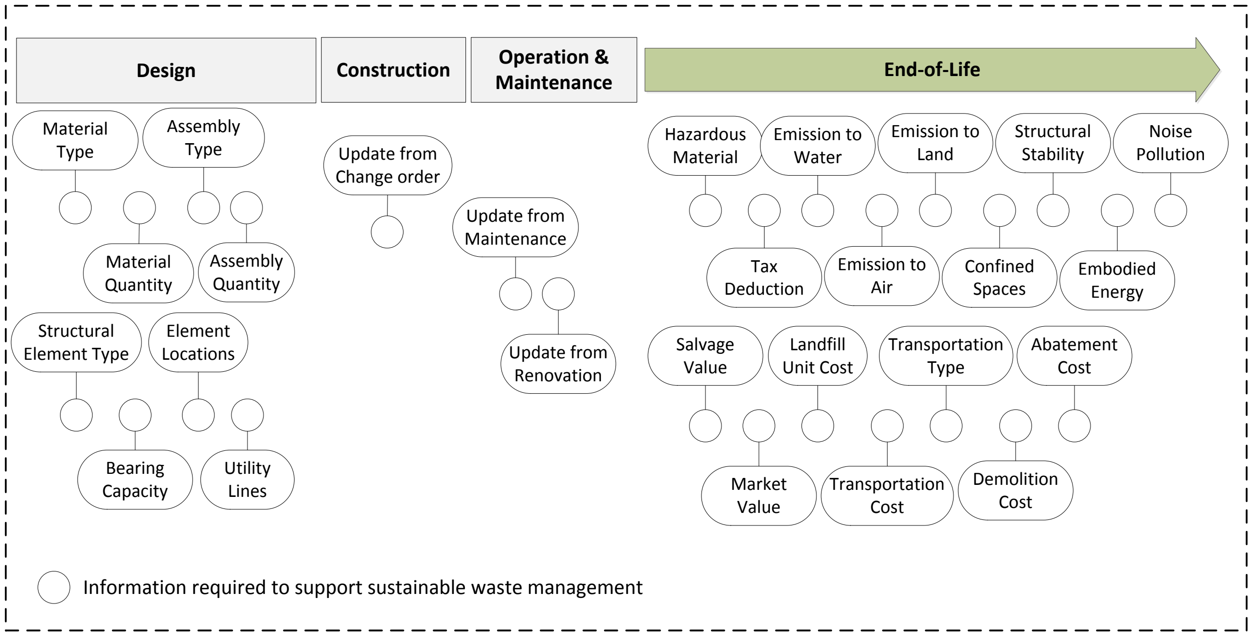

Figure 2: Problem Statement

To overcome the defined problem, this research proposed the following research goal and objectives.

1.3. Research Goal and Objectives

The goal of the research is to offer a method of storing and managing end-of-life information in an efficient and effective manner to support sustainable demolition waste management decision making at end-of-life. To align with this goal, the following research questions are developed to define the objectives of this study.

- *What information is required to analyze sustainable demolition waste management alternatives at the end-of-life of a building?*
- *What are the sources of the required information?*
- *How should the required information be managed at the end-of-life of a building?*
- *How can the end-users access the required information at the end-of-life of a building to conduct sustainable waste management analyses?*

In order to address these research questions, the following three research objectives are defined:

Objective #1: Identify needed information to support sustainable demolition waste management decision making.

- Identify information required to analyze sustainable demolition waste management scenarios from economic, environmental, and social perspectives.
- Classify the required information based on available information sources.

Figure 3 highlights Objective 1. The circles represent information required to support sustainable demolition waste management decision making at end-of-life. Each circle is associated with an example of the type of information required for decision making. The required information is then classified based on its sources including information protocols within the BIM-based model, safety codes and regulations, LCI databases, and end-of-life sources of information.

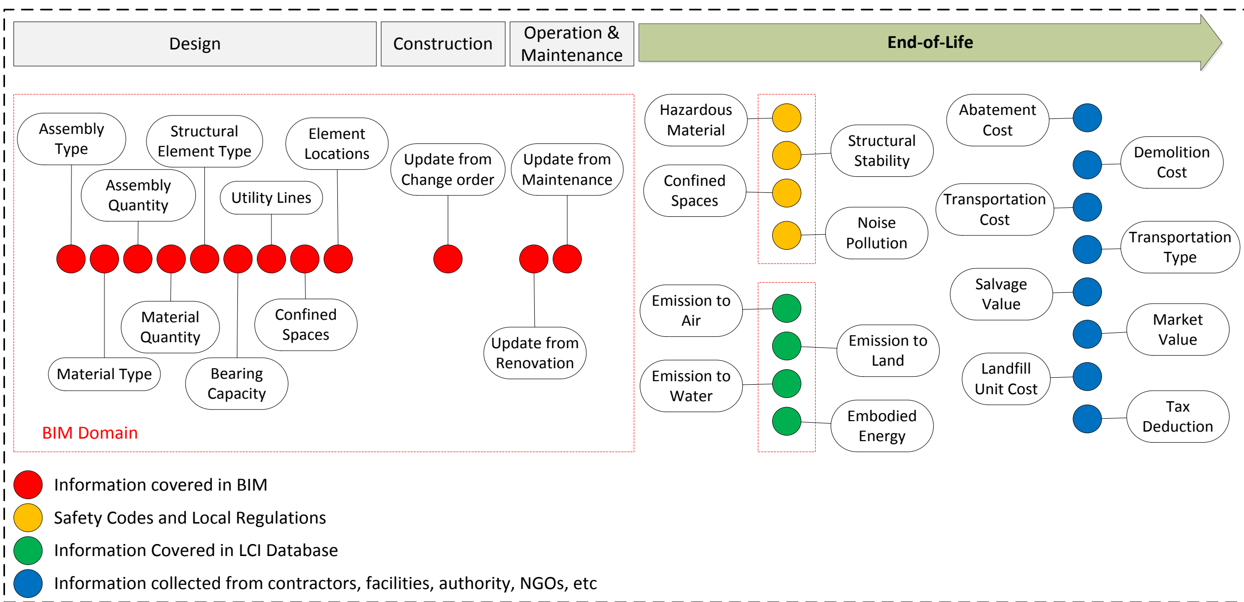

Figure 3: Objective 1- Information Identification

Objective #2: Develop an object-oriented data model to store and manage the required information at the end-of-life of a building.

- The following steps should be completed to develop the model (Figure 4):
    - Develop Use Cases to illustrate the general interactions between stakeholders within the life cycle of a building.
    - Develop Static UML Class diagram to indicate the required classes, attributes, and their relationships within the sustainable demolition waste management system.
    - Develop Sequence Diagrams to elaborate the class interactions within the sustainable demolition waste management system.

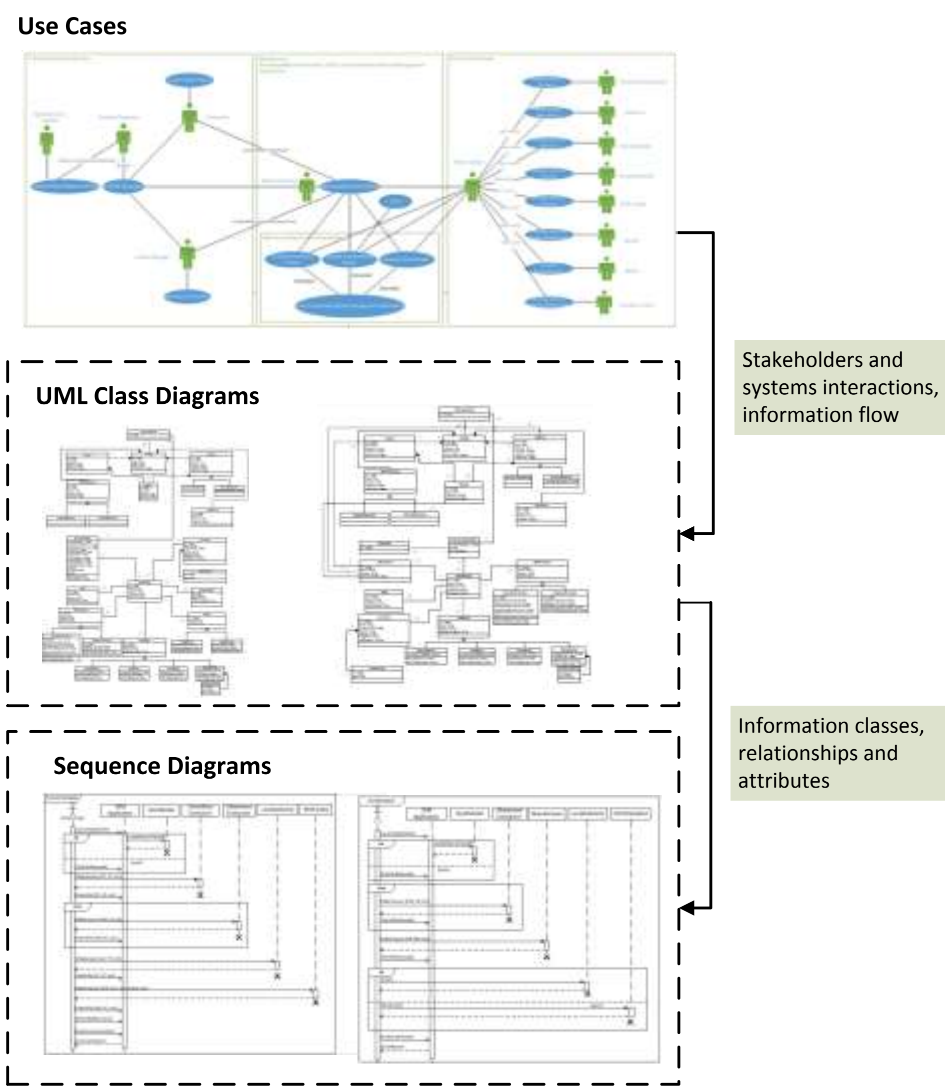

Figure 4: Objective 2 - Object-oriented Data Model Development

Objective #3:Object-oriented Data Model Verification

The following characterizations of the model should be verified to achieve Objective 3 (Figure 5):

- Scope Verification
- Flexibility Verification
- Implementability Verification
  - Design and develop a prototype waste management application to illustrate the interactions of the end-users with the proposed OODM. Generate user interfaces to show how the end-users can conduct the economic evaluation, environmental and human health assessment, and social analysis.
  - Conduct a case study analysis to demonstrate how the user can interact with the waste management application.

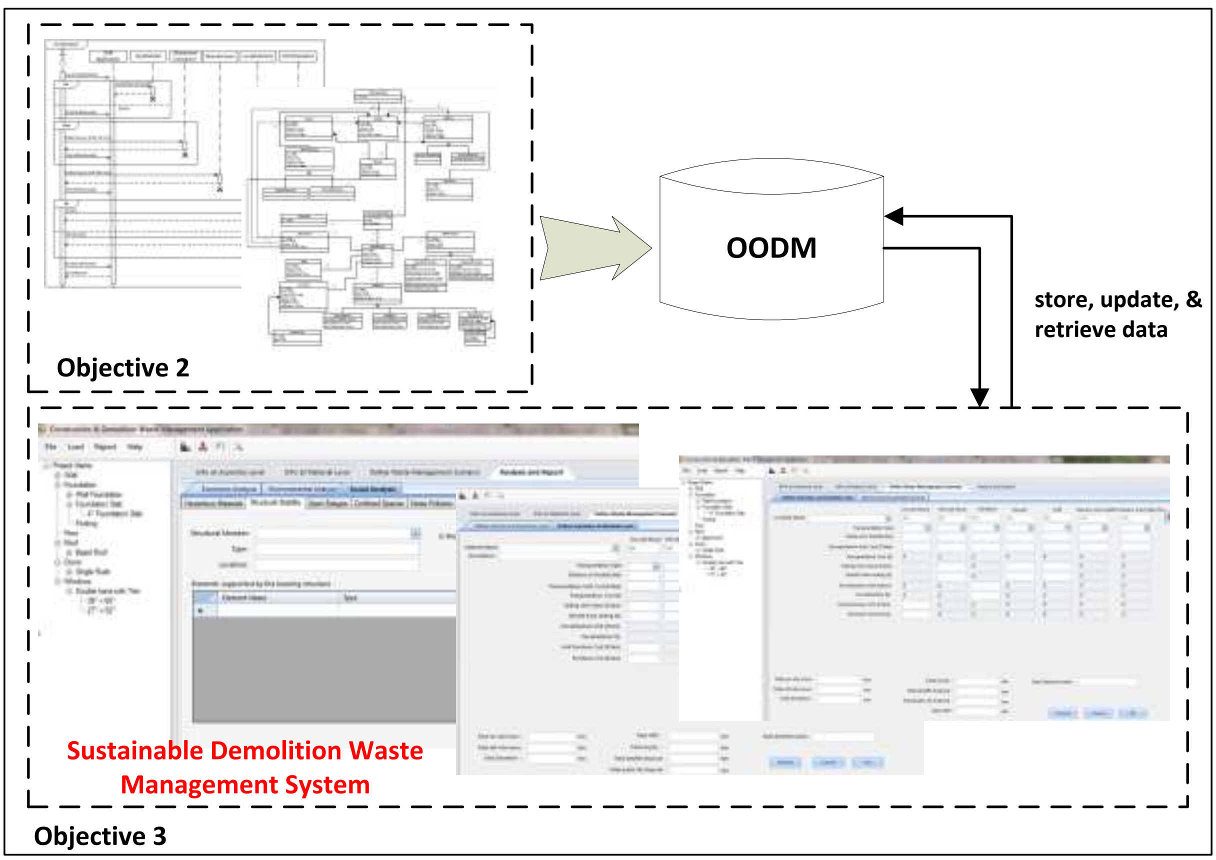

Figure 5: Objective 3 - OODM Verification

The next section elaborates the research methods that were applied to achieve the defined goal and objectives of this study.

1.4. Research Methods

This study utilizes various research methods to accomplish the stated objectives. Table 1 summarizes the types of research methods used in this study.

Table 1: Research Methods Used

Method	Objective #1 Information Analysis	Objective #2 Data Model Development	Objective #3 Verification
Information Analysis Process Modeling Document Analysis	X		
Object-oriented Data Model Development Use Case Diagram UML Class Diagram Sequence Diagram		X	
OODM Verification			X

Objective #1: Identify needed information to support sustainable demolition waste management decision making process.

In order to identify information required for sustainable demolition waste management, the following methods are applied:

Process Modeling: A theoretical process model of building end-of-life operations is defined using the Business Process Modeling Notation (BPMN) (OMG, 2011). BPMN is a graphical method intended to provide a clear understanding of a procedure within an organization. The process model was developed based on a case study, and was validated by interviews. The primary aim of the process model is to identify operations at the end-of-life of a building. These operations include *permit process, abatement report process, historical preservation report process, waste management plan development, actual demolition and deconstruction, waste treatment, and clean up.*

Cost-benefit Analysis: Cost-benefit analysis method is based on evaluating the C&D waste management with the associated costs and benefits. This method is very popular and widely used by previous efforts in the area of waste management (Yuan et. al., 2011; Begum et. al., 2006; Duran et. al., 2006; COVEC, 2007; Coelho and Brito, 2011). The aim of applying this method in this research is to identify information required to assess the economic impacts of waste management scenarios.

Life Cycle Assessment (LCA): LCA is a quantitative method, which aims to assess environmental and social impacts through the whole product life cycle. In line with an increasing awareness of LCA within the construction industry (Eaton and Amato, 1998), its application was recently expanded for the purpose of C&D waste management. This study follows the International Organization for Standardization guideline to model the environmental and social assessment of the demolition waste management alternatives. The purpose of applying the LCA method is to identify information required to assess the environmental and human health impacts of waste management scenarios.

OSHA Safety Codes Analysis: The OSHA safety codes for demolition process (OSHA, 2014) are also analyzed in order to highlight information required to provide a safe environment for workers and neighbors. The codes address the possible hazards that may exist in a demolition project including exposure to hazardous materials, falls from openings, noise and air pollutions, etc.

Objective #2: Develop an object-oriented data model to store and manage the required information through the building lifecycle.

To achieve objective #2, an object-oriented data model is developed. The aim of the model is to store and manage the required information and provide reliable and accurate information to the demolition contractors for end-of-life operations.

In order to visualize and construct the object-oriented data model, Unified Modeling Language (UML) is used. The UML is a set of models and notations that has become the standard language used for graphically depicting object-oriented models (Naiburg and Maksimchuk, 2001). The UML allows users to represent multiple perspectives of a system by providing different types of graphical diagrams. This study uses the following graphical diagrams:

Class Diagram: Class diagram is one of the static diagrams in the UML. The primary aim of development of a class diagram is to address structural characteristics of the domain of interest. In Class diagrams data is stored as objects. Each object is an instance of a class, which encapsulates the data and behavior we need to store about that object. In the context of this study, a class is an entity type that has a role in the sustainable demolition waste management (e.g., *BuildingClass, AssemblyClasss, MaterialClass, RecyclingfacilityClass, etc*). Each class of an object shares a common set of attributes and behaviors. For instance, the *AssemblyClass* contains a group of building assemblies, in which all assemblies have in common the properties of description, function, quantity, etc. The assemblies also exhibit common behavior by sharing operations such as CalUsefulLife (for calculating the remaining useful life).

Sequence Diagram: Sequence Diagram is an interaction diagram that shows how classes and objects interact in a given situation. The sequence diagram is used for presenting how processes, within a system, operate with one another. For the purpose of this study, a set of sequence diagrams was developed to elaborate the relationships between classes including MaterialClass, AssemblyClass, LandfillClass, RecyclingFacilityClass, etc.

Use Case Diagram: Use Case Diagram: The use case diagram is applied to capture the functions that are the behavioral requirements of a system. In other words, the use case diagram informs us how a system should work, and elaborates the interactions between the developed system and various actors and other systems.

Objective #3: Verify the Object-Oriented Data Model.

To achieve Objective 3, three characterizations of the model were verified to demonstrate the potential application of the model at the end-of-life operations. These characterizations include 1) scope, 2) flexibility, and 3) implementability.

1.5. Contributions

The major contribution of this research is an object-oriented data model, which functions as an ontology to support the waste managers decision-making process by more efficient management of information at the end-of-life phase (Figure 6). The object-oriented data model aims to support the waste managers to more efficiently store and manage the information at the end-of-life phase. Furthermore, this model can serve as the core information storage for the proposed sustainable demolition waste management application. The contributions and benefits of the research are discussed in detail in Chapter 6, Section 6.2.

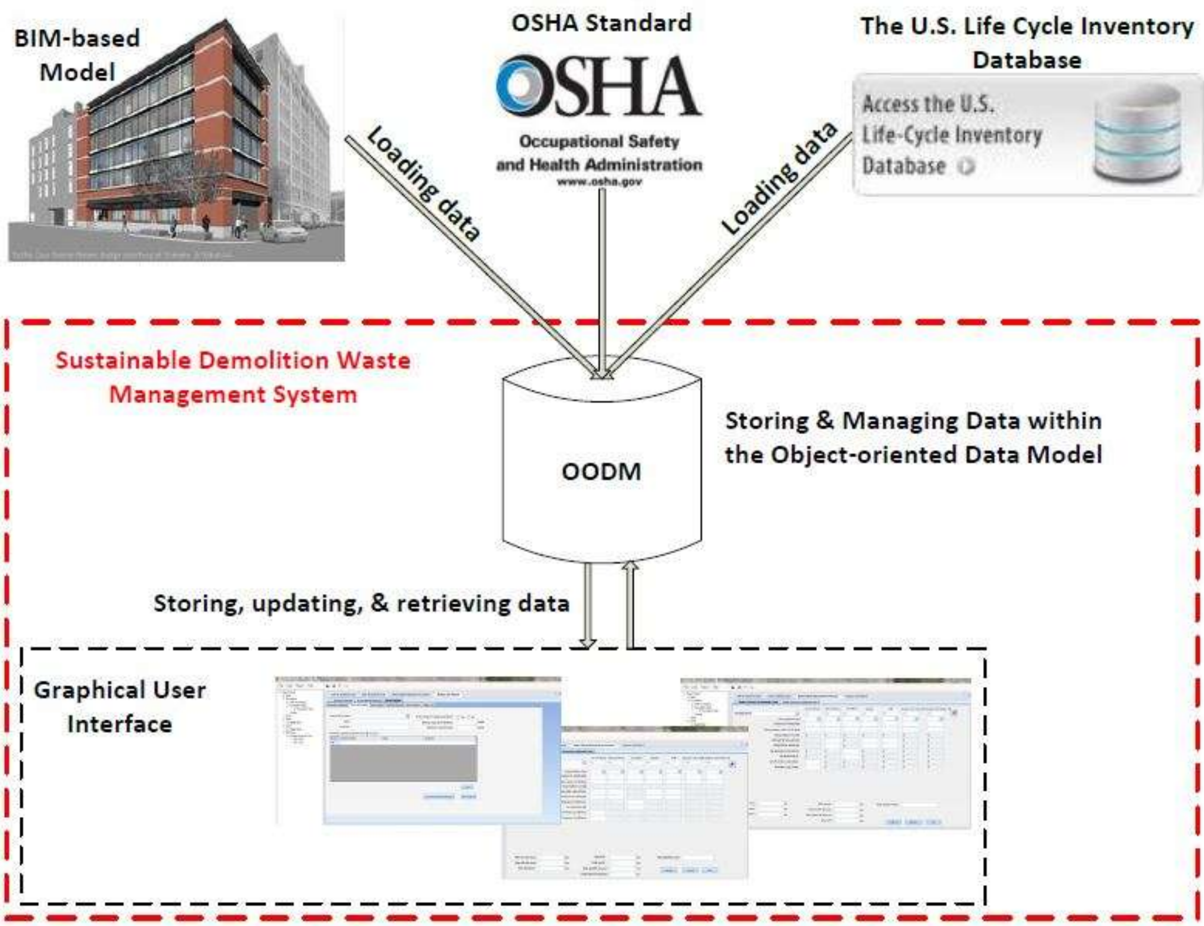

Figure 6: Contribution of the Study

1.6. Document Organization

Chapter 1. *Introduction* aims to provide an overview of the document and lays out the problem statement, research goal and objectives, proposed research methods, limitations of the study, and the contribution of this work.

Chapter 2. *Background & Literature Review* consists of a review of the previous and relevant literature to the identified problem and objectives. This includes an analysis of different approaches within the concept of sustainable demolition waste management including construction & demolition waste management practices, documented impacts of the generated waste on the economy, environment, and society, and analysis methods to assess these impacts (e.g., LCA and Cost-benefit Analysis). Potential application of BIM technology and information standards schemas (e.g., IFC and COBie) are also discussed in this chapter.

Chapter 3. *Identify Information Required for Sustainable Demolition Waste Management Decision Making* is a chapter that discusses the development of the demolition waste management process model and elaborates the analysis methods used to identify the information needed to support sustainable demolition waste management at the end-of-life phase. This chapter is developed in response to Objective #1.

Chapter 4. *Object-oriented Data Model Development* discusses the development process of the object-oriented data model in response to Objective #2. The development process includes *Use Case Diagrams*, *UML Classifications*, and *Sequence Diagrams*.

Chapter 5. *OODM Verification* is organized to verify the potential application of the proposed object-oriented data model. This was achieved by verifying scope, flexibility, and implementability characterizations of the model. Chapter 5 was developed in response to Objective #3.

Chapter 6. The *Conclusion and Future Research Work* chapter summarizes the findings and discusses the contribution and benefits of the research. This chapter also includes discussion of possible future research tracks and how they can be conducted.

2. BACKGROUND AND LITERATURE REVIEW

2.1. Introduction

The generated waste from demolition activities represents one of the largest waste streams in the U.S. This huge amount of waste has various impacts on the environment, society, and economy. Hence, there is an urgent need to properly manage the demolition waste in order to not only mitigate the diverse impact of the waste, but also benefit from potential opportunities within the waste management system. For example, recycling and reusing of waste may not only reduce the impact on the environment, but also can provide job opportunities within the society.

A proper waste management approach should take all the impacts of the generated waste into consideration. However, economic performance is still the main driver when it comes to managing demolition waste, while the social and environmental aspects have a much lower priority (Wang et al., 2010; Yuan, 2012). To address the existing conflict of interests, recent studies applied the principle of sustainable development in C&D waste management in order to satisfy all *three pillars* of sustainable development, namely environmental development, social development, and economic development (Roussat et al., 2009; Klang et al., 2003; Yuan et al., 2012; Yuan, 2013). These efforts resulted in the development of different decision making models, methods, and tools aimed at assisting the stakeholders in evaluating the impacts of the demolition waste from environmental, social and economic perspectives.

Sustainable demolition waste management demands decision makers (e.g., demolition contractors and owners) deal with a huge amount of information at the end-of-life of a facility. However, the current sources of information are error-prone, resource-demanding, and time-consuming. That being said, BIM can serve as a great tool for decision makers, for not only providing accurate information, but also streamlining the analysis of different waste management alternatives by providing readily available information.

This chapter begins with a general definition of terms mentioned in this study. A literature review on the topics of demolition waste management and BIM technology is also discussed.

2.2. Construction and Demolition (C&D) Waste

C&D waste generally refers to the debris generated during construction, renovation, and demolition activities of structures. Structures may refer to residential/non-residential buildings as well as roads, bridges, industrial facilities, etc. Despite the general definition of C&D waste, each state may have its own regulations and codes, by which they define the C&D waste. For instance, the state of California defines the C&D waste as debris generated by demolition and new construction of structures such as residential and commercial buildings and roadways. Based on this definition the C&D waste includes concrete, wood, asphalt, metals, drywall, and many miscellaneous and composite materials. California does not exclude inert waste from the C&D waste (Franklin Associate, 1998). On the other hand, the state of North Carolina defines C&D waste as solid debris resulting solely from construction, remodeling, repair, or demolition operations on buildings, pavement, or other structures. The North Carolina state does not include inert debris, land debris, and yard debris in its C&D waste stream (Franklin Associate, 1998).

This study defines C&D waste as any debris generated during new construction, renovation, and demolition operations. Referring to this general definition, C&D waste comprises inert and non-inert waste including concrete, asphalt, wood, drywall, metals, roofing, floor tile, and clearing debris.

2.3. Building-related Demolition Waste

Building-related demolition waste includes all debris produced during the demolition of a building (both residential and non-residential). Demolition activities generate large quantities of waste in a relatively short period of time. Franklin Associate (1998) estimated that the generated waste resulting from the demolition of a building can be 20 to 30 times as much as construction debris. The demolition waste mainly consists of wood, brick, drywall, asphalt shingles, plastic, roofing, plastics, and metals.

2.4. Impacts of Demolition Waste Management

Until the early 1990s, C&D waste was considered to be environmentally benign (Clark et al., 2006). However, the growing awareness on environmental and social impacts of C&D waste has changed that perception during the last two decades. Multiple studies have been conducted to address the diverse impacts of the demolition waste. Some of them only took the economic impacts into consideration, while the recent studies were concerned more about the environmental and social impacts. Furthermore, a few studies considered all three impacts including economic, environmental, and social impacts in their waste management analyses.

Budget constraint is one of the main concerns of demolition contractors and owners at the end-of-life of a building (Tam and Tam, 2006). The economic impact of a demolition waste management alternative is calculated based on incurring costs and gaining benefits resulting from implementing that alternative. The common incurring costs include *demolition and deconstruction cost, cost of sorting*, *landfill disposal cost*, *sorting facilities cost,* and *transportation cost*. The benefits that may be gained due to applying more environmentally friendly alternatives may include *revenue from selling wastes*, *tax reduction*, and *saving due to less disposal costs* (Wang et al., 2004; Coelho and Brito, 2011; Duran et al., 2006; Begum et al., 2006; Yuan et al., 2011).

On the other hand, the environmental impacts resulting from the demolition waste include, but are not limited to, wasting natural resources (Esin and Cosgun, 2007), diminishing land resources for waste landfilling (Poon et al., 2003), contamination of soil and water resources by hazardous pollution (TuTech, 2004; Agamuthu, 2008; Esin and Cosgun, 2007), emitting noise and air pollution (Symonds Group, 1999; Leigh and Patterson, 2005), and, in the larger scale, increasing global warming and ozone depletion (TuTech, 2004). It should be considered that some of these environmental impacts would ultimately affect human health in society through contaminated water, ozone depletion and air pollution.

2.5. Demolition Waste Management Agenda in the U.S.

Demolition waste can be managed by applying different waste management strategies, ranging from reuse to recycling to disposal in landfills. Waste managers are required to make decisions to mitigate the impacts of the generated waste. In line with making environmentally friendly decisions, the U.S. Environmental Protection Agency (EPA) proposed a waste management hierarchy as an agenda for waste managers (EPA, 2013). This hierarchy is intended to serve as an agenda for waste managers to reduce the environmental impacts of the demolition waste. The hierarchy comprises of five waste management scenarios (Figure 7): waste reduction, reuse, recycling, energy recovery, and disposal. The environmental impacts due to implementing each scenario are ascending from low to high. Source reduction is the primary strategy to reduce the impacts of the waste on the environment, followed by reuse, recycling, energy recovery, and finally, disposal that is the least environmentally preferred strategy.

Figure 7: EPA Waste Management Hierarchy (EPA, 2013)

Waste reduction, sometimes called waste minimization, is simply creating less waste at the source. This strategy is the most effective and efficient method to minimize the generation of construction and demolition waste, which ultimately eliminates many environmental impacts (Peng et al., 1997; Esin and Cosgun, 2007). In addition, waste reduction can reduce the cost for waste transporting, recycling, and disposal (Poon et al., 2001; Esin and Cosgun, 2007). Buying in bulk, reducing packaging, redesigning products, and reducing toxicity are different forms of waste reduction at the construction stage. However, waste reduction at the end-of-life is based on how properly the demolition waste is collected and sorted. Demolition and deconstruction (selective dismantling) are two common practices to collect and sort the waste at the building end-of-life.

After waste reduction, the most effective environmentally-preferred strategies are reuse and recycling. Reuse usually means using the same material in the construction more than once, specifically using the material again for the same function (e.g., reuse wood flooring in construction). The demolition waste that cannot be reused, is considered for recycling. Recycling refers to collecting, sorting, and processing recyclable waste into new products. The next waste treatment practice is energy recovery from waste. This method is the conversion of non-recyclable waste materials into useable heat, electricity, or fuel. This process is often called waste-to-energy (WTE). The last waste management strategy is disposing the waste into either landfills or public fill reception facilities. Despite the tendency of the construction industry to consider the C&D waste as inert waste to be disposed in landfills, this practice is considered the least environmentally-preferred strategy.

The waste management scenarios defined by EPA have different impacts from economic, environmental, and social perspectives. The following section overviews previous studies that considered the impacts of the C&D waste.

2.6. Models, Methods, and Tools in Demolition Waste Management

Table 2 represents studies conducted on the C&D waste management. As indicated in the table, the studies were identified based on their focuses on the impact categories including environmental, social, and economic. The aims of these studies were either to address the impacts resulting from the C&D waste management activities or to facilitate the waste management process by using or proposing decision making methods and tools.

As previously mentioned, the economic impact is still the most important criterion while analyzing the waste management alternatives within the decision making process (Wang et al., 2010; Yuan, 2012). Therefore, many studies considered different economic factors of C&D waste management for their analyses. For instance, a study by Wang et al. (2004) evaluated the potential economic impacts of legal restrictions on construction contractors and C&D waste processors. Duran et al. (2006) also developed a model to assess the economic viability of creating markets for recycled C&D waste. Begum et al. (2006) conducted a cost-benefit analysis to investigate the feasibility of waste minimization through various mathematical equations. Zhao et al. (2010, 2011) also assessed the economic feasibility of recycling facilities for C&D waste. In addition, a waste management plan was proposed by Mills et al. (1999) to select the most cost-effective waste management strategy.

In line with the increasing awareness on environmental and social impacts of C&D waste, some endeavors have been recently made to consider these impacts in waste management decision making analysis. For example, Ortiz et al. (2010) analyzed three different waste management alternatives, including recycling, incineration, and landfilling, in order to evaluate environmental impacts of each alternative. In addition, a study by Coelho and Brito (2011) quantified comparable environmental impacts of different waste management alternatives in accordance with processes involved in each alternative (e.g., transportation, selective dismantling, recycling). In respect to social impacts, Rocha & Sattler (2009) investigated social impacts from C&D waste reuse in Brazil from a qualitative point of view. Furthermore, Yuan (2012) developed a model to quantitatively evaluate the social performance of C&D waste by using a system dynamics (SD) approach.

Table 2 Studies on C&D Waste Management

Studies	***Environmental***	***Social***	***Economic***
Mills et al. (1999)			X
Wang et al. (2004)			X
Coelho & Brito (2011)			X
Guy & McLendon (2001)			X
Begum et al. (2006)			X
Duran et al. (2006)			X
Symonds Group (1999)			X
Peng et al. (1997)			X
Tam (2008)			X
COVEC (2007)			X
Zhao et al. (2010)			X
Yuan et al. (2011)			X
Zhao et al. (2011)			X
Golton et al. (1994)	X		
Trankler (1992)	X		
Trankler et al. (1996)	X		
Ortiz et al. (2010)	X		
Balazs et al. (2001)	X		
Yuan (2012)		X	
Rocha & Sattler (2009)	X	X	X
Klang et al. (2003)	X	X	X
Roussat et al. (2009)	X	X	X
Yuan et al. (2012)	X	X	X
Yuan (2013)	X	X	X

While many studies investigated C&D waste management from one individual point of view (e.g., economic impact), there are few studies that emphasized the importance of considering all three aspects of sustainable development when managing the C&D waste. For instance, Roussat et al. (2009) used the Multi-criteria Decision Analysis (MCDA) approach in the context of choosing a sustainable demolition waste management strategy for a case study in the city of Lyon, France. This method of demolition waste management takes into consideration the sustainable development principles, including economic aspects, environmental consequences, and social issues. A model was also developed by Klang et al. (2003) to evaluate demolition waste management systems for their contribution to sustainable development.

Furthermore, Yuan et al. (2012) proposed a decision support tool projecting C&D waste reduction in line with the waste management situation of a given construction project. Yuan et al. conducted this research by using system dynamics methodology. This methodology is a systematic approach that can deal with the complexity of C&D waste management by considering interrelationships and dynamics of any social, economic, and managerial system. Yuan (2013) also identified 30 key indicators affecting the overall effectiveness of C&D waste management from a sustainable development point of view.

The following sections elaborate two of the widely used methods by the previous studies namely Cost-benefit Analysis and Life Cycle Assessment (LCA).

Cost-Benefit Analysis

The economic impact of demolition waste management is calculated based on incurring costs and gaining benefits. Cost-benefit analysis is a method that aims to help demolition contractors and owners to evaluate the costs and benefits resulting from demolition waste management activities. This method is very popular and widely used by previous efforts in the area of waste management (Yuan et. al., 2011; Begum et. al., 2006; Duran et. al., 2006; COVEC, 2007; Coelho and Brito, 2011).

Multiple variables may be considered for conducting the cost-benefit analysis. The variables are mainly dependent on the type of the project and the accessibility of required information. Some studies only included one phase of demolition waste management (e.g., recycling) in their analyses, while other studies were conducted more comprehensively by considering different phases within demolition waste management activities (e.g., actual demolition, waste collection, transportation, etc). For example, a study by Duran et al. (2006) considered the economic viability of C&D waste recycling. He only assessed the variables that affect the recycling process of materials including (transportation costs, landfill costs, and recycling cost). A report prepared for the Ministry of Environment of New Zealand also highlights the cost and benefits of the recycling process (COVEC, 2007). The costs that were considered in this report include the cost of collection and sorting, but not the value of the recycled materials in end-use markets. On the other hand, *savings in landfill cost* and *saved cost of collection for disposal* are considered as the main stream for gaining benefits. Yuan et al. (2011), however, utilized the cost-benefit analysis method by emphasizing on a wider spectrum of C&D waste management, which includes many variables. The costs addressed in Yuan's study include *cost of collecting*, *cost of sorting*, *cost of recycling*, *disposal cost*, *transportation costs*, and *environmental cost*. The benefits are *revenue from selling wasted materials*, *transportation cost saving*, *disposal cost saving*, and *purchasing cost saving*.

Life Cycle Assessment (LCA)

According to International Organization for Standardization (ISO 14040; ISO 14044, 2006), LCA is a "compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle." The Society of Environmental Toxicology and Chemistry (SETAC) also defined LCA as “a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment; to assess the impact of those energy and materials used and releases to the environment; and to identify and evaluate opportunities to affect environmental improvements” (Anon, 1993).

In the building industry, LCA can be conducted at four levels: material, product/assembly, building, or industry (Bayer and Gentry, 2010). Depending on the goal and scope of the assessment, decision makers (e.g. manufacturers, architects, designers, waste managers, etc) can conduct the LCA at each level; For instance architects may conduct LCA at the material level in order to select the most environmentally friendly materials for a project. LCA can be also performed at the building level in order to guide architects to define the environmental footprint of a proposed project, either as part of an iterative design methodology that seeks to minimize the environmental impact of a project, or to comply with regulatory requirements.

According to ISO 14040, LCA consists of four steps: (1) Goal and Scope Definition, (2) Inventory Analysis, (3) Impact Assessment, and (4) Interpretation (Figure 8).

1) *Goal and Scope Definition*:

In this step, the products or assemblies to be assessed are defined. In addition, the LCA practitioner needs to define the scope and the boundary of the assessment as well as the functional unit. The type of methods, impact categories, and set of data that needs to be collected are identified. System boundary and functional unit definition are important elements of this component. Functional Unit is a description of a product or system to be assessed. The functional unit helps the practitioners to compare the results of a LCA of a product with a similar product. The functional unit is defined based on the needs of the assessment. At the building level assessment, the functional unit can be defined as the entire life cycle of the building from the design stage to the demolition phase. On the other hand, the functional unit can be also defined as per-square-foot, which is only calculated within one life cycle stage (e.g., end-of-life). System Boundary defines the scope of the assessment. The system boundary indicates what products, assemblies, and building life stages are considered for the LCA.

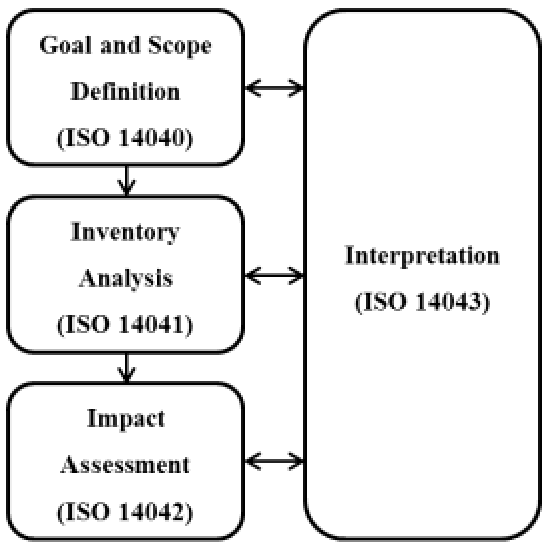

Figure 8: LCA Steps according to ISO 14040

2) *Life Cycle Inventory (LCI) Analysis*:

The life cycle inventory analysis is the most critical step in LCA. In this step, the inputs including energy and resources and the outputs including the emissions to atmosphere, water, and soil are quantified. The inputs and outputs are then combined in the process flow chart and related to the functional basis (Bayer and Gentry, 2010). At this stage an inventory of all the inputs and outputs to and from the production system is prepared. As an example, the inputs may include electricity consumption and the outputs may include CO_2. If the LCI results are consistent and accurate, the products and processes can be compared and evaluated enabling decision makers to make more environmentally friendly decisions.

According to a LCA Guideline developed for AIA, databases and LCA-based tools are critical in providing accurate and reliable results (Bayer and Gentry, 2010). In the next section, the LCA-based tools are highlighted.

3) *Life Cycle Impact Assessment*:

The life cycle impact assessment translates the result of LCI analysis into impacts on environment and human health. The effects are categorized in various impact categories in order for the users to gain a better understanding of the impacts. For example, the quantified emission of CO_2 is translated to its impact on depletion of the ozone layer. Furthermore, a single value result can be obtained by applying weights to the LCI result. In this case, only one single value is reported rather than multiple impact categories.

4) *Interpretation*:

In order to report the LCA result in the most informative way, the results are interpreted. The aim of the interpretation step is to help decision makers to easily compare different scenarios, and ultimately, make environmentally friendly decisions.

LCA-based Tools

Since measuring and quantifying environmental impacts of buildings is a complex task, LCA experts have developed tools to simplify the LCA process (Table 3). Following the Athena Institute's tool classification system (Trusty, 2000), all tools are classified in three groups based on their scope.

Tools at level 1 are designed to assess the environmental impact at individual product or simple assembly level (e.g., ceiling coverings or roof assemblies). Level 1 also represents LCA tools that are able to be compared in terms of the economic impacts of different materials. Furthermore, tools in level 1 can be grouped as Level 1A and Level 1B. Level 1A is specifically designed for LCA experts while the level 1B tools are intended for use by industry practitioners who want to get the LCA results readily and in a simple format. Level 2 tools are aimed for whole building or complete building assembly analysis. These tools are specifically developed to provide specific analysis of buildings such as operating energy, life cycle costing, lighting, and life cycle environmental effects. Tools at level 3 are used to conduct more comprehensive whole building assessment, which covers sustainability concerns of buildings including environmental, social, and economic aspects. Inputs for the environmental impact assessment in tools at this level are extracted from tools at level 2. Depending on the tool, level 3 tools may be applied to new designs or existing buildings.

Table 3: LCA-based Tools Classification (Adapted from Trusty, 2000)

	Tool	Country	Scope	Comments
Level 1	**Level 1A**			
	SimaPro	Netherlands	Product	Can be used internationally if the data is available for that specific region
	GaBi	Germany		
	Umberto	Germany		
	TEAM	France		
	Level 1B			
	BEES	USA	Product	Combines LCA & Cost
	LCAiT	Sweden		Useful for manufacturers
	TAKE-LCA	Finland		LCA Comparison of HVAC
Level 2	Athena IE	Canada/USA	Assembly	Useful for regions where the tools were intended to be used
	BRI LCA	Japan		
	EcoQuantum	Netherlands		
	Envest	United Kingdom		
	Green Guide	United Kingdom		
	LISA	Australia		
	LCA Design	Australia		
Level 3	BREEAM	United Kingdom	Whole Building	Use LCA data from Level 2
	GBTool	International		
	Green Globes	Canada/USA		

The most basic LCA tool takes inputs in the form of material take-offs (in area or volume) and converts it into mass. Then it attaches this mass value to the LCI data available from an LCI database and other sources. This step results in quantities of inputs and outputs of a product system. The inputs and outputs may include the use of resources and releases to air, water, and land associated with the system.

LCA at the End-of-Life

At the end-of-life, LCA can be conducted by focusing on the energy consumed and the environmental waste produced during the demolition and waste management activities. It can also cover the impacts of the transportation during these operations. In addition, recycling and reuse activities related to demolition waste can also be included in the LCA at the end-of-life.

Any person involved in demolition waste management can leverage the LCA method in order to make informed decisions. This person can be a site manager, demolition contractor, waste manager, or owner. The LCA at the end-of-life would help the stakeholders to:

- prioritize materials that offer the greatest environmental savings
- identify materials that offer the greatest economic savings
- define processes that have the biggest impact

Regardless of what model, method, and tool is used for the purpose of analyzing the impacts of demolition waste management scenarios, managing the waste at the end-of-life operations requires waste managers to deal with a huge amount of information. The need for accessing readily available and accurate information gets even more essential when the project team decides to analyze the alternatives by considering all sustainable factors, including economic, environment, and social impacts. The following section discusses the need for information management at the end-of-life phase and elaborates the BIM solutions for managing the information at the end-of-life phase.

2.7. Information Management at End-of-Life

The volume of required information that needs to be managed at the end-of-life of a building can vary upon the goal of the waste management. If the owner is only concerned with the economic factor, the main set of information that needs to be collected is the types and quantities of the materials and the transportation and landfill costs. In addition, if the goal encompasses the environmental and human health impacts, the waste manager also needs to have information on potential waste scenarios for materials (e.g., recycling and reuse), the embodied energy and emissions of materials, and potential waste management hazards, etc. This section highlights sources of information that could support sustainable demolition waste management decision making at the end-of-life.

The required information can be retrieved from different sources, including on-site surveys, drawings, Life Cycle Inventories (LCI), regulatory codes and standards (e.g., local codes and OSHA standards), and end-of-life information sources (e.g., inquiries from demolition and abatement contractors, salvage and new material markets, and recycling facilities). Types of general information that can be retrieved from the drawings and on-site surveys include material types, material quantities, possible waste management scenarios for the generated waste, and potential hazards (Roussat et al., 2009). Furthermore, information that is required to support environmental and human health impacts of the generated waste can be retrieved from LCI databases. These databases provide the waste manager with information such as the embodied energy of materials, raw material resources, emissions to air, water, and land, etc (PRé Consultants, 2010). Regulatory codes and standards are other sources of information that address safety standards and waste diversion requirement for a building (OSHA, 2014). A set of information that needs to be collected from different stakeholders at the end-of-life of a building is categorized as the end-of-life information sources.

Currently, these sources of information are fragmented at the end-of-life phase, which makes the data-collection and data management a very source-demanding and time-consuming task. The next section discusses different uses of BIM technology throughout the building lifecycle and its potential application to streamline data management at the end-of-life of a building.

Building Information Modeling (BIM)

BIM is a new technology within the construction industry aiming to manage various aspects of a facility during its life cycle. BIM aims to manage all the information related to a building with the intent to retrieve that information for various purposes, such as cost estimation or thermal performance. Many studies considered different applications of BIM within the lifecycle of a facility. Succar (2009) considered the application of BIM in three major phases, namely Design [D], Construction [C], and Operation [O]. Each phase is subdivided into sub-phases, and each sub-phase is further subdivided into multiple activities, sub-activities and tasks. For instance: [D] Design Phase, [D1] Architectural, Structural and Systems Design, [D1.1] Architectural Design, [D1.1a] Conceptualization, [D1.1a.01] 3D Modeling.

BIM applications were also identified in a guideline named BIM Project Execution Planning Guide by Penn State University (2009). According to this guideline, BIM technology can be used in 25 different applications during the lifecycle of a facility. These applications are divided into Primary BIM Uses and Secondary BIM Uses. Some primary BIM applications include cost estimation, phase planning, site planning, design reviews, energy analysis, 3D coordination, maintenance scheduling, and building systems analysis. In addition to the primary application of the BIM technology, the secondary uses of BIM may include structural analysis, lighting analysis, LEED evaluation, construction system design, digital fabrication, asset management, and space management.

Despite the vast application of BIM technology in the construction industry, no study considered the application of this technology for the purpose of sustainable demolition waste management. As already mentioned, sustainable demolition waste management demands decision makers (e.g., demolition contractors and owners) deal with a huge amount of information at the end-of-life of a facility. However, the current sources of information are error-prone, resource-demanding, and time-consuming. That being said, the recent advancement in BIM technology and IT solutions streamlines data management by proposing building information data models such as IFC and COBie.

Information Protocols - Data Model Standards

Industry Foundation Classes (IFC) and the Construction Operations Building Information Exchange (COBie) are two popular data model standards within the Architectural, Engineering, and Construction (AEC) industry (Lucas, 2012).

IFC is a neutral standard to describe, exchange, and share information throughout the life cycle of a building. It is developed and maintained by buildingSMART and registered with ISO as ISO16739 (buildingSMART, 2013). ISO16739 identifies IFC as an open international standard with the aim to improve communication and productivity by reducing the loss of information during transmission from one application to another (ISO, 2013).

COBie is another product model standard widely used within the AEC industry. As an information exchange specification, it aims to store information throughout the life cycle of a building and deliver them to facility managers for use during the operation and maintenance phase. COBie eliminates the current process of transferring massive amounts of documents to the facility managers by identifying and only capturing information that is required to support decision making during the operation and maintenance phase of a building (East, 2007).

Though IFC and COBie intend to provide information to decision-makers throughout the life cycle of a building, these standards are lacking in providing information required to support sustainable demolition waste management at the end-of-life operations. Hence, this study proposes an object-oriented data model that aims to provide the required information to support sustainable demolition waste management decision making.

Summary of Background & Literature Review

This chapter discussed the background and literature on the current construction and demolition waste management practice within the industry. Furthermore, this chapter addressed different models, methods, and tools proposed by previous studies in the domain of C&D waste management. Two of widely used methods including Cost-benefit analysis and Life Cycle Assessment were further elaborated within this chapter. It was discussed that though the methods, models, and tools can help waste managers to manage the waste sustainably, collecting and managing data to be used by these tools are very time-consuming and resource-demanding tasks. To address this indentified problem, potential application of BIM solutions at the end-of-life operations was laid out by giving an introduction on BIM technology and information protocols and data model standards.

The next chapters throughout the document discuss methods that were applied to identify the required information, the methods used to develop the object-oriented data model, and model verification, and use case analysis to demonstrate the implementability of the proposed model.

3. IDENTIFYING INFORMATION REQUIRED FOR SUSTAINABLE DEMOLITION WASTE MANAGEMENT DECISION MAKING

In response to Objective 1, this chapter elaborates the process of the development of a model to clarify end-of-life operations and stakeholders involved within demolition and waste management activities. In addition, a flowchart was developed to illustrate a set of processes that need to be followed by the waste manager to develop the waste management plan.

Furthermore, this chapter includes the methodologies used to identify and classify information required to support sustainable demolition waste management decision making at the end-of-life of a building. These methodologies consist of cost-benefit analysis (Wang et al., 2004; Begum et al., 2006; Zhao et al., 2010), LCA (ISO 14040, 2006), and document analysis of OSHA Standards for Demolition (OSHA. 2014).

3.1. Process Model Development

A process model of building end-of-life operations was developed based on a public sector project that included 44,000 gross square feet of demolition (Figure 9). To develop the process model, the demolition and abatement meetings are observed to make sure that the main stakeholders and general processes involved in end-of-life operations were included within the model. After the model was developed, an on-site interview was conducted with the project manager of the demolition project in order to make sure that the model represents the end-of-life processes that were being discussed in the meetings.

Furthermore, to verify the process model, three construction practitioners were interviewed. The process model consists of three main stakeholders including the owner, general contractor, and demolition contractor. To make sure the developed model represents the end-of-life operations, the stakeholders were selected from different companies, who were involved in multiple demolition projects. Nine construction practitioners, including five demolition contractors, two owners, and two general contractors, were contacted through phone calls and emails. Three out of nine contacted practitioners agreed to interview. The interview was a one-hour face-to-face session. The first interviewee was involved with plus 100 demolition projects on the east coast. He was acting as the owner and general contractor in all his previous demolition project experiences. The second interviewee was a general contractor who is responsible for hiring demolition contractors for end-of-life operations. The third interviewee was the division manager of a demolition contractor with 80 plus demolition project experiences in the east coast.

The interview started by giving an introduction about the purpose of this study. The process model was then illustrated to the interviewees in four levels, namely *Abetment Assessment*, *Historical Assessment*, *Bid Process & Abatement*, *Demolition Operations & Waste Management Development Plan*. The interviewees verified *Abatement Assessment* process. However, the demolition contractor and the general contractor emphasized that the *Historical Assessment* report is rarely required for private sector projects. That being said, they verified the *Historical Assessment* requirement for public sector buildings. The *Bid & Abatement* processes were also verified by the interviewees. However, the owner pointed out that, depending on the size of the project, the general contractor may demolish the building by his/her own without retaining the demolition contractor. To verify the *Waste Management Plan* level, the processes involved in the development of the plan was illustrated to the interviewees as depicted in Figure 10. Though the interviewees confirmed the processes addressed within the waste management development flowchart, they emphasized that developing a waste management plan highly depends on local codes and regulations, owners' green values, and contractors' financial incentives.

As depicted in Figure 9, the owner hires an asbestos investigator to conduct building survey and provide a report that addresses the existence of any hazardous materials within the building. Furthermore, a third party is assigned the responsibility of providing a report that reflects any historical features value that may exist within the building. Once the hazardous material and historical features value reports are ready, the owner creates the bid document and hires the general contractor. The general contractor then hires a demolition contractor to start the demolition process. The demolition contractor is responsible for submitting all requirements and reports to acquire the demolition permit. Depending on the size of the demolition contractor, the abatement process can be operated by the demolition contractor him/herself or by an abatement contractor.

After having the demolition permit issued, the demolition contractor is responsible to develop a waste management plan. If the owner has waste diversion goals, the waste management plan is required to satisfy those goals. There might be different reasons to establish a waste diversion goal by the owner. These reasons include complying with local codes (e.g., California Green Building Standards Code (CBSC, 2014)), pursuing green building certifications (e.g., LEED), or the commitment of the owner to green values (e.g., The Virginia Tech Climate Action Commitment Resolution, 2009).

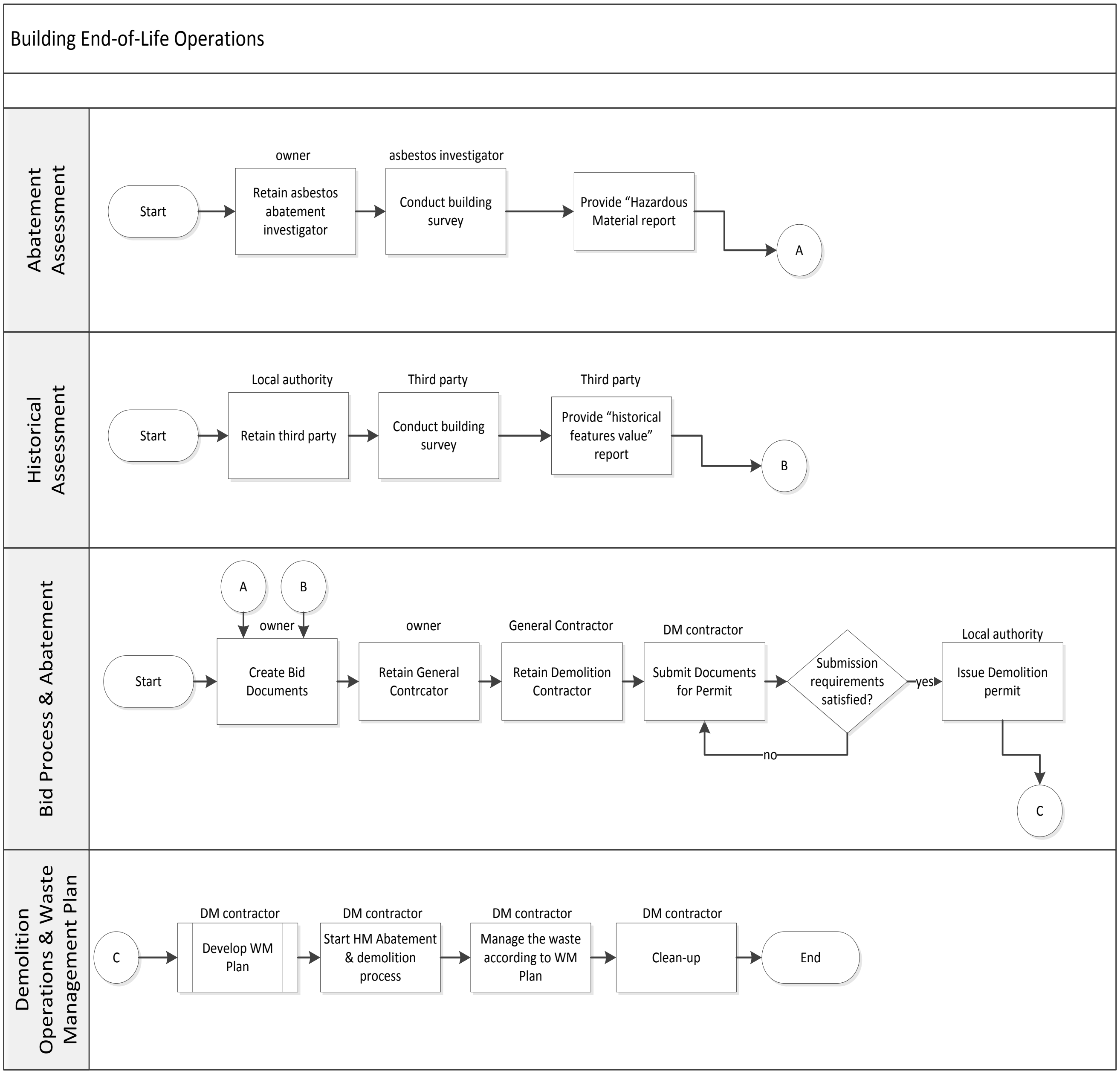

Figure 9: Building end-of-life operations

Figure 10 presents a flowchart to indicate processes involved in development of a waste management plan. The flowchart was developed as a synthesis of the existing waste management guidelines and reports (EPA, 2013; Resource Venture, 2005; Macozoma, 2002; Vleck, 2001). The flowchart starts with analyzing the generated waste to identify the waste types and quantities. Then the waste management goal is set in order to comply with minimum waste recovery requirements set by local/state authorities (e.g., California Green Building Standards Code (CBSC, 2014), NGOs (e.g., the U.S. Green Building Council (USGBC)) or fulfill the economic, environmental, or social objectives of the owner or the demolition contractor. For instance, the owner can set a goal to divert 50% of demolition waste from landfill in pursuing a LEED certification.

After the goal is set by the owner, the demolition contractor needs to identify possible demolition waste management alternatives. Each alternative should comply with the goal requirements specified within the contract. The alternatives should indicate the demolition operations, which are going to be conducted to remove the building (traditional demolition vs. deconstruction), as well as the destinations of each waste stream (e.g. reuse, recycling, incineration, landfill disposal).

The next step is to analyze the alternatives in order for the demolition contractor to select an alternative that does not only satisfies the waste management goal, but also is financially-feasible and environmentally and socially-responsible. That being said, conducting such analysis would be very challenging due to the complexity of the decision making process. Many studies have been conducted to streamline the analysis by developing and proposing various models, tools, and methods. Some of these studies only considered one individual impact of C&D waste in their analysis, while a few studies analyzed different waste management alternatives with a combination of two or more factors, e.g., economic, environmental, and social.

As depicted in Figure 10, the boundary and the scope of this study is concerned with the processes involved in developing the waste management plan including analyze generated waste, set waste management goals, and define and analyze the waste management alternatives.

To analyze the waste management alternatives, a set of information is required. The next section elaborates methods used to identify and classify the required information to support sustainable demolition waste management decision making and the end-of-life of a building.

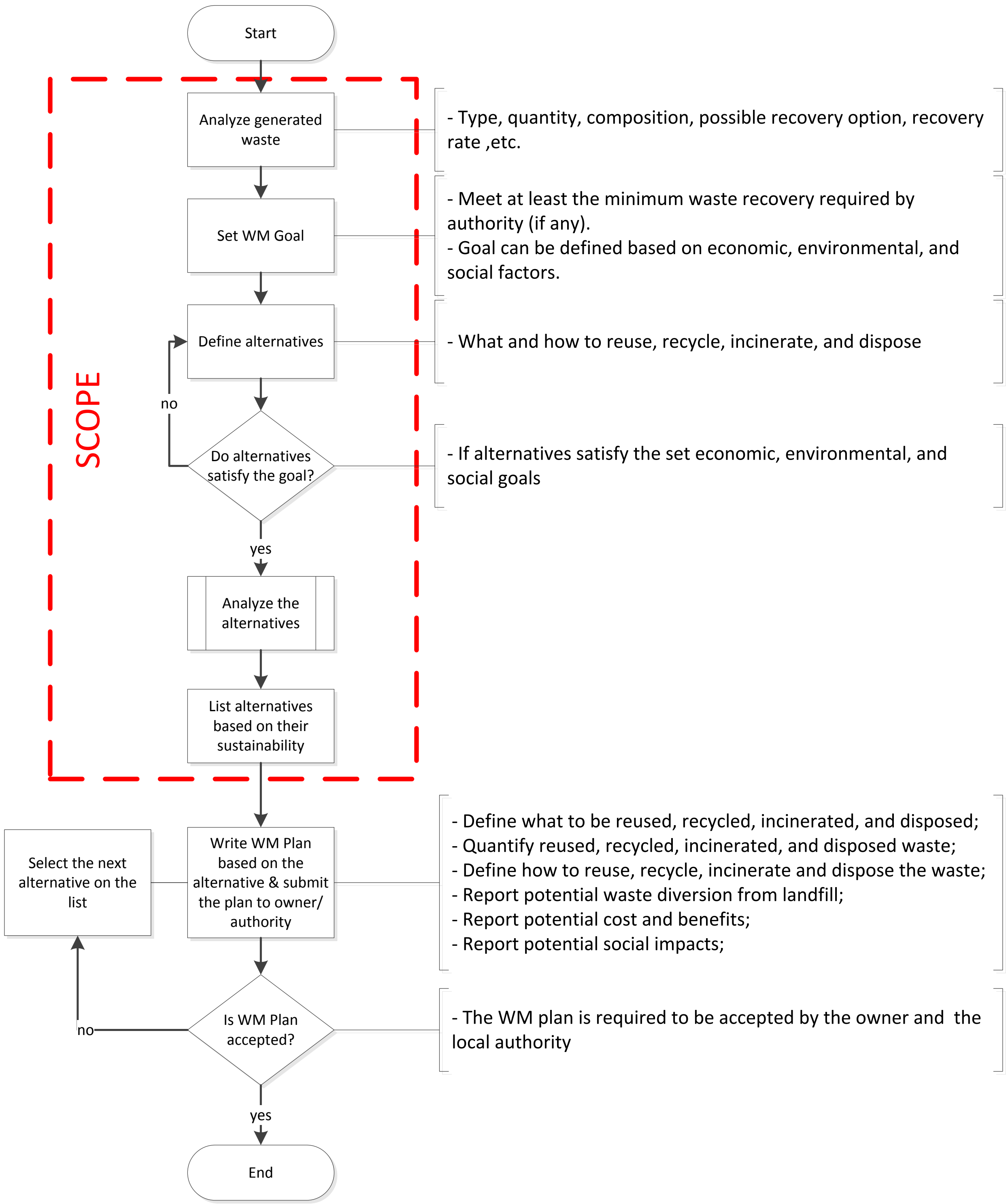

Figure 10: Demolition Waste Management Plan Development Flowchart

3.2. Identifying the Required Information

The following section describes different methods used to identify information required to analyze economic, environmental, and social impacts of demolition waste. The identified information is further classified based on its source of origin into four main categories including Information Protocols (e.g., IFC and COBie), Life Cycle Inventory Databases (LCIDB) (e.g., USLCI Database), Safety Codes & Standards (e.g., Local Safety Codes, OSHA Standards), and End-of-Life Stakeholders for information inquires (e.g., Demolition and Abatement Contractors, Salvage and Material Markets, and Recycling Facilities).

Information Required to Support Economic Impact Analysis

In order to identify information required to assess the economic impacts of demolition waste, cost-benefit analysis is used. The formulas for cost-benefit analysis are as follow:

Cost-benefit analysis = total cost of waste management - total benefits of waste management

- Cost of Waste Management = demolition cost + deconstruction cost + on-site sorting cost + total disposal cost + sorting facilities cost + transportation cost
    - Demolition cost = building area × unit cost of demolition
    - Deconstruction Cost = $\sum_{i=1}^{n} unit\ of\ assembly\ i\ \times unit\ cost\ of\ deconstruction\ of\ assembly\ i$
    - On-site sorting cost = total amount of waste required to be sorted on-site × unit cost of sorting
    - Total Disposal Cost = total waste disposed into public fill facilities and landfills × unit disposal cost
        - total waste disposed into public fill facilities = total inert waste (100% inert) disposed in public fill × unit public fill charge
        - total waste disposed into landfills = total mixed waste (<50% inert) disposed in landfills × unit landfill charge
    - Sorting Facility Cost = total mixed waste (>50% inert) sent to sorting facilities × unit sorting facilities charge
    - Transportation Cost = total disposal waste × unit cost of transportation
        - Total disposal waste = [total inert waste (100% inert) disposed into public fill + total inert waste (<50% inert) disposed in landfills + total inert waste (>50%

inert) sent to sorting facilities + total waste sent to recycling facilities* + total waste sent to Waste-to-Energy (WTE) facilities*]

* if the demolition contractor and the owner are responsible for delivering the waste to the recycling and WTE facilities the transportation cost applies.

- Total benefits of waste management = revenue from selling waste + saving due to prevented purchase costs of new materials + tax reduction due to donation to third party
  - Revenue from Selling Wastes = [total salvage waste sold within the market × unit value of salvage waste + total waste sold to recycling facilities × unit value of selling recycling waste + total waste sold to WTE facilities × unit value of selling incinerable waste]
  - Saving due to prevented purchase costs of new materials = total salvage waste reused on-site + unit price of new materials
  - Tax Reduction = total waste donated to the third party × unit tax reduction of donating the salvaged waste

The detailed information required for cost-benefit analysis of different waste management scenarios is presented in Table 4. The required information is further classified based on its source of origin into two sources, namely Information Protocols and End-of-Life Stakeholders (Table 4).

Table 4: Required Information to Support Cost-benefit Analysis and its Source of Origin

Information	Info. Covered in IFC/COBie	Info. inquired from End-of-Life Stakeholders
Building type	X	
Building location	X	
Building area	X	
No of stories	X	
Building assembly types	X	
Building assembly quantities	X	
Building product types	X	
Building product quantities	X	
Building material types	X	
Building material quantities	X	
Reusable assembly types		X
Reusable assembly quantities	X	
Reusable product type		X
Reusable product quantities	X	
Reusable material types		X
Reusable material quantities	X	
Recyclable material types		X
Recyclable material quantities	X	
Sorting unit cost for on-site sorting		X
Storage unit cost		X
Deconstruction unit cost		X
Landfill unit charge		X
Public fill unit charge		X
Sorting facility unit cost		X
Transportation unit charge		X
Transportation distance		X
Waste type (inert/non-inert)		X
On-site needs of reusable materials		X
Expected uselife of products		X
Expected uselife of assemblies		X
Processing cost on reusable materials		X
Retail prices of new materials		X
Market value of reusable materials		X
Unit value of recyclable materials		X
Incinerable product types		X
Incinerable product quantities	X	
Incinerable material types		X
Incinerable material quantities	X	
Unit value of incinerable materials		X
Tax deduction unit		X

Information Required to Support Environmental Impact Analysis

To identify information required to assess the environmental impacts of demolition waste, the LCA method is applied. Figure 11 highlights the demolition/deconstruction process as well as waste treatment scenarios. The red dashed lines represent the scope of LCA. The environmental and human health impacts of the waste management scenarios are presented bellow. The impacts that is colored in green represent the inputs (e.g., energy and raw materials), and the red coded impacts represent the outputs (e.g, CO2, H+, etc).

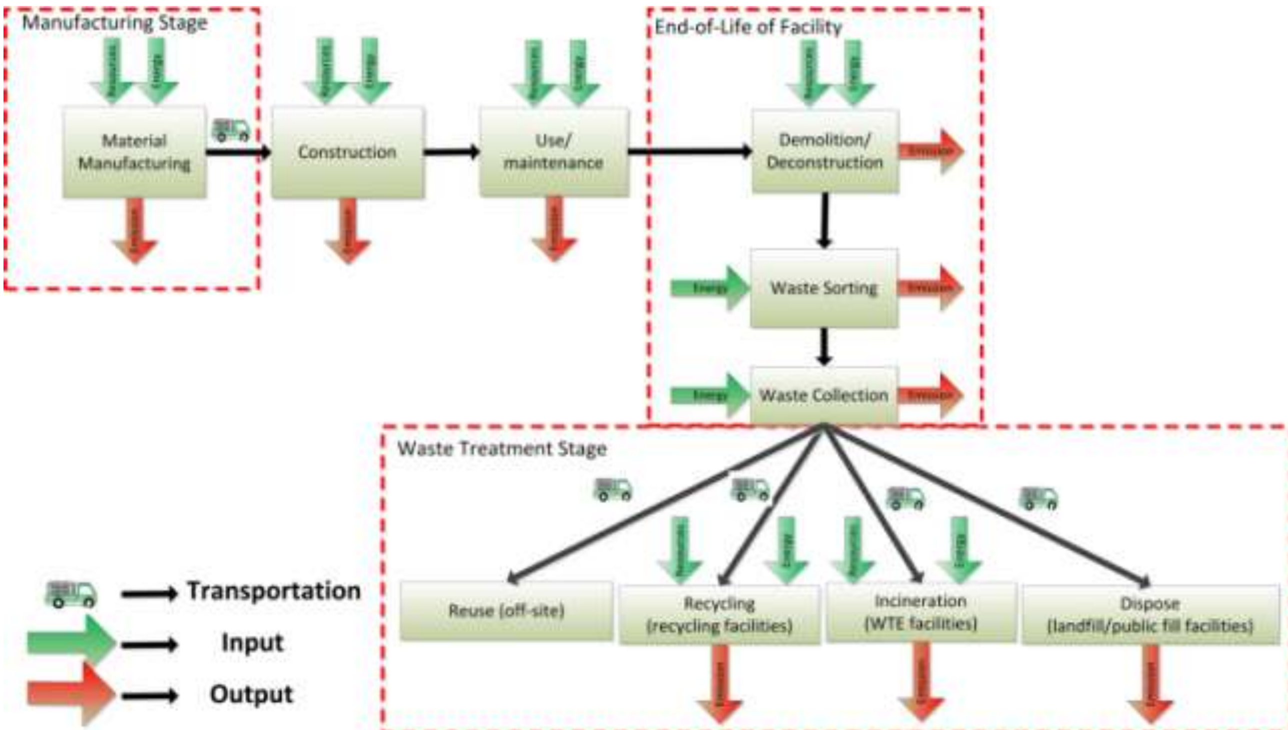

Figure 11: Waste management Scenarios - Inputs and Outputs

1. Manufacturing Stage (MS)
    a. raw material acquisition
    b. transportation to the manufacturing unit
    c. manufacturing process to make the final product
        - Input
            - Embodied Energy of Materials (MJ)
            - Resource Use/Raw Materials (Kg, L, M^3)
        - Environmental & Human Health Impact

- Global Warming Potential (Kg CO_2 eq.)
- Acidification Potential (Moles of H^+ eq.)
- Human Health Criteria (Kg PM10 eq.)
- Eutrophication Potential (Kg N eq.)
- Ozone Depletion Potential (Kg CFC-11 eq.)
- Smog Potential (Kg O_3 eq.)

2. End-of-Life Stage
   a. demolition/deconstruction of the whole building (D)
      - Input
        - Energy used to demolish/deconstruct the building (MJ)
      - Environmental & Human Health Impact
        - Global Warming Potential (Kg CO_2 eq.)
        - Acidification Potential (Moles of H^+ eq.)
        - Human health Criteria (Kg PM10 eq.)
        - Eutrophication Potential (Kg N eq.)
        - Ozone Depletion Potential (Kg CFC-11 eq.)
        - Smog Potential (Kg O_3 eq.)
   b. sorting the waste (S)
      - Input
        - Energy used to sort waste (MJ)
      - Environmental & Human Health Impact
        - Global Warming Potential (Kg CO_2 eq.)
        - Acidification Potential (Moles of H^+ eq.)
        - Human health Criteria (Kg PM10 eq.)
        - Eutrophication Potential (Kg N eq.)
        - Ozone Depletion Potential (Kg CFC-11 eq.)
        - Smog Potential (Kg O_3 eq.)
   c. collection of waste (C)
      - Input
        - Energy used to collect the waste (MJ)
      - Environmental & Human Health Impact
        - Global Warming Potential (Kg CO_2 eq.)
        - Acidification Potential (Moles of H^+ eq.)
        - Human health Criteria (Kg PM10 eq.)
        - Eutrophication Potential (Kg N eq.)
        - Ozone Depletion Potential (Kg CFC-11 eq.)
        - Smog Potential (Kg O_3 eq.)

3. Waste Treatment Stage
   a. transportation of the waste to the recycling facilities (TR)
      - Input
        - Energy used to transport the waste (MJ)
      - Environmental & Human Health Impact
        - Global Warming Potential (Kg CO_2 eq.)
        - Acidification Potential (Moles of H^+ eq.)

    - Human health Criteria (Kg PM10 eq.)
    - Eutrophication Potential (Kg N eq.)
    - Ozone Depletion Potential (Kg CFC-11 eq.)
    - Smog Potential (Kg O3 eq.)

b. recycling process (RW)
  - Input
    - Energy used in recycling facilities to recycle the waste (MJ)
    - Resource Use (Kg, L, M^3)
  - Environmental & Human Health Impact
    - Global Warming Potential (Kg CO2 eq.)
    - Acidification Potential (Moles of H+ eq.)
    - Human health Criteria (Kg PM10 eq.)
    - Eutrophication Potential (Kg N eq.)
    - Ozone Depletion Potential (Kg CFC-11 eq.)
    - Smog Potential (Kg O3 eq.)

c. transportation of the waste to the WTE facility (TI)
  - Input
    - Energy used to transport the waste (MJ)
  - Environmental & Human Health Impact
    - Global Warming Potential (Kg CO2 eq.)
    - Acidification Potential (Moles of H+ eq.)
    - Human health Criteria (Kg PM10 eq.)
    - Eutrophication Potential (Kg N eq.)
    - Ozone Depletion Potential (Kg CFC-11 eq.)
    - Smog Potential (Kg O3 eq.)

d. incineration of waste (IW)
  - Environmental & Human Health Impact
    - Global Warming Potential (Kg CO2 eq.)
    - Acidification Potential (Moles of H+ eq.)
    - Human health Criteria (Kg PM10 eq.)
    - Eutrophication Potential (Kg N eq.)
    - Ozone Depletion Potential (Kg CFC-11 eq.)
    - Smog Potential (Kg O3 eq.)

e. transportation of the waste to be reused off-site (TR)
  - Input
    - Energy used to transport the waste (MJ)
  - Environmental & Human Health Impact
    - Global Warming Potential (Kg CO2 eq.)
    - Acidification Potential (Moles of H+ eq.)
    - Human health Criteria (Kg PM10 eq.)
    - Eutrophication Potential (Kg N eq.)
    - Ozone Depletion Potential (Kg CFC-11 eq.)
    - Smog Potential (Kg O3 eq.)

f. transportation of the waste to the disposal destinations (TD)
  - Input

- Energy used to transport the waste (MJ)

- Environmental & Human Health Impact
  - Global Warming Potential (Kg CO_2 eq.)
  - Acidification Potential (Moles of H^+ eq.)
  - Human health Criteria (Kg PM10 eq.)
  - Eutrophication Potential (Kg N eq.)
  - Ozone Depletion Potential (Kg CFC-11 eq.)
  - Smog Potential (Kg O_3 eq.)

g. disposing inert waste into public fill facilities (DP)
  - Global Warming Potential (Kg CO_2 eq.)
  - Acidification Potential (Moles of H^+ eq.)
  - Human Health Criteria (Kg PM10 eq.)
  - Eutrophication Potential (Kg N eq.)
  - Ozone Depletion Potential (Kg CFC-11 eq.)
  - Smog Potential (Kg O_3 eq.)

h. disposing non-inert waste into landfill (DL)
  - Global Warming Potential (Kg CO_2 eq.)
  - Acidification Potential (Moles of H^+ eq.)
  - Human Health Criteria (Kg PM10 eq.)
  - Eutrophication Potential (Kg N eq.)
  - Ozone Depletion Potential (Kg CFC-11 eq.)
  - Smog Potential (Kg O_3 eq.)

- Environmental & Human Health Impacts:
  - Total Energy Consumption (MJ) = $\sum_{i=2}^{3}$ Energy Consumption i
  - Total Resource Use (Kg, L, M^3) = $\sum_{i=2}^{3}$ Resource Use i
  - Total Global Warming Potential (Kg CO_2 eq.) = $\sum_{i=2}^{3}$ Global Warming Potential i
  - Total Acidification Potential (Moles of H^+ eq.) = $\sum_{i=2}^{3}$ Acidification Potential i
  - Total Human health Criteria (Kg PM10 eq.) = $\sum_{i=2}^{3}$ Human Health Criteria i
  - Total Eutrophication Potential (Kg N eq.) = $\sum_{i=2}^{3}$ Eutrophication Potential i
  - Total Ozone Depletion Potential (Kg CFC-11 eq.) = $\sum_{i=2}^{3}$ Ozone Depletion Potential i
  - Total Smog Potential (Kg O_3 eq.) = $\sum_{i=2}^{3}$ Smog Potential i
- Environmental and Human Health Benefits due to reuse, recycling and incineration:
  - Saved Embodied Energy of Materials = Embodied Energy of materials during manufacturing stage that is preserved by recycling and reuse of the waste (MJ)).
  - Saved Resource Use = Use of resources to manufacture the materials that is saved at the end-of-life by reusing and recycling of the waste (Kg, L, M3).
  - Prevented Embodied Emissions of Materials at the Manufacturing Stage = Embodied Emissions of materials during manufacturing stage that is prevented due to recycling and reuse.
  - Prevented Emissions of Materials at the End-of-Life Stage = Emissions of materials due to disposal that is prevented due to recycling and reuse.

The detailed information required for LCA analysis for the waste management scenarios is presented in Table 5. The required information is further classified based on its source of origin into three sources, namely Information Protocols, Life Cycle Inventory Databases, and End-of-Life Stakeholders (Table 5).

Table 5: Required Information to Support LCA Analysis

Information	Covered in IFC/COBie	Info. Covered in LCIDB	Info. inquired from End-of-Life Stakeholders
Building type	X		
Building location	X		
Building area	X		
No of stories	X		
Building assembly types	X		
Building assembly quantities	X		
Building material types	X		
Building material quantities	X		
Reusable assembly types			X
Reusable assembly quantities	X		
Reusable product type			X
Reusable product quantities	X		
Reusable material types			X
Reusable material quantities	X		
Recyclable material types			X
Recyclable material quantities	X		
Waste type (inert/non-inert)			X
Incinerable product types			X
Incinerable product quantities	X		
Incinerable material types			X
Incinerable material quantities	X		
Average equipment diesel consumption per hour			X
Average hours of equipment operations using diesel fuel			X
Average equipment electricity consumption per hour			X
Average hours of equipment operations using elec.			X
Embodied energy of assemblies		X	
Embodied emission of assemblies		X	
Embodied energy of materials		X	
Embodied emission of materials		X	
Energy consumption by recycling facilities		X	
Emissions by recycling facility		X	
Transportation type			X
Emissions due to incineration		X	
Emissions from landfill		X	
Emissions from public fill		X	

Information Required to Support Social Impact Analysis

This study considers the social impacts resulting from the end-of-life activities within two main categories including *Safety* and *Quality of Life*. Each category is further divided into sub-categories. These factors have been through the OSHA standard for demolition activities (2014) and literature survey (Yuan, 2012; Yuan et al., 2013).

- Safety
    - Short term/immediate safety considerations
        - Exposure to hazardous materials (OSHA, 2014)
            - Crystalline silica-containing materials (e.g., concrete, brick, tile, mortar).
            - Asbestos Containing Materials (ACM) (e.g., thermal system insulation, vinyl floor tile, home siding & shingles, transit (including cement piping), flame retardant materials (e.g., gloves, curtains) and roof flashing)
            - Lead-based paint materials (e.g., painted surfaces and pipes)
            - Flammable and combustible materials
        - Physical working conditions (OSHA, 2014; Yuan, 2012)
            - Open edges
            - Confined spaces
            - Bearing capacity (e.g. floor)
            - Application of the structural members (bearing vs. non-bearing)
            - Deteriorated structural elements
            - Locations of all utility lines
            - Noise pollution
        - Long-term safety consideration (human health problems resulting from emissions due to generated waste during demolition and waste treatment stages) (LCA)
- Quality of Life (Yuan, 2012; Yuan et al., 2013)
    - Employment
    - Land use due to landfilling (LCA)
    - Resource depletion (LCA)

Since there is currently no methodology to evaluate all social impacts, this study focused on two impact areas to identify the required information. Impacts related to long-term safety (*human health*), *land use* and *resource depletion* were evaluated in the previous section using the LCA methodology. For the purpose of assessment of the other social impact categories related to worker safety, this study analyzed the OSHA Demolition Codes under 1926 Subpart T - Demolition standard (2014). The social impact related to employment opportunities and job growth is not included in the scope this study. Further explanation on this limitation is discussed in the limitation section.

OSHA Safety Codes Analysis:

The OSHA safety codes address the possible hazards that may exist in a demolition project including exposure to hazardous materials, falling from openings, noise and air pollutions, etc. (OSHA, 2014) The codes, which have been extracted from the OSHA website are presented as Appendix A. The detailed information required for providing a safe environment during the demolition and waste management operations is presented in Table 6. The required information is further classified based on its source of origin into three sources, namely Information Protocols, Safety Codes and Standards, and End-of-Life Stakeholders.

Table 6: Required Information to Support Social Analysis

Information	Info. covered in IFC/COBie	Info. addressed in Safety Codes & Standards	Info. inquired from End-of-Life Stakeholders
Building type	X		
Building location	X		
Building area	X		
No of stories	X		
Building assembly types	X		
Building assembly quantities	X		
Building product types	X		
Building product quantities	X		
Building material types	X		
Building material quantities	X		
Raw material types	X		
Raw material quantities	X		
Crystalline silica-containing material types		X	X
Crystalline silica-containing material quantities	X		
Crystalline silica-containing material locations	X		
Asbestos Containing Material (ACM) types		X	X
Asbestos Containing Material (ACM) quantities	X		
Asbestos Containing Material (ACM) locations	X		
Lead-based paint material types		X	X
Lead-based paint material quantities	X		
Lead-based paint material locations	X		
Flammable and combustible material types		X	X
Flammable and combustible material quantities	X		
Flammable and combustible material locations	X		
Corrosive, or toxic material types		X	X
Corrosive, or toxic material quantities	X		
Corrosive, or toxic material locations	X		
Bearing capacity of structural elements	X		X
Applications of structural members (bearing Vs. non-bearing)	X		
Deteriorated structural elements			X
Locations of all utility lines	X		X
Potential openings to consider fall protection	X		X
Noise level of equipment			X
Confined Spaces (storage tanks, ventilation, exhaust ducts) location	X		X

Summary of Information Identification

The first step to manage the generated waste sustainably is to identify information that is required to support decision making analyses. This chapter elaborated the methods used to identify the information required to support sustainable demolition waste management decision making practice. The identified information was further classified based on its source of origin into four information sources including Information Protocols (e.g., IFC and COBie), Life Cycle Inventory Databases (e.g., USLCI Database), Safety Codes and Standards (e.g., Local Safety Codes, OSHA Standards), and End-of-Life Stakeholders for information inquiries (e.g., Demolition and Abatement Contractors, Salvage and Material Markets, and Recycling Facilities).

The sources of information addressed in this chapter are fragmented at the end-of-life operations, which makes the decision-making process a very resource-demanding and time-consuming task in terms of data collection and data management. In response to this obstacle, the next chapter elaborates methods used to develop an object-oriented data model. The proposed model aims to offer a method for storing and managing end-of-life information in an efficient and effective manner to support sustainable demolition waste management decision making at the end-of-life of a building.

4. OBJECT-ORIENTED DATA MODEL FOR SUPPORTING INFORMATION MANAGEMENT AT THE END-OF-LIFE

After the required information was identified and classified based on its source of origin, this chapter discusses how the information can be collected from the information sources and managed within an integrated data repository. To achieve this, an object-oriented data model is proposed. The aim of the model is to offer a method for storing and managing end-of-life information in an efficient and effective manner to support sustainable demolition waste management decision making at the end-of-life of a building.

In order to visualize and construct the object-oriented data model, Unified Modeling Language (UML) was used. The UML is a set of models and notations that has become the standard language used for graphically depicting object-oriented models (Naiburg and Maksimchuk, 2001). UML allows us to represents multiple perspectives of a system by providing different types of graphical diagrams. This study uses the following graphical diagrams:

4.1. Use Case Diagrams

The use case diagram is used to capture the functions that are the behavioral requirements of a system. In other words, the use case diagram informs us how a system should work, and elaborate the interactions between the developed system and various actors and other systems (Ref). This study developed two use case diagrams based on information analysis in Chapter 3. The required information was identified and classified based on its source of origin within four information sources including Information Protocols (e.g., IFC and COBie), Life Cycle Inventory Databases (e.g., USLCI Database), Safety Codes and Standards (e.g., Local Safety Codes, OSHA Standards), and End-of-Life Stakeholders for information inquiries (e.g., Demolition and Abatement Contractors, Salvage and Material Markets, and Recycling Facilities). The developed use cases illustrate how the waste manager can interact with other information sources in order to collect the required information at the end-of-life of a building.

Use Case Diagram #1: The first use case diagram highlights how the waste manager collects information from the stakeholders at the end-of-life of a building (Figure 12). For instance, the waste manager needs to make inquiries from the demolition contractor, abatement contractor, and salvage market to collect information on total demolition cost, total abatement cost, and unit value of salvage materials respectively. To verify the use case diagram, three interviews were conducted with practitioners. All the practitioners have been actively involved in waste management activities at the end-of-life of multiple projects. The recruitment approach as well as the structure of the interviews are further discussed in Chapter 5, Section 5.1. The sets of information, from Chapter 3, Section 3.2, were presented to the interviewees and the processes of data collection were discussed with them. The interviews verified the stakeholders and data collection processes depicted within the Figure 12.

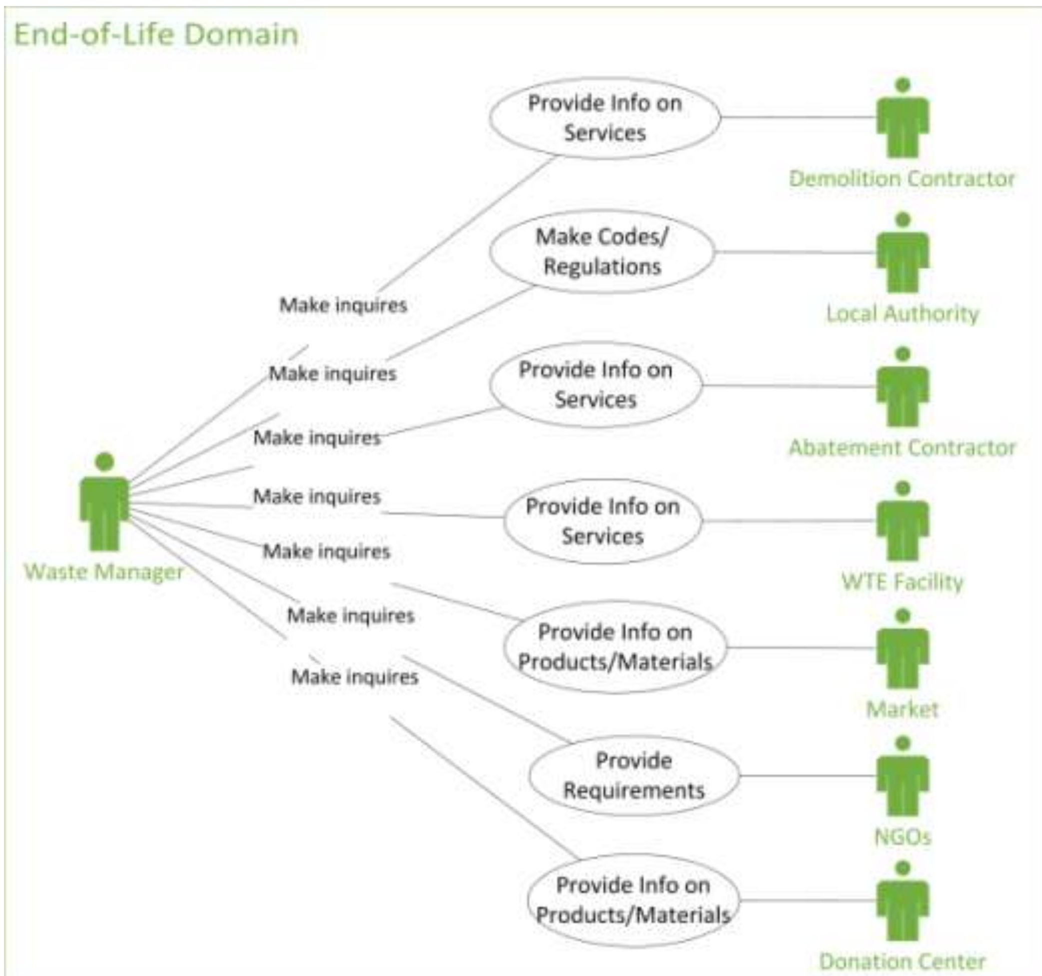

Figure 12: End-of-Life Domain Use Case

Use case Diagram #2: The first use case diagram elaborated how the information can be collected from different stakeholders at the end-of-life of a building. The second use case diagram is further proposed to demonstrate how the information from other data sources, including Life Cycle Inventory Databases (e.g., USLCI database), BIM-based Model (e.g., Revit model), and Safety Codes & Standards (e.g., OSHA Standards for Demolition), can be stored within the proposed object-oriented data model (Figure 13). The stored information is further can be retrieved to be used for conducting economic, environmental, and social analysis of the generated waste.

In the context of the proposed sustainable waste management system (use case diagram #2), it is assumed that the BIM-based model covers as-built information of the building and being updated during the building lifecycle. This requirement of using as-built BIM-based model is further discussed in Chapter 6, Section 6.1. Once the required information is loaded from the external data sources, the information is stored within related UML classes, which will be discussed in the next section. The use case diagram #2 will be used as the main structure of a sustainable waste management prototype application, which will be discussed in Chapter 5.

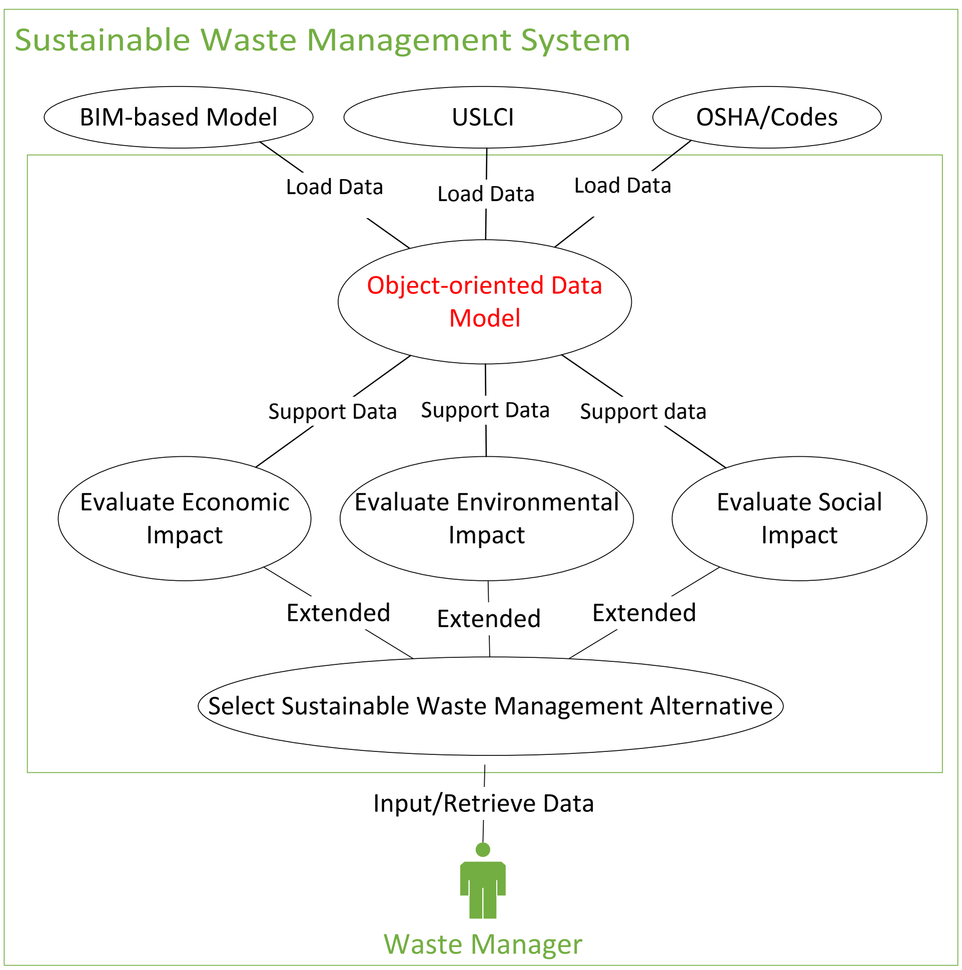

Figure 13: Sustainable Demolition Waste Management Use Case

4.2. UML Class Diagrams

The object-oriented data model is developed as a UML Classification. Figure 14 illustrates the whole UML classification to give a general presentation of the model, while Figure 15, 16, and 17 elaborate the detailed presentation of the classification.

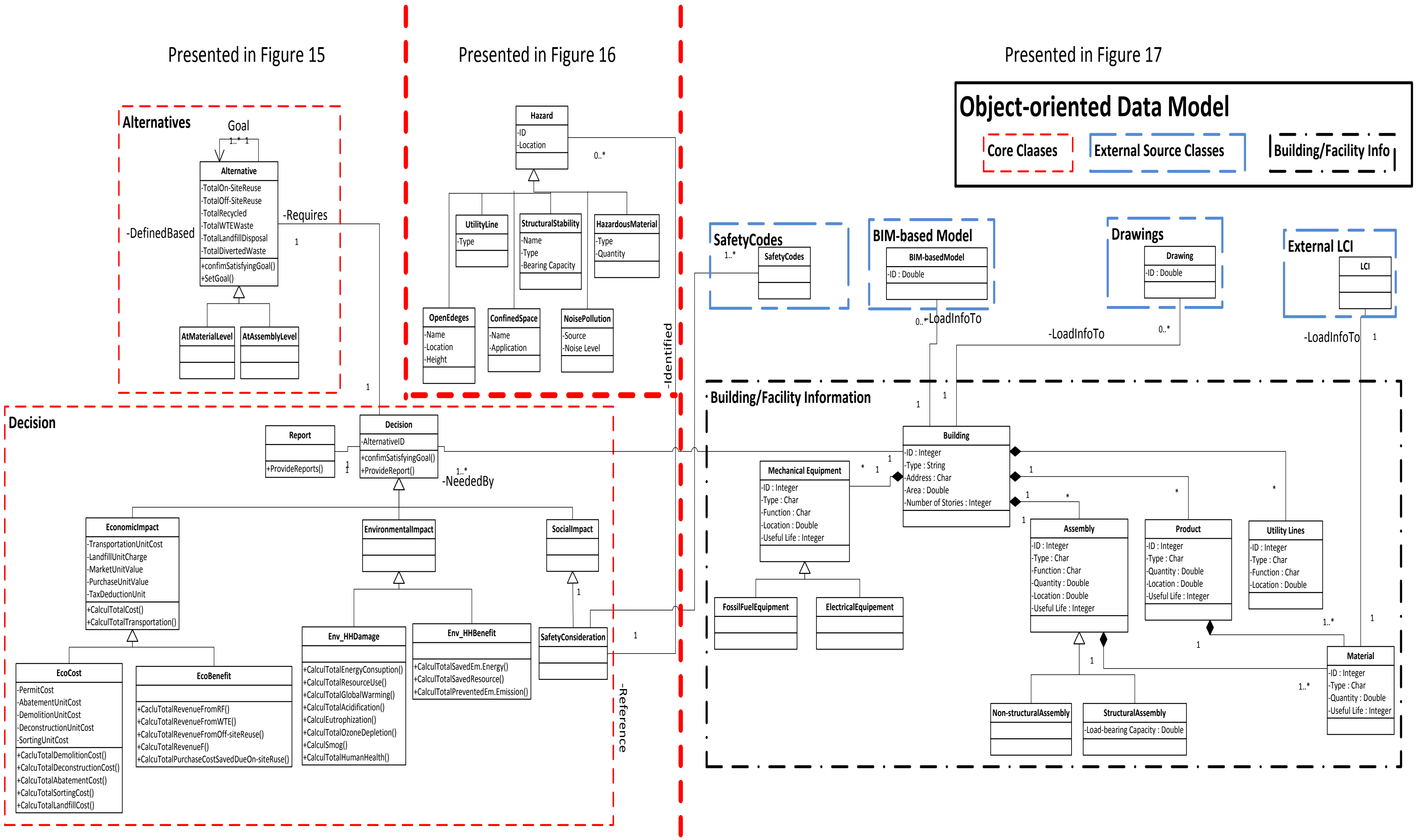

Figure 14: Object-oriented Data Model - UML Classification

The classification consists of multiple classes, which encapsulates the information required to support sustainable demolition waste management. The core of the classification is the `Goal`, `Alternative`, and `Decision` (Figure 15). The `Goal` class holds variables related to the waste management goal set by the waste manager. As an example, to set the goal of total diverted waste, the waste manager needs to refer to any codes and requirements set by the authority and the NGOs. The goal also requires the fulfillment of the owner's needs and satisfaction. The `Alternative` class, which consists of two subclasses of `AtMaterialLevel`, and `AtAssemblyLevel`, aims to hold variables of different waste management alternatives as well as confirm that each alternative complies with the waste management goal. The `Alternative` class, further, requires the `Decision` class to evaluate the economic impacts (`EconomicImpact` class), environmental and human health impacts (`EnvironmentalImpact` class), and social impacts (`SocialImpact` class) of the defined alternatives. Each of these classes, which operate to evaluate the impacts of alternatives, consists of subclasses. `EcoCost` and `EcoBenefit` are two subclasses of the `EconomicImapct` class that evaluate and report the costs and benefits associated with each alternative respectively. `Env_HHDamge` and `Env_HHBenefit` are two subclasses of the `EnvironmnetalImapct` class aiming to evaluate and report the environmental and human health damages and benefits associated with each alternative respectively.

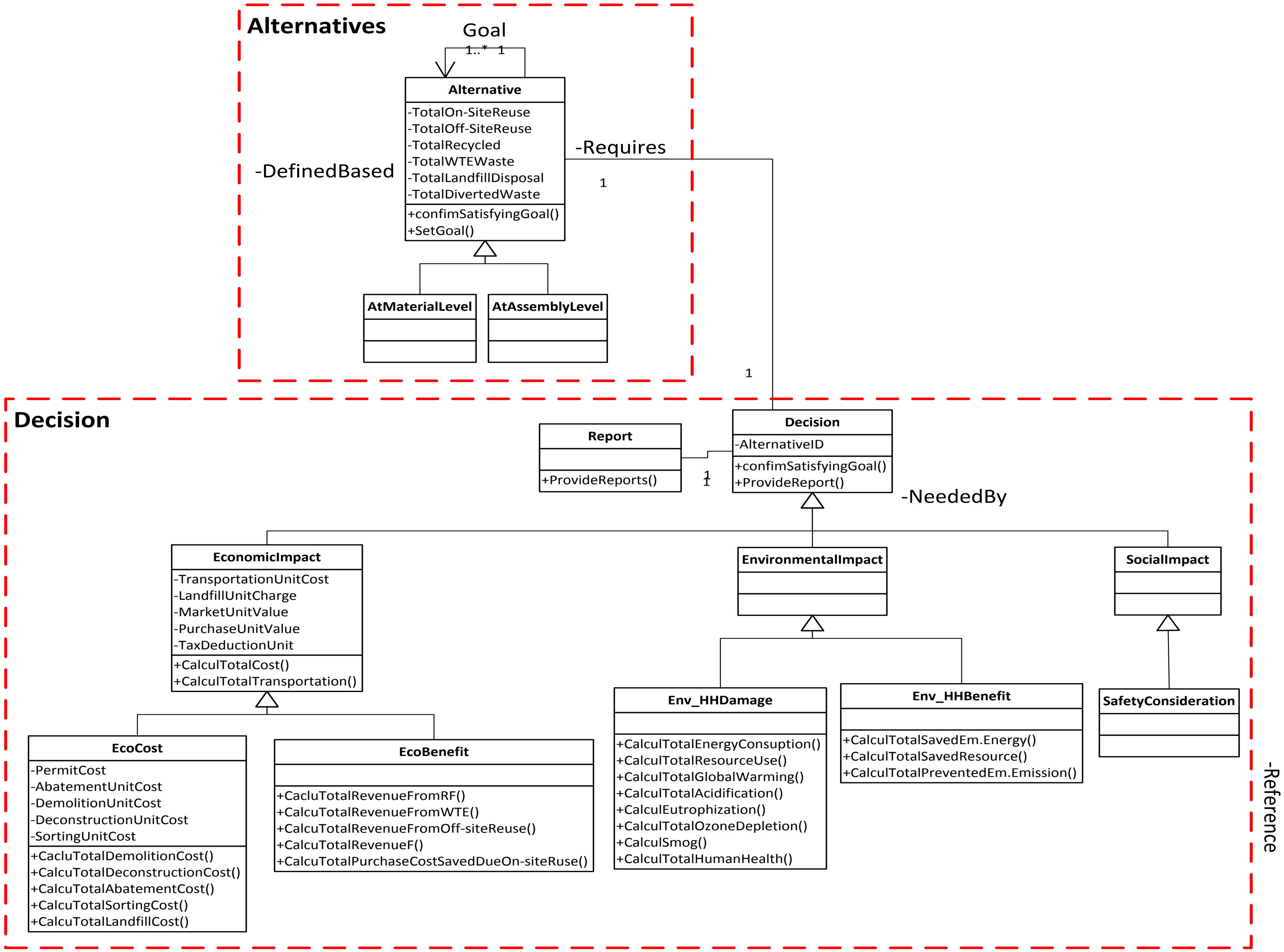

Figure 15: UML Core Classes

Furthermore, the `SocialImpact` class captures the possible hazards associated with the waste management practice as well as safety instructions to mitigate the hazards. The `Hazard` class lists possible hazards that may exist on the job site and consists of subclasses including `HazardousMaterial`, `StructuralStability`, `NoisePollution`, `UtilityLine`, `OpenEdges`, and `ConfinedSpace` (Figure 16). The `SafetyCode` class is structured according to the existing demolition and waste management codes and holds the safety information related to demolition and waste management practices. Finally, the `Report` class encapsulates the information related to the decision-making analyses (from the `Decision` class) and provides reports for the waste manager.

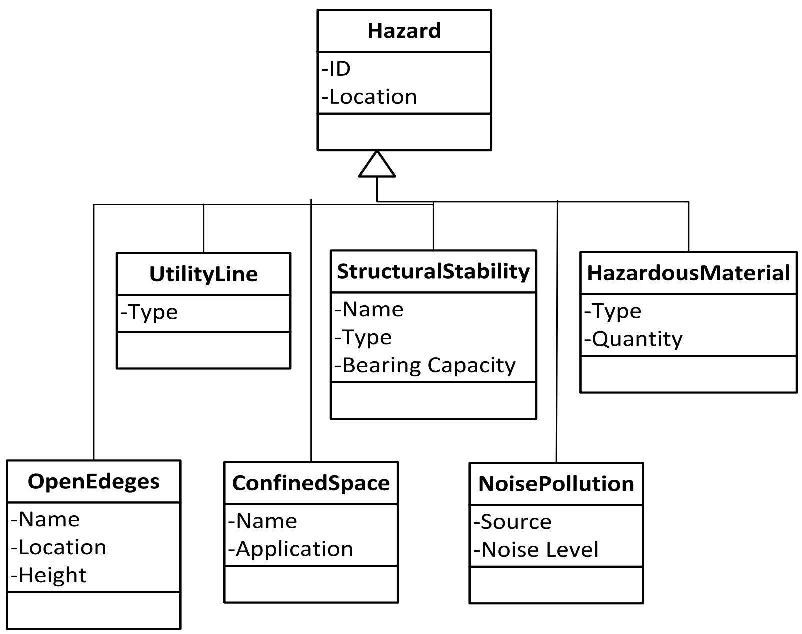

Figure 16: UML Hazard Class

In addition to the above-mentioned classes, the object-oriented data model consists of other classes associated with physical building properties (Figure 17). The aim of these classes/subclasses is not only to store data, but also to provide required data for classes that operate impact assessments (`EconomicImapct`, `EnvironmnetalImapct`, and `Social`). The `Building`, `Material`, `Assembly`, `Product`, `UtilityLine`, `UtilityEquipment`, `ConfinedSpace`, and `OpenSpace` classes hold data related to the building/facility. The `LCI` class holds material data required to conduct the environmental and human health impact analysis.

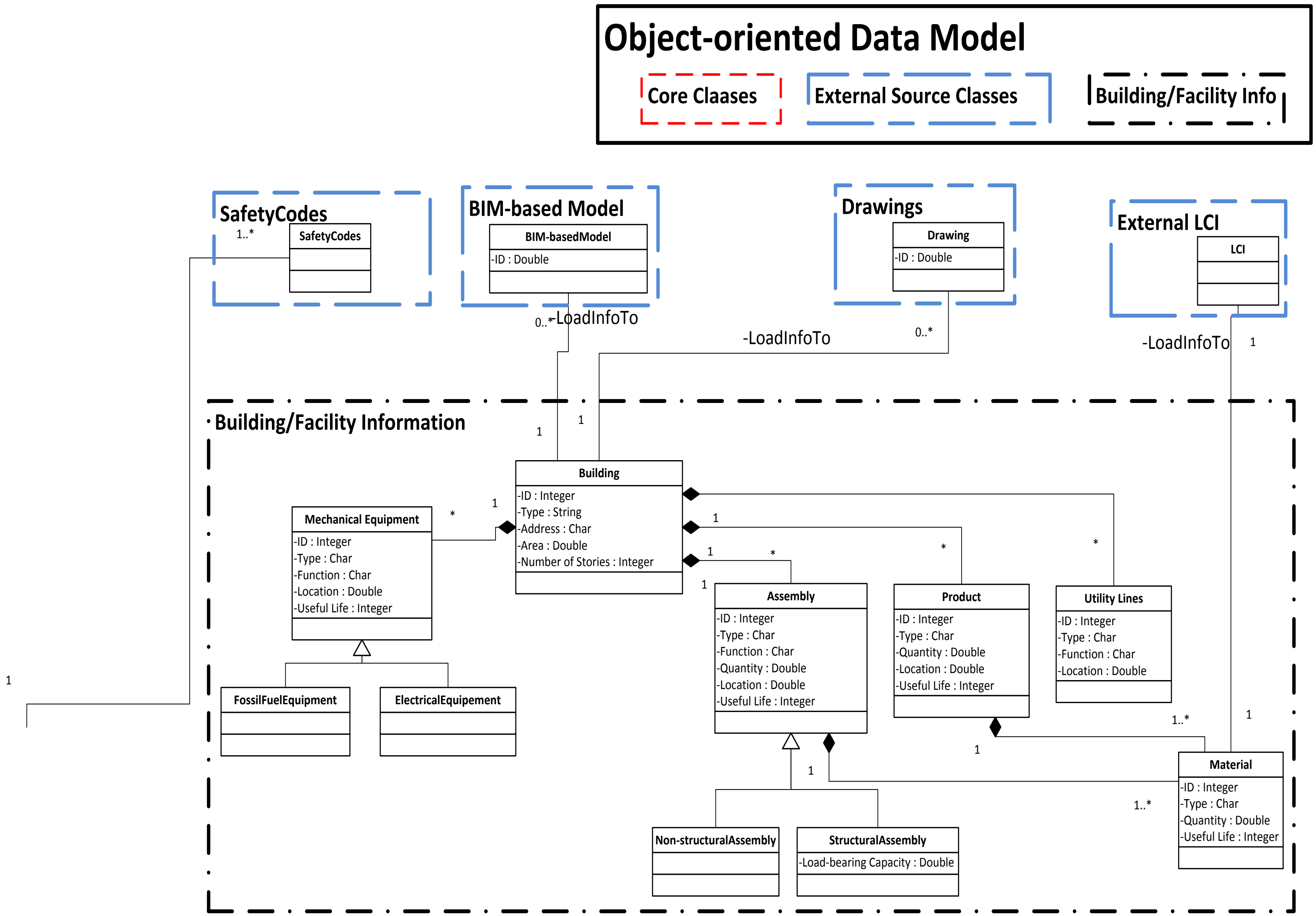

Figure 17: UML External Source and Building/Facility Info Classes

4.3. Sequence Diagram

A Sequence Diagram is an interaction diagram that shows how classes and objects interact in a given situation. The sequence diagram is used for presenting how processes, within a system, operate with one another. For the purpose of this study, managing demolition waste generated at the end-of-life of a one-story residential building is determined as an example to show how the classes interact. The waste manager is responsible to manage the generated waste by taking all three pillars of sustainable development into consideration including economic development, environmental concerns, and social responsibilities.

In order for the waste manager to interact with the information in the data model, a `WMApplication` (waste management application) class is defined. The `WMApplication` class consists of various user interfaces. Each user interface either collects information from or provides information to the waste manager. The following sequence diagrams illustrate how the waste manager interacts with the `WMApplication` class and the other classes within the object-oriented data model.

As depicted in Figure 18, the waste manager launches the waste management application and either loads the building-related information from the BIM-based model, in this case Revit model, or enters the information through building drawings. The information, which is captured at this stage include types and quantities of assemblies and materials of the given building. The building-related information is then stored into `Building`, `Assembly`, `Product`, and `Material` classes. The waste manager then sets the waste management goal through inquiry of the owner and the NGOs in order to make sure that the goal fulfills their requirements. Furthermore, the waste manager is required to review local codes in order to comply with regulations. The attributes of the goal address variables such as estimated demolition and waste management cost, expected benefits of selling materials, expected completion date of end-of-life operations, and waste diversion. After setting the goal, the waste manager defines the waste management alternatives and confirms that the defined alternatives comply with the goal. To define each alternative, the waste manager is responsible for determining various variables such as final destinations for waste (e.g., on-site reuse, off-site reuse, recycling facility, landfill) and transportation type (e.g., truck or ship). The goal and alternative information is stored into `Goal` and `Alternative` classes through the waste management application. At this point, the building-related information and variables for the goal and alternatives are stored into related classes.

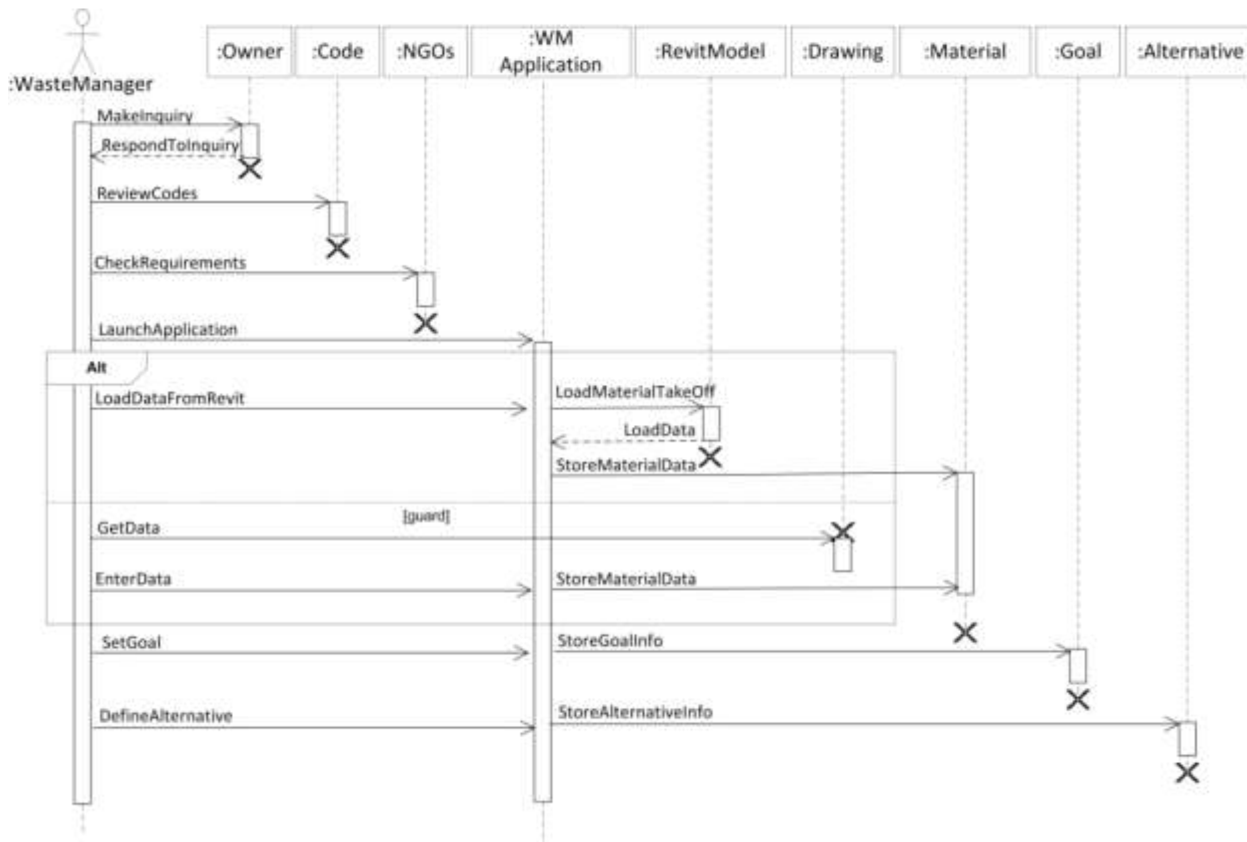

Figure 18: Sequence Diagram - Setting Goals and Alternatives

To analyze the economic impacts of an alternative (Figure19), the waste manager needs to make inquiries from different parties. For instance, the waste manager needs to make inquiries from the demolition contractor in order to determine the costs associated with demolition, deconstruction, sorting, storage, and transportation activities. Furthermore, the waste manager needs to determine the permit cost and disposal cost by referring to local authority. Other incurring costs and market value for the salvaged materials can be gained from waste management facilities including sorting facilities, recycling facilities, waste-to-energy facilities, and the salvage market. After gaining the information, which is required for economic decision-making analysis from various parties, the information is stored into `EconomicImpact` class through the waste management application. The Decision class is further initiated by an order of the waste manager through the waste management application. The `Decision` class retrieves the required information from `EconomicImpact` and `Alternative` classes and calculates the costs and benefits associated with each alternative. Finally, the `Report` class produces economic impact reports to help the waste manager evaluate the economic impacts of each waste management alternative that was proposed for the given building.

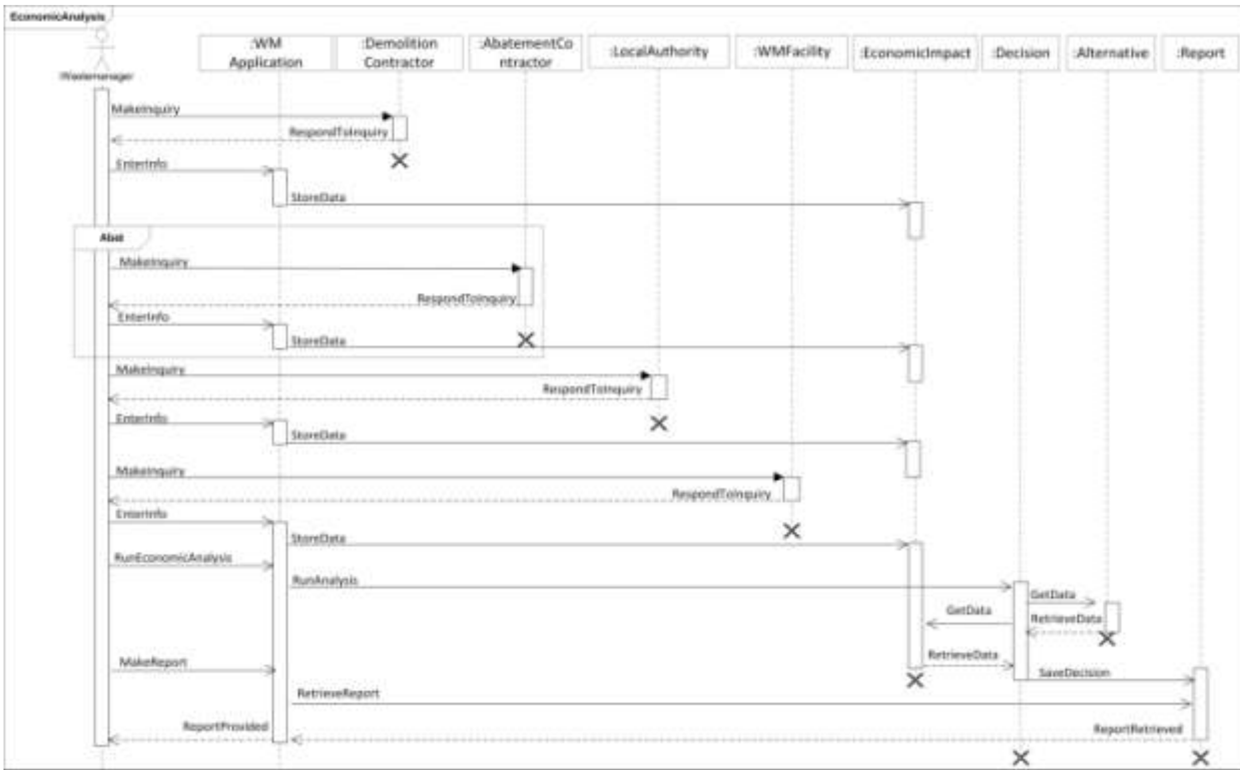

Figure 19: Sequence Diagram - Economic Analysis

The same scenario repeats for the environmental and human-health impact analysis (Figure 20). The waste manager collects the required information through the demolition contractor and waste management facilities. The information collected at this stage includes types of equipment used in demolition and deconstruction of the given building, sorting, storing, and transporting the generated waste as well as the distances to the waste management facilities. Furthermore, processes involved in recycling and energy recovery of the waste are required to be identified by the waste manager. After making inquiries on equipment and processes, the related information is stored within the `EnvironmentalImpact` class through the waste management application.

In addition to the above information, the environmental decision-making analysis requires an extensive Life Cycle Inventory (LCI) database. The LCI database intends to deliver information on energy and the materials used in the given building (inputs) and wastes (outputs) released to the environment as the result of the building end-of-life operations. The LCI database helps the waste manager to assess the impact of those inputs and outputs to the environment and human health (Anon, 1993). Once the `LCIDatabase` class is loaded through the waste management application, the data is stored into the `EnvironmentalImpact` class. The `Decision` class is further initiated by an order of the waste manager through the waste management application. The `Decision` class retrieves the required information from `EnvironmentalImpact` and `Alternative` classes and calculates the environmental and human health impacts associated with each alternative. Finally, the `Report` class produces reports to help the waste manager to evaluate the environmental and human health impacts of each waste management alternative that was proposed for the given building.

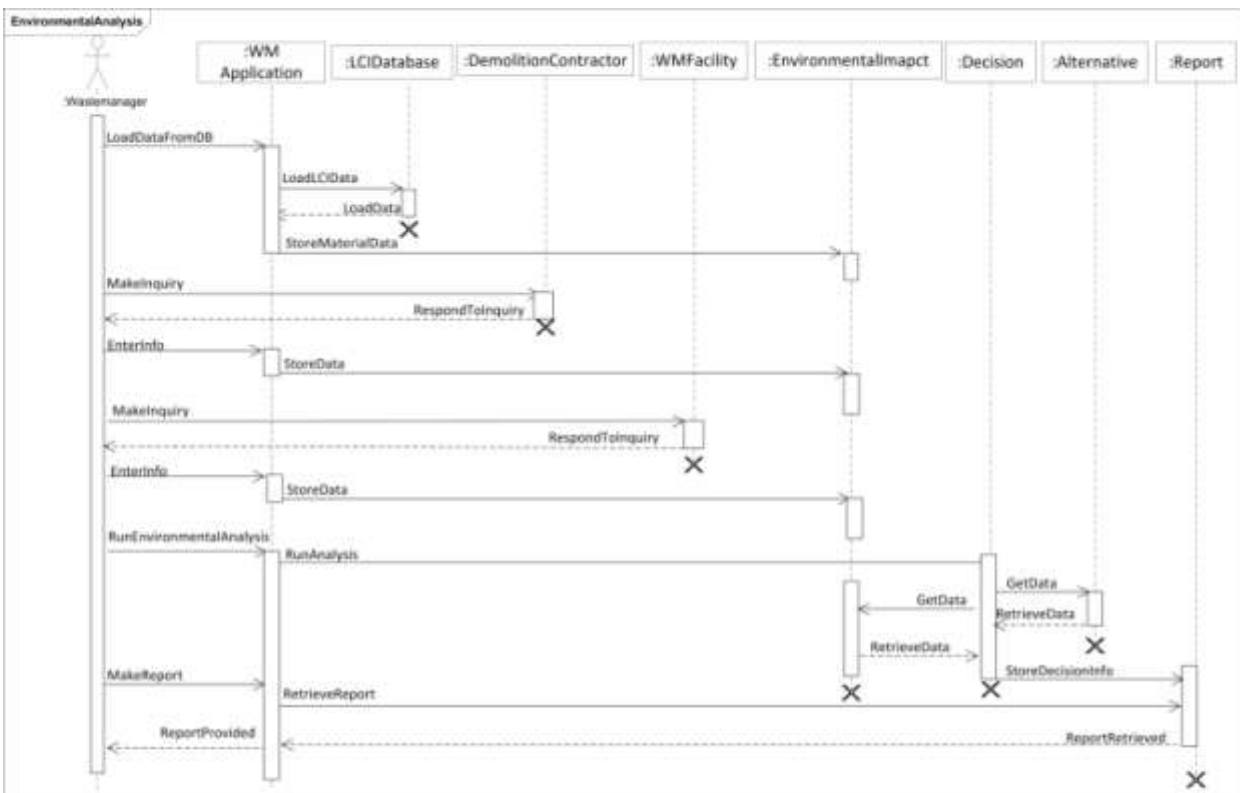

Figure 20: Sequence Diagram - Environmental Analysis

The social analysis aims to identify hazards on the job site and provides safety instructions to mitigate possible short and long term injuries. Unlike the economic and environmental impact analyses, which concentrate on the waste management alternatives, the social impact analysis is focused on general activities involved in the end-of-life operations of the given building. Therefore, regardless of the waste management alternative, the safety analysis identifies hazards and provides necessary safety instructions to the waste manager and the demolition contractor in order to prevent injuries. Figure 21 illustrates how the waste manager and the demolition contractor can interact with the object-oriented data model using the waste management application.

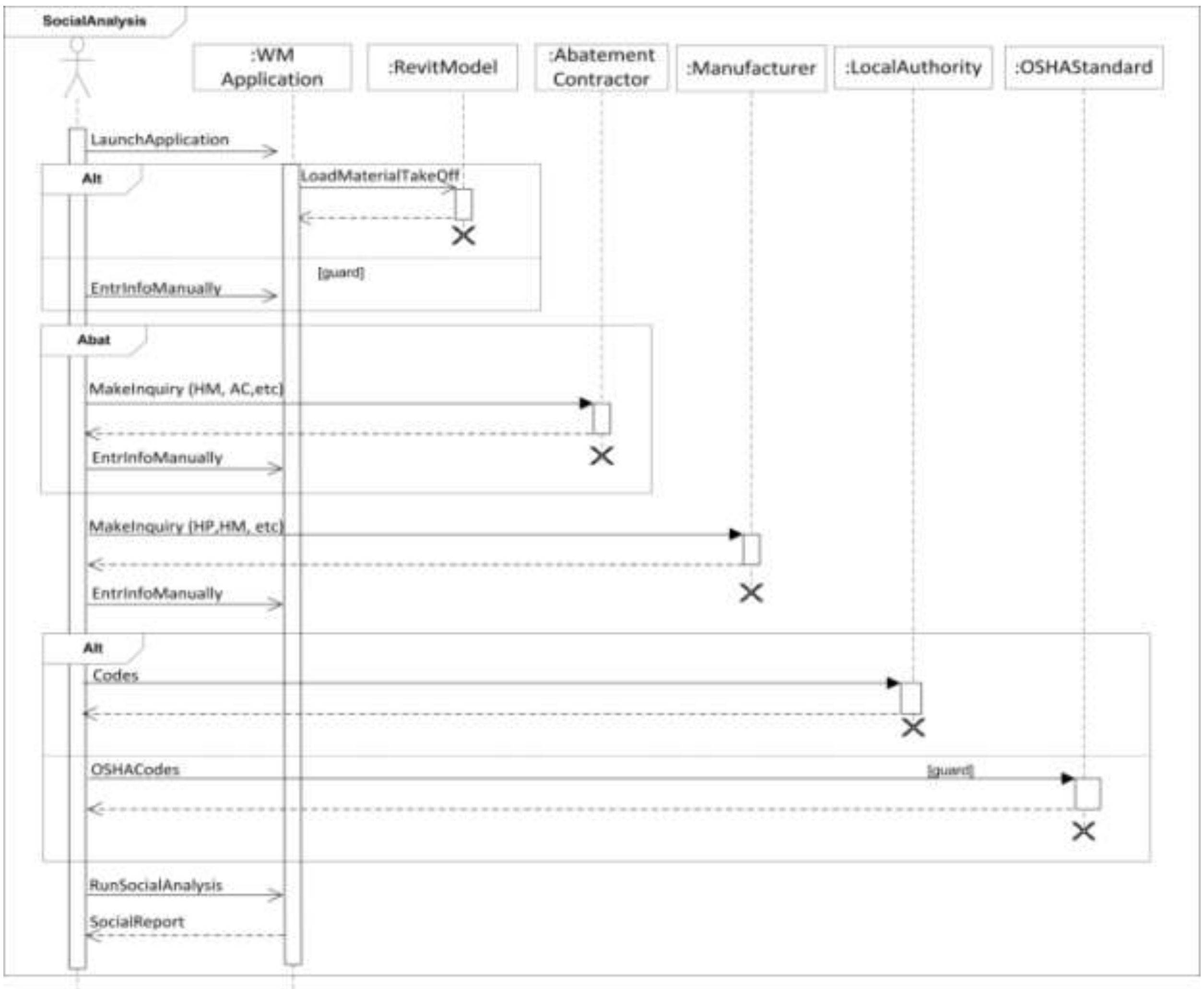

Figure 21: Sequence Diagram - Social Analysis

The waste manager as well as the demolition contractor are responsible to identify possible hazards before the actual demolition and waste management activities for the building can be launched (Figure 21). The possible hazards can be identified by on-site survey (e.g., confined spaces, deteriorated structural elements, and working level height more than 6') and Revit-based model and drawings (e.g, locations of electrical wires and gas tanks, bearing capacity of structural elements, etc.). Furthermore, the abatement contractor is required to conduct tests in order to identify the existence of any hazardous materials, such as asbestos-containing and lead-painted materials. After identifying the hazards on the site, the information is stored within the `Hazard` class by either the waste manager or the demolition contractor using the waste management application. Furthermore, possible safety impacts of the identified hazards are predicted and stored within the `SafetyImapct` class. For instance, the possible safety impact of a deteriorated structural element could be injuries or death due to structural collapse. Cancer could be also a long term safety impact on workers who are exposed to lead-painted materials.

Once the user runs the social analysis, the Decision class is initiated by retrieving hazards information from the Hazard class as well as safety instructions from the `SafetyCode` class. The Decision class then identifies proper safety instructions according to the hazards. Finally, the social analysis report is provided to the waste manager and the demolition contractor by the `Report` class, which encompasses the results of a decision-making analysis conducted within the `Decision` class.

Summary of Object-oriented Data Model Development

This chapter illustrated the methods used to develop the object-oriented data model. The development of data model was presented using UML diagrams including UML Classification Diagrams, Use Case Diagrams, and Sequence Diagrams. The Use Case diagrams were created to identify the main stakeholders involved in the end-of-life operations, and to indicate the interactions between these stakeholders. Furthermore, the structure of the UML Classification diagram was depicted to present classes, objects, and operations required to store and manage the information identified in Chapter 3. The sequence diagrams were then developed to illustrate how the UML classes can interact with each other in order to support sustainable demolition waste management practice at the end-of-life of a building. The developed sequence diagrams will be further used to develop the sustainable waste management application at Chapter 5.

5. VERIFICATION OF THE OBJECT-ORIENTED DATA MODEL

The objective of this chapter is to verify the object-oriented data model within the domain of end-of-life operations. For this purpose, three characterizations of the data model need to be verified including 1) scope, 2) flexibility, and 3) implementability (Turkaslan-Bulbul and Akin, 2007). Scope refers to information coverage of the proposed OODM. Flexibility addresses potential adaptability of the model for future expansions. Finally, implementability verification is used to illustrate that the proposed OODM supports sustainable demolition waste management decision making at the end-of-life of a building. Each of these steps is further discussed within this chapter.

5.1. Scope - Verify Information Coverage

Chapter 3 discussed the methods and sources that were used to identify the required information that should to be included within the OODM. That being said, the information coverage of the OODM needs to be further verified. This study considered interviewing the industry practitioners to get their feedback on the information coverage of the OODM. To recruit the interviewees, nine industry practitioners, including five demolition contractors, two owners, and two general contractors, were contacted through phone calls and emails. These practitioners have been actively involved with multiple demolition projects throughout the State of Virginia. Three out of nine contacted practitioners agreed to attend the interview. Those include one owner, one general contractor, and one demolition contractor. The interviews were conducted individually and face to face. Each interview took approximately one hour.

The interview started with giving an introduction about the purpose of this study and elaborating the end-of-life operation process model. Then the cognitive walkthrough method, which aims to familiarize the interviewees to application user interfaces (Spencer, 2000), was used to illustrate the sustainable demolition waste management prototype application. It was explained to the interviewees that how information can be loaded from external sources such as BIM-based model. Furthermore, other user interfaces were demonstrated to the interviewees to show them how the required information can be collected from the other stakeholders (e.g., market value of salvage materials), and saved within the application database.

While explaining the prototype application user interfaces to the demolition contractor, he expressed his interest in the Define Alternative tab. He believed it is a great idea to develop an application that would be able to save attributes for different waste management alternatives, and evaluate the impacts of each alternative. He highlighted that the importance of this feature is to evaluate the costs and benefits of each alternative. On the other hand, the owner expressed his interest in environmental analysis reports. He emphasized that this feature can help owners pursue their green values more wisely.

Once the prototype application was illustrated to the interviewees, they were asked to provide their feedback on the information coverage of the proposed application. To streamline the feedback process, the sets of information in Chapter 3, including required information for cost-benefit analysis (Tables 4), environmental impact analysis (Table 5), and social analysis (Table 6), were presented to the interviewees. The interviewees were asked to confirm or reject the presented information by giving a check mark. The overall coverage of the information was verified by the interviewees. However, two interviewees addressed one factor, which was not covered by the OODM. That factor was information on spaces surrounding the building. The information on the surrounding spaces is required for the demolition contractor to lay out the demolition and waste management activities in a way to make sure the safety of the workers and people outside of the job-site is guaranteed.

5.2. Flexibility - Adaptability of the Model for Future Expansions

One of the challenges in developing data models is maintaining the model despite changes. The flexibility of the model can be verified if future changes and expansions can be applied within the model without a need for restructuring the entire model (Turkaslan-Bulbul, 2006). The proposed OODM was developed based on the object-oriented data modeling method. In this method, the structure of the model consists of objects, attributes, and operations. Each object represents a component within the end-of-life operations (e.g., building assembly, building material, hazardous material, etc). One of the important characteristics of the OODM method is that objects, attributes, and operations can be simply added, changed, and deleted without disturbing the function of the model. For instance, at the scope verification stage, it was determined that information on surrounding spaces was not considered within the OODM. That being said, the `Surrounding Space` class and its related attributes were simply added to the model without disturbing the structure and function of the model (Figure 22).

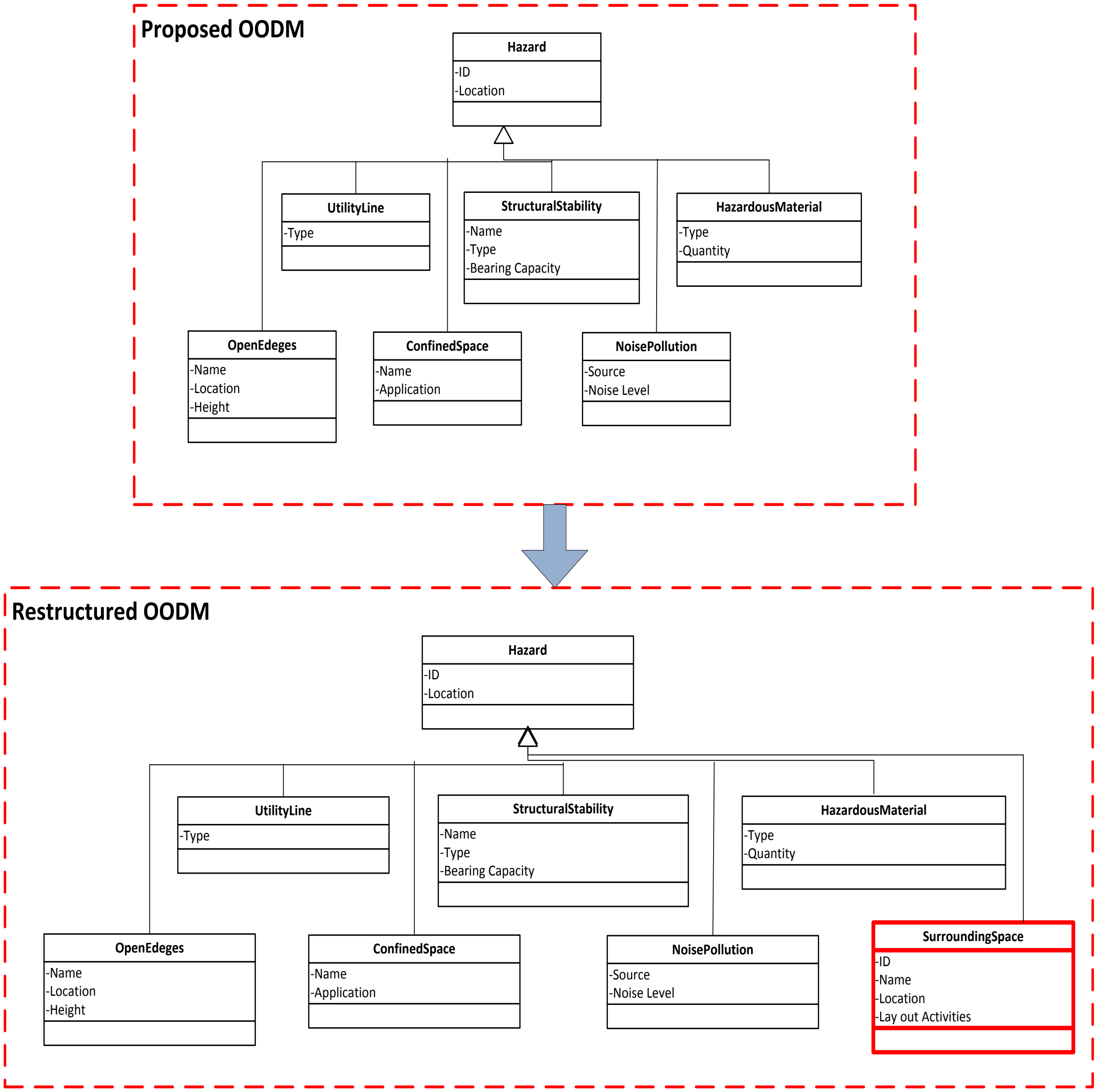

Figure 22: OODM Flexibility

5.3. Implementability

A case study analysis was conducted to demonstrate the implementability of the proposed object-oriented data model. Two steps were taken in order to develop the case study a) develop a prototype application that allows the user to interact with the OODM, and b) conduct economic, environmental, and social analyses for the case study. The case study along with the two steps are presented in the following sections.

Case Study Analysis

The case study is a single-family wood-frame building in Blacksburg, VA (Figure 23). The Revit model of the building was provided by Habitat for Humanity and used for retrieving material and assembly types (Figure 24) and quantities. To analyze economic, environmental, and social impacts of the generated waste at the end-of-life of the case study, the following two steps were taken:

Figure 23: Case Study 3D Model

a) Develop a Prototype application that allows the user to interact with the OODM through user interfaces

A sustainable waste management application was developed to demonstrate how the user can interact with the OODM. The user interfaces were developed to illustrate how the required information can be either loaded from external databases or collected directly from the end-user. The order of the user interfaces were structured based on Sequence Diagrams presented in Chapter 4. In addition, the information that is collected within the user interfaces represents information that was identified in Chapter 3. Finally, all the collected information is stored within the UML Classes, which was presented in Chapter 4, Section 4.2, to be retrieved for the purpose of sustainable demolition waste management decision making for the generated waste at the end-of-life of the case study. The prototype application user interfaces are depicted and discussed throughout the next step.

b) Conduct economic, environmental, and social analyses for the case study

This step elaborates processes that need to be followed by the user in order to analyze the economic, environmental, and social impacts of the generated waste at the end-of-life of the case study.

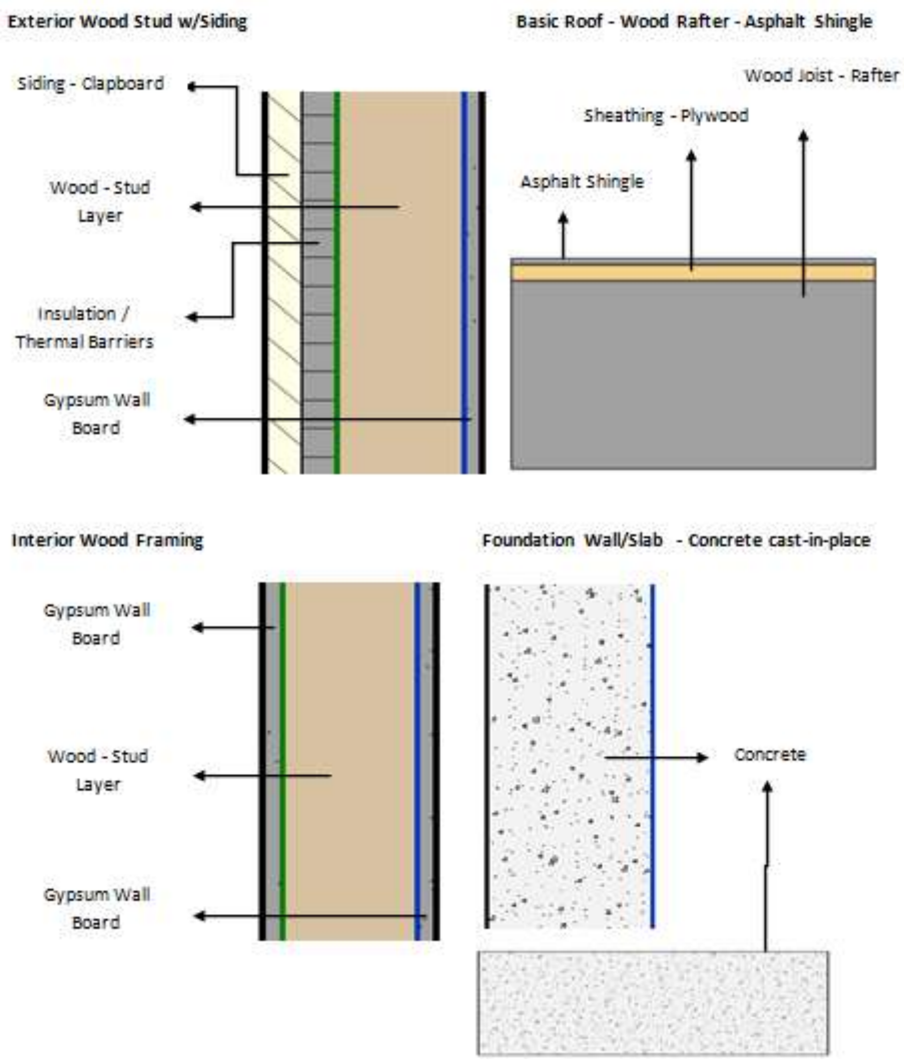

Figure 24: Structural Assemblies of the Case Study - Extracted from Revit Model

Create a New Project

The first interface collects general information on the case study (Figure 25). The information includes project name, building type, number of stories, address, building height, and the gross floor area of the building. All general information about the building is stored as attributes within the `Building` class.

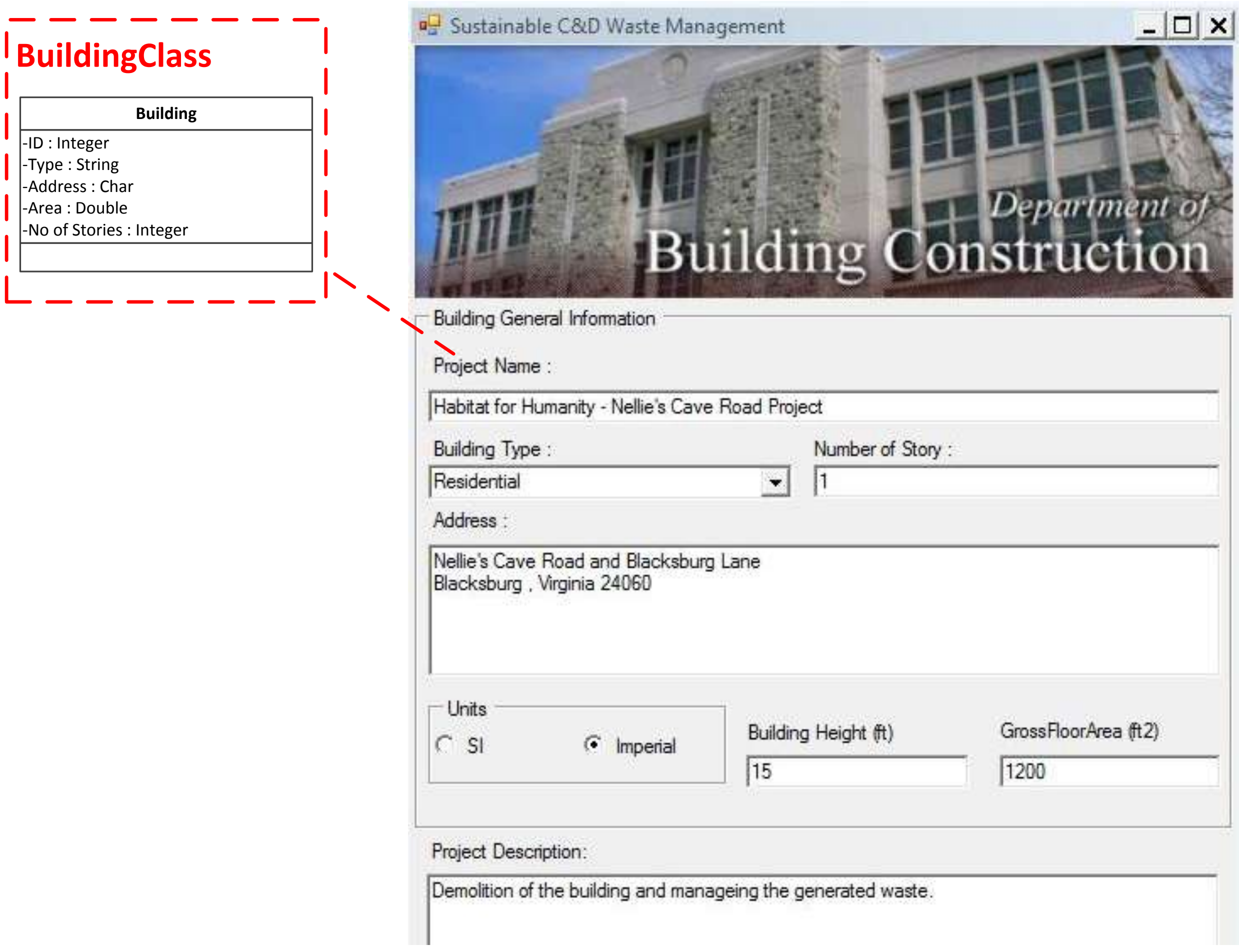

Figure 25: New Project Interface

Load Building-related information from Revit

The building-related information on assemblies and materials were exported from the Revit model of the case study in Excel format (Figure 26). This information included `Assembly Code`, `Assembly Description`, `Material Name`, `Material Area`, and `Material Volume`. The information is then loaded into the application. Figure 27 represents the imported information within the WM application.

	A	B	C	D	E
1	Assembly Code	Assembly Description	Material: Name	Material: Area	Material: Volume
2	A1010200	Foundation Walls	Concrete - Cast-in-Place Concrete	41 SF	27.56 CF
3	A1010200	Foundation Walls	Concrete - Cast-in-Place Concrete	6 SF	4.00 CF
4	A1010200	Foundation Walls	Concrete - Cast-in-Place Concrete	25 SF	16.44 CF
5	A1010200	Foundation Walls	Concrete - Cast-in-Place Concrete	67 SF	44.44 CF
6	A1010200	Foundation Walls	Concrete - Cast-in-Place Concrete	65 SF	43.11 CF
7	A1010200	Foundation Walls	Concrete - Cast-in-Place Concrete	24 SF	16.00 CF
8	A1010200	Foundation Walls	Concrete - Cast-in-Place Concrete	4 SF	2.67 CF
9	A1010200	Foundation Walls	Concrete - Cast-in-Place Concrete	19 SF	12.44 CF
10	A1010200	Foundation Walls	Concrete - Cast-in-Place Concrete	4 SF	2.67 CF
11	A1010200	Foundation Walls	Concrete - Cast-in-Place Concrete	17 SF	11.11 CF
12	A1010110	Strip Footings	Concrete - Cast-in-Place Concrete	190 SF	69.00 CF
13	A1010110	Strip Footings	Concrete - Cast-in-Place Concrete	30 SF	9.00 CF
14	A1010110	Strip Footings	Concrete - Cast-in-Place Concrete	105 SF	37.00 CF
15	A1010110	Strip Footings	Concrete - Cast-in-Place Concrete	273 SF	100.00 CF
16	A1010110	Strip Footings	Concrete - Cast-in-Place Concrete	265 SF	97.00 CF
17	A1030400	Foundation Slab	Concrete - Cast-in-Place Concrete	123 SF	40.87 CF
18	A1030400	Foundation Slab	Concrete - Cast-in-Place Concrete	64 SF	21.33 CF
19	A1030400	Foundation Slab	Concrete - Cast-in-Place Concrete	992 SF	330.59 CF
20	B10	Superstructure	Concrete - Cast-in-Place Concrete	10 SF	2.00 CF
21	B10	Superstructure	Concrete - Cast-in-Place Concrete	10 SF	2.00 CF
22	A1010100	Footings & Pile Caps	Concrete - Cast-in-Place Concrete	16 SF	4.00 CF
23	A1010100	Footings & Pile Caps	Concrete - Cast-in-Place Concrete	16 SF	4.00 CF
24	A1010200	Foundation Walls	Concrete - Cast-in-Place Concrete	13 SF	8.43 CF
25	A1010200	Foundation Walls	Concrete - Cast-in-Place Concrete	26 SF	17.22 CF

Figure 26: Extracted Info from Revit in Excel Format

In case of any needed changes in the assembly and material information, the user can manually makes his/her changes. The information is then stored within the `Assembly` class and `Material` class within the Structured Query Language (SQL) database to be retrieved later for the purpose of the decision making.

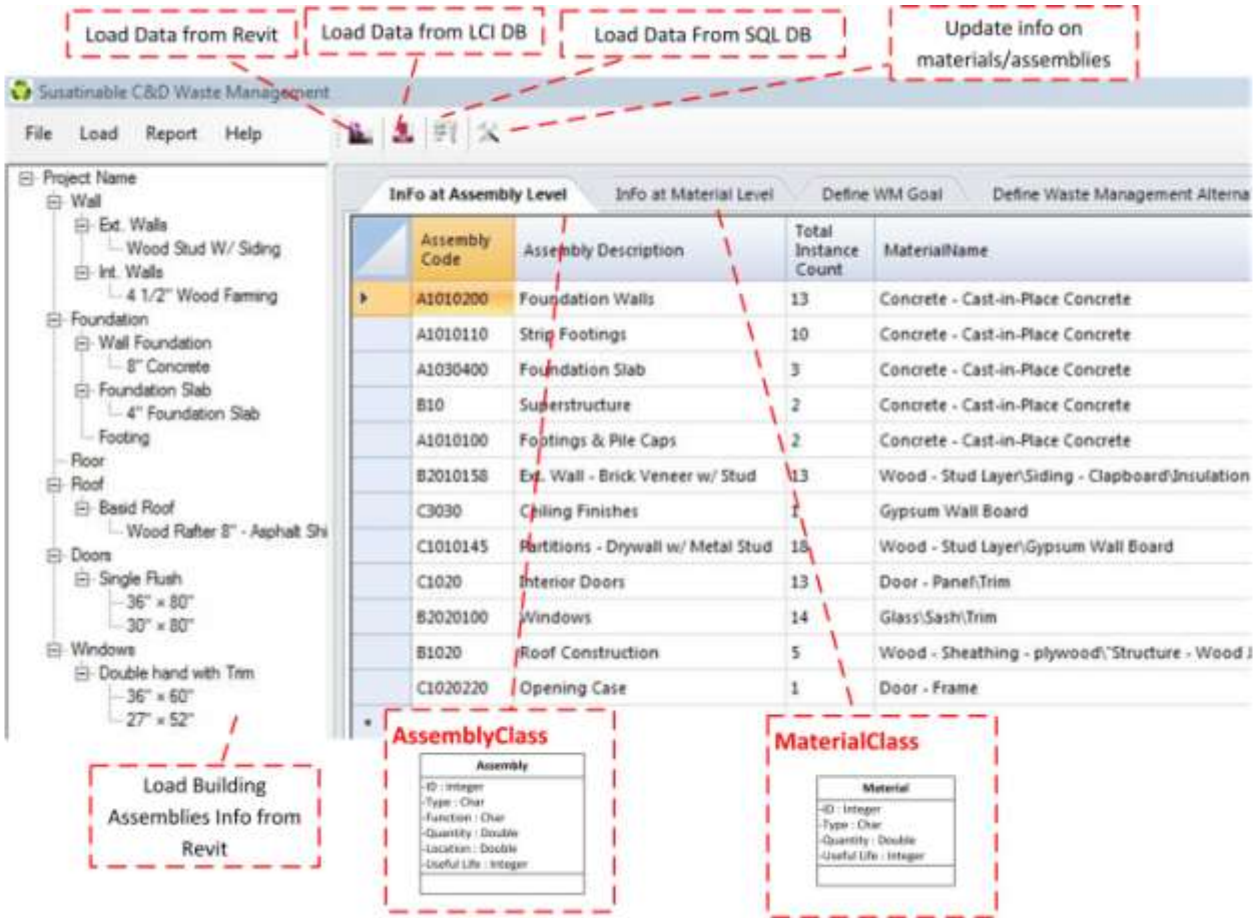

Figure 27: Building-related Info Loaded from Revit

Demolition Waste Estimation

C&D waste estimation has always been a critical factor in waste management decision making. Previous studies have been conducted to address C&D waste estimation (Poon et al., 2001; Jalali, 2007). This application estimates the generated waste resulting from demolition of the case study at its end-of-life. Figure 28 depicts the information that was retrieved from the SQL database. Furthermore, the values including demolition volume and demolition weight were calculated. In this figure, the demolition factor represents the coefficient of demolition volume. For instance if the volume of a wall foundation assembly is 213 CF, after demolishing the building the demolition volume would increase to 235.15 CF (213.78 CF × 1.1 = 235.15 CF). The demolition volume is especially important if transportation cost is calculated based on the volume of the generated waste. Furthermore the densities of the materials are used to calculate the weight of the generated waste. The weight of waste is critical in order to calculate costs and benefits as well as environmental impacts of the generated waste.

InFo at Assembly Level | InFo at Material Level | Define WM Goal | Define Waste Management Alternatives | Analysis and Report

ID	Material Name	Material Area (SF)	Volume (CF)	Demolition Factor	Demolition Volume (CF)	Density (lb/CF)	Demolition Weight (lb)	Waste Type
261	Concrete - Cast-in-Place Concrete	323	213.78	1.1	235.158	150	32067	inert
262	Concrete - Cast-in-Place Concrete	1144	406	1.1	446.6	150	60900	inert
263	Concrete - Cast-in-Place Concrete	1179	392.79	1.1	432.069	150	58918.5	inert
264	Concrete - Cast-in-Place Concrete	20	4	1.1	4.4	150	600	inert
265	Concrete - Cast-in-Place Concrete	32	8	1.1	8.8	150	1200	inert
266	Wood - Stud Layer	1472	427.07	1.05	448.4235	1.42	606.4394	Non-inert
267	Wood - Stud Layer	956	278.64	1.05	292.572	1.42	395.6688	Non-inert
268	Siding - Clapboard	1452	120.86	1.12	135.3632	31	3746.66	Non-inert
269	Insulation / Thermal Barriers - Semi-rigi...	1458	121.22	1.1	133.342	2	242.44	Non-inert

Figure 28: Waste Estimation Interface

Another attribute of the generated waste is the type of the waste. The waste can be inert or non-inert. This application has pre-defined settings for each material. Knowing the total amount of inert and non-inert waste is important in order to calculate disposal costs. Inert waste is required to be disposed into public fill facilities while non-inert waste has to be disposed into landfills.

Although the attributes including demolition factor, density, and type of waste are predefined for each material, they can be modified by the user using the setting form (Figure 29). For instance, concrete is considered as inert waste. However, if any lead-based painting leaks into the concrete then the concrete is not considered inert anymore and the setting needs to be changed to non-inert.

Figure 29: Material and Assembly Setting Form

Define Waste Management Goal for the Case Study

The user can define the waste management goal within the WM Goal tab (Figure 30). This tab calculates the total inert and non-inert waste based on the information provided in Info at Material Level tab. The values that need to be defined are total cost, project duration, total on-site reuse, total off-site reuse, total recycle, and finally total diverted waste. These values are important to be defined by the user in order to fulfill the owner's goal and comply with codes and regulations directed by authorities and NGOs. For instance, if the owner pursues a LEED certification that requires 40% diverted waste rate, the demolition contractor needs to satisfy this factor when defining the waste management goal. The collected information at this tab would be stored as the goal attributes within the `Goal` class. The next section elaborates how the goal attributes are satisfied by confirming the compliance of alternatives with the goal.

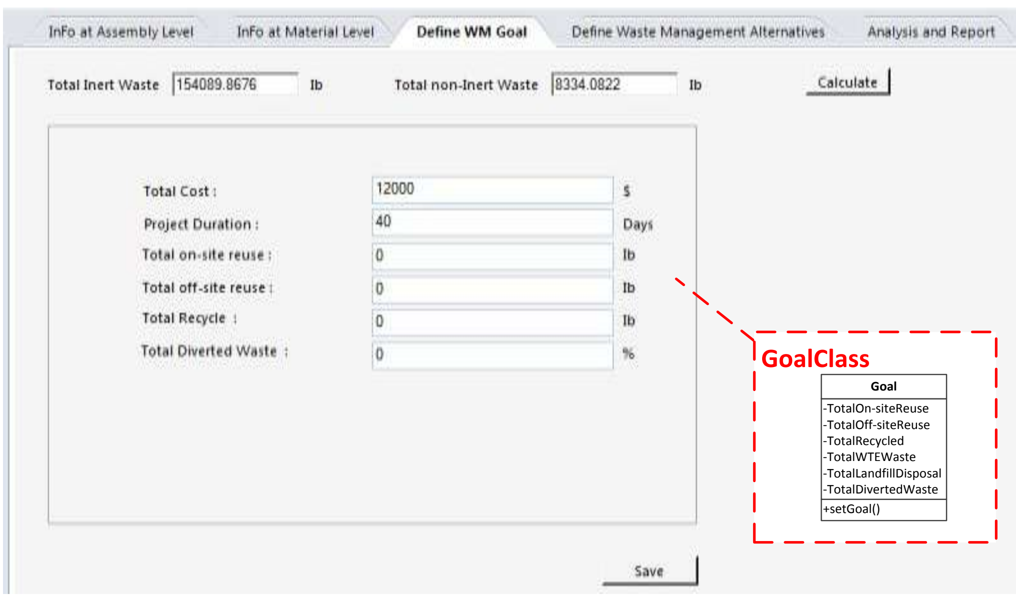

Figure 30: Waste Management Goal User Interface

The application calculates total inert and non-inert demolition waste weight for the case study. These amounts are 154089.86 lb for the total inert waste and 8334.08 lb for the total non-inert waste. It was assumed that the hard cost for the case study is $12000 and the expectation is to demolish the building and manage the generated waste in 40 days. Furthermore, since there are no codes of minimum diverted waste in Blacksburg, the amounts for total on-site and off-site reuse and total recycling waste are set to zero. That being said, if the case study was located within the State of California, California State Law, Green Code Standards requires a waste diversion rate of 50% from the landfills (CBSC, 2014). Figure 30 represents the calculated demolition waste weight and the WM goal interface for the case study.

Waste Management Alternatives

After defining the goal, waste management alternatives need to be proposed. As it is discussed in Chapter 3, Section 3.1, each alternative should indicate the demolition operations, which are going to be conducted to remove the building (traditional demolition vs. deconstruction), as well as the destinations of each waste stream (e.g. reuse, recycling, incineration, landfill disposal).

In Define Waste Management Alternative tab (Figure 31), the user has this option to define alternatives in two levels: assembly level and material level. This option is given to the user to facilitate defining waste management alternatives. For instance, if the whole external wall assembly needs to be disposed into a landfill, the user can simply select the assembly and specify 100% waste disposal into landfill. In this case, the application considers the landfill scenario for all materials within the wall assembly. On the other hand, if the waste manager decides to reuse the wood stud within the wall assembly, he or she can define the reuse scenario for the wood stud at the material level and considers the landfill scenario for the rest of materials within the assembly. One thing that should be considered in defining the alternatives is that all percentages under the waste management scenarios should add up to 100% to represent the whole assembly and the whole amount of generated waste. Otherwise, the application gives an error saying that "the percentages should add up to 100%". One more important check that needs to be done is to make sure that each waste management alternative complies with the waste management goal. If the goal is not satisfied, the user gets an error saying that "the waste management goal requirement is not met. Please redefine your alternative." After defining the alternatives, all entries are stored within the `Alternative` class.

Other information collected at this tab include Transportation Type, Distance to WM Facility, Transportation Unit Cost, Transportation Cost per scenario, Selling Unit Value, Benefit From Selling Salvage, Tax Deduction, and Purchase Cost. As it is depicted in Figure 31, all collected information is stored with the related classes. To clarify more about this tab, an example is presented in the following user interface. It is assumed that 100% of the concrete waste generated as the result of demolition of the foundation walls is recycled in a recycling facility with a distance of 28 miles from the job site. The transportation method is by truck. The transportation unit cost is $3/mile. This given information comes to the total transportation cost of $84 for the recycling scenario of the concrete waste.

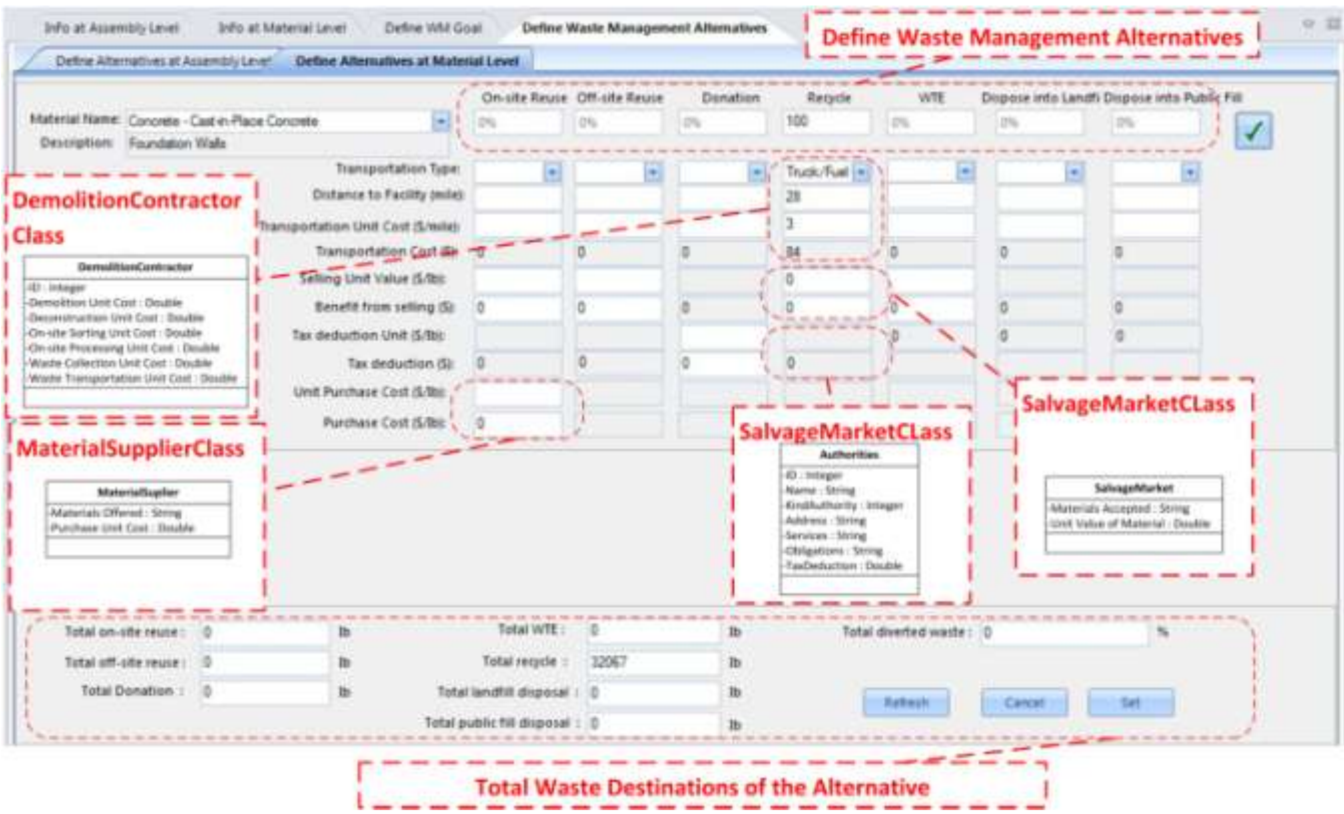

Figure 31: Define Waste Management Alternative Interface

The total waste destinations of each alternative are defined at the bottom of the waste management alternative tab. These amounts represent total on-site reuse, total off-site reuse, total donation, total waste sent to WTE facilities, total materials recycled, total landfill disposal, and total public fill disposal. All these amounts are calculated by adding up the defined amount of waste sent to each waste scenario destination. For instance, if 20% of total concrete waste weight resulting from demolition of the foundation walls is reused on-site while the remaining 80% is sent to a public fill facility that is the disposal destination for inert waste. In addition, 45% of the concrete waste resulting from strip footings is reused on-site and the remaining 55% of the waste is disposed into a public fill facility. In this case, the total on-site reuse for this alternative is equal to: (total weight of foundation wall concrete waste × 20% + total weight of strip footing concrete waste × 45%). The same formula results in the total public fill facility disposal: (total weight of foundation wall concrete waste × 80% + total weight of strip footing concrete waste × 55%).

One last critical factor, which is defined within this tab, is called total diverted waste. Total diverted waste is calculated as = (total waste reused on-site + total waste reused off-site + total waste recycled) / total generated waste.

For the purpose of this case study, the following waste management alternative was defined. It was assumed that the case study, so called existing building, reaches its end-of-life and needs to be demolished. It was also assumed that a new construction is going to happen on the same site. The new construction requires materials that can be provided either from purchasing new materials or reusing and recycling the waste generated as the result of the demolition of the existing building. The waste management scenarios considered for the case study are as follow:

- The building is demolished and the generated waste is sorted on-site. The hazardous waste is also abated.
- The concrete waste is diverted from the landfill and sent to a recycling facility. The need for aggregate for the new construction is bought from the same recycling facility.
- The rest of generated waste is sent either to a landfill or a public fill facility

Sustainable Waste Management Analyses and Reports

After collecting all the required information and storing them in proper classes within the SQL database, the economic, environmental and social impacts of each alternative can be analyzed.

Economic Impact Analysis and Report

The first analysis is concerned with the economic impacts of waste management alternatives. Figure 32 represents the costs and benefits associated with waste management activities, as they were addressed in Chapter 3, Section 3.2. The costs include Permit Cost, Abatement Cost, Demolition Cost, Deconstruction Cost, Cost of Sorting, Landfill Disposal Cost, and Public Fill Disposal Cost. The Permit Cost, Abatement Cost, and Demolition Cost are entered by the user based on inquiries from the authority, abatement contractor, and demolition contractor respectively. The rest of the costs are calculated based on information provided on the Define Waste Management Alternative tab. The benefits that are calculated by the application include Total Revenue from Selling Waste to Recycling Facility, Total Revenue From Selling Waste to WTE facility, Total Revenue from Selling Waste to Third Party, and Total Purchase Cost Saved due to On-site Reuse. All benefits are calculated based on information provided on the Define Waste Management Alternative tab. All information on costs and benefits of each alternative is stored within the `EconomicAnalysis` class and a cost-benefit analysis report is provided to the user by clicking on cost-benefit report at the bottom.

To conduct the cost-benefit analysis of the proposed waste management alternative for the case study, the waste manager needs to make inquiries from different parties in order to calculate costs and benefits associated with the alternative. For the aim of this case study, costs and benefits of demolition activities and market value for recycled and new materials were assumed based on online sources (MRSWA, 2014; FloydCova, 2004). The rates were assumed for the purpose of conducting cost-benefit analysis of the case, which is located in Montgomery County, VA. Therefore, these rates may differ for different counties.

The associated costs and benefits of the second alternative includes:

- Costs = permit cost + abatement cost + demolition cost + on-site sorting cost + recycling cost for concrete waste + transportation cost to send the concrete waste to recycling facility + disposal tipping cost for the rest of generated waste + transportation cost for disposing the rest of materials + purchase cost for recycled aggregate
- Benefits = purchased cost saved due to buying recycled aggregate + disposal cost saved due to prevention of disposing concrete waste into public fill facility.

As it can be seen in Figure 32, the total costs for the second alternative decreased to $9494.

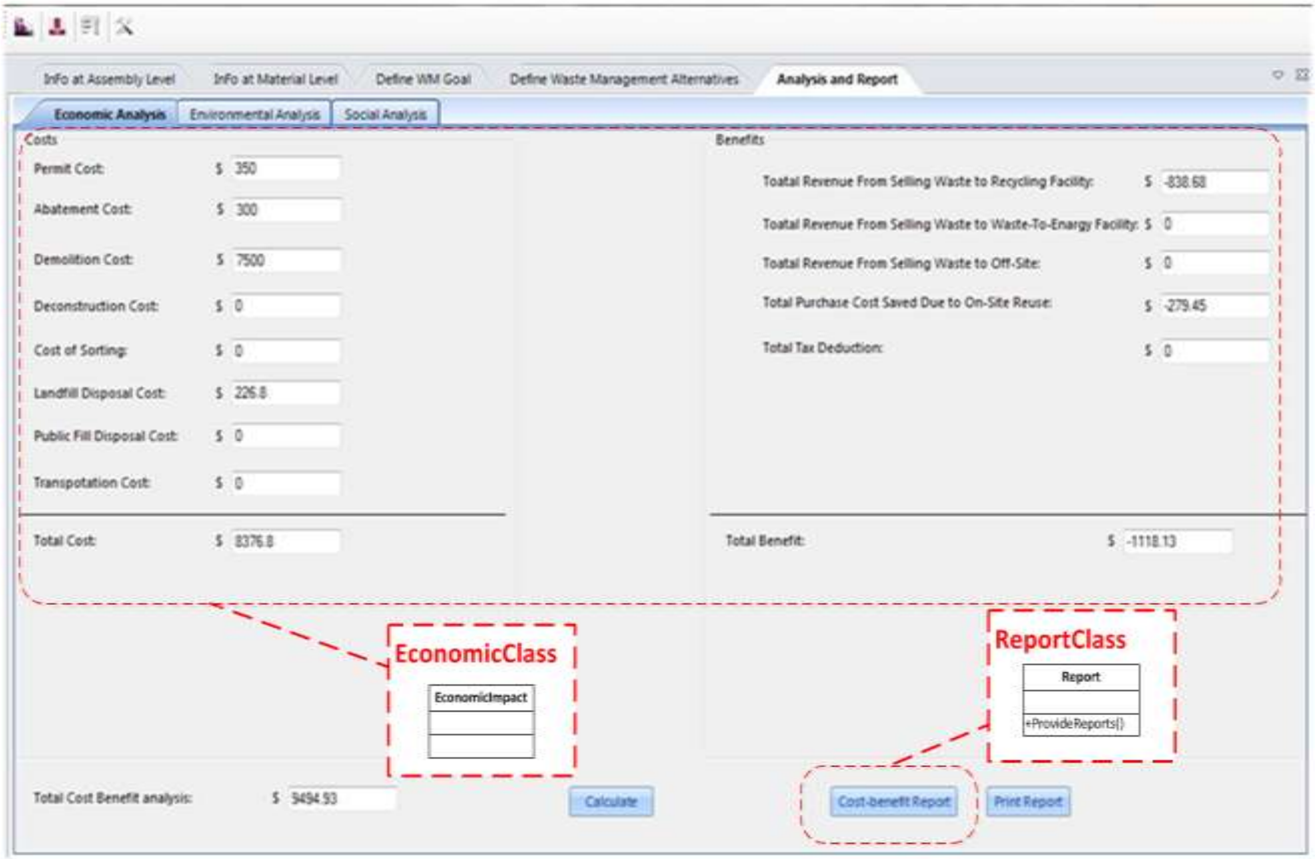

Figure 32: Cost-benefit Analysis - Case Study Analysis

Environmental Impact Analysis and Report

The environmental impacts associated with waste management activities were addressed in Chapter 3, Section 3.2. These impacts can be evaluated within three levels including the material level, assembly level, and whole building level. The type of analysis desired by the end user can determine the level with which the environmental report needs to be created. For example, if the waste manager is interested in the environmental impact of a specific waste management alternative for an assembly, the environmental report should reflect the analysis at assembly level. On the other hand, if the waste manager's only concerns are with one type of a material and its environmental impacts, the analysis is then reported at the material level. That being said, all variables that are reported as the environmental impacts are the same in all three level and include Energy Consumption, Resource Use, Global Warming Potential, Acidification Potential, Eutrophication Potential, Ozone Depletion Potential, Smog Potential. In addition to these impacts, the application calculates potential environmental benefits of each alternative including the Embodied Energy and Resources saved and Embodied Emission prevented due to reuse and recycling of the waste. All these environmental impacts and benefits are calculated based on information collected at the Info at Material Level, Info at Assembly Level, and Define Waste Management Alternative tabs and stored within the `EnvironmentalImpact` class. An environmental impact analysis report is provided to the user by clicking on Environmental Report on the bottom. For the purpose of the case study, the environmental analysis was conducted for the proposed alternative at Material Level. Figure 33 represents the result of the analysis.

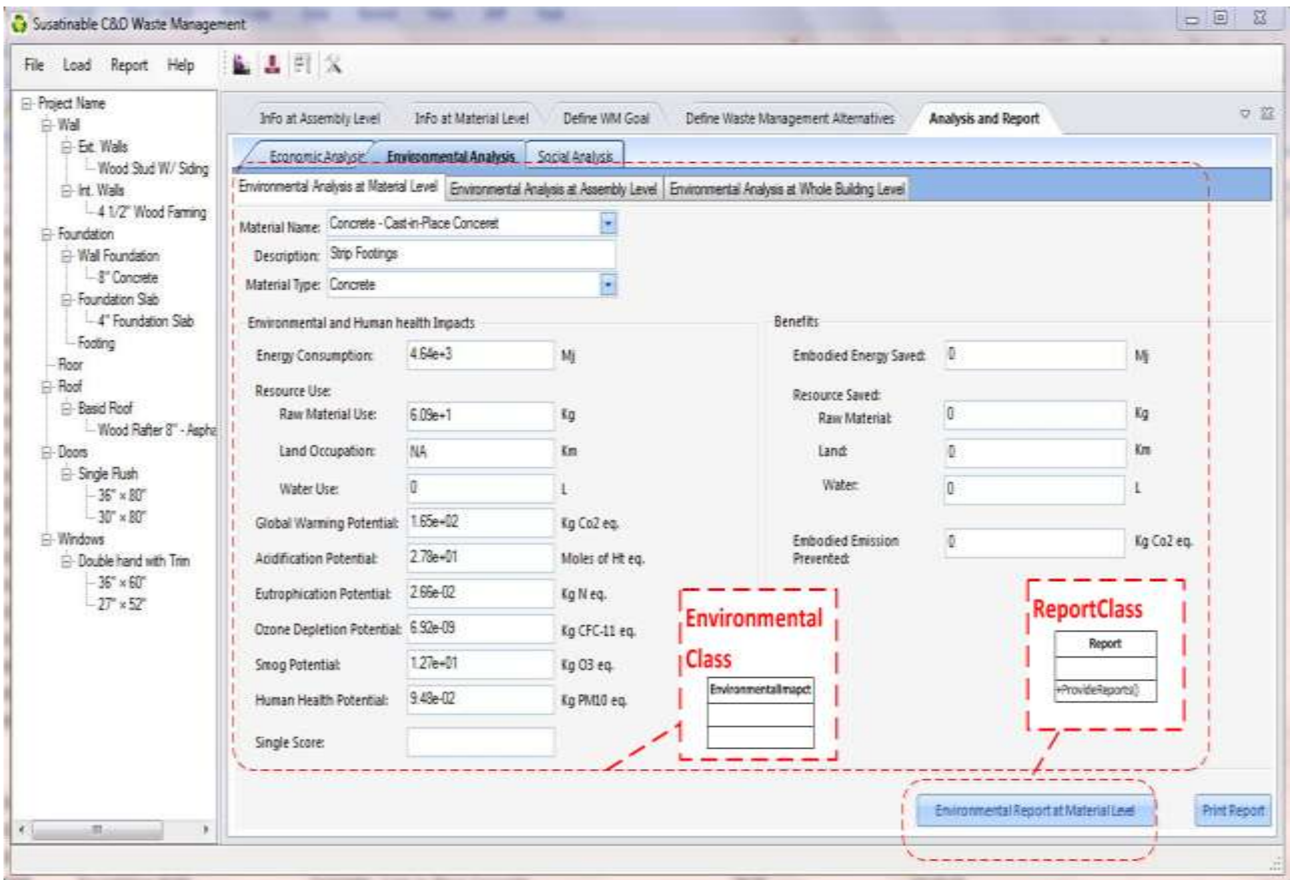

Figure 33: Environmental Impact Analysis - Case Study Analysis

Social Impact Analysis - Safety Analysis and Reports

The WM prototype application also addresses the safety concerns that may exist on the job site during demolition of the building as well as the waste management procedures. In Chapter 3, Section 3.2., the potential hazards and safety instructions were addressed according to OSHA Standard for demolition (OSHA, 2014). The potential hazards include Hazardous Materials, Structural Instability, Open Edges, Confined Spaces, Noise Pollution, Disconnected Utility Lines, and Surrounding Spaces. Each of these potential hazards along with proper safety instructions are addressed in the following sections. Examples were made for the case study to highlight what information is required.

Hazardous Materials

Potential hazardous materials that endanger the safety of the workers include crystalline silica-containing materials, asbestos containing materials, lead-based paint materials, and flammable and combustible materials. On-site tests and assessments are required to be conducted before any worker can enter the job site. A hazardous material report is then created based on the tests and assessments to notify the demolition contractor of any potential hazards (Figure 34).

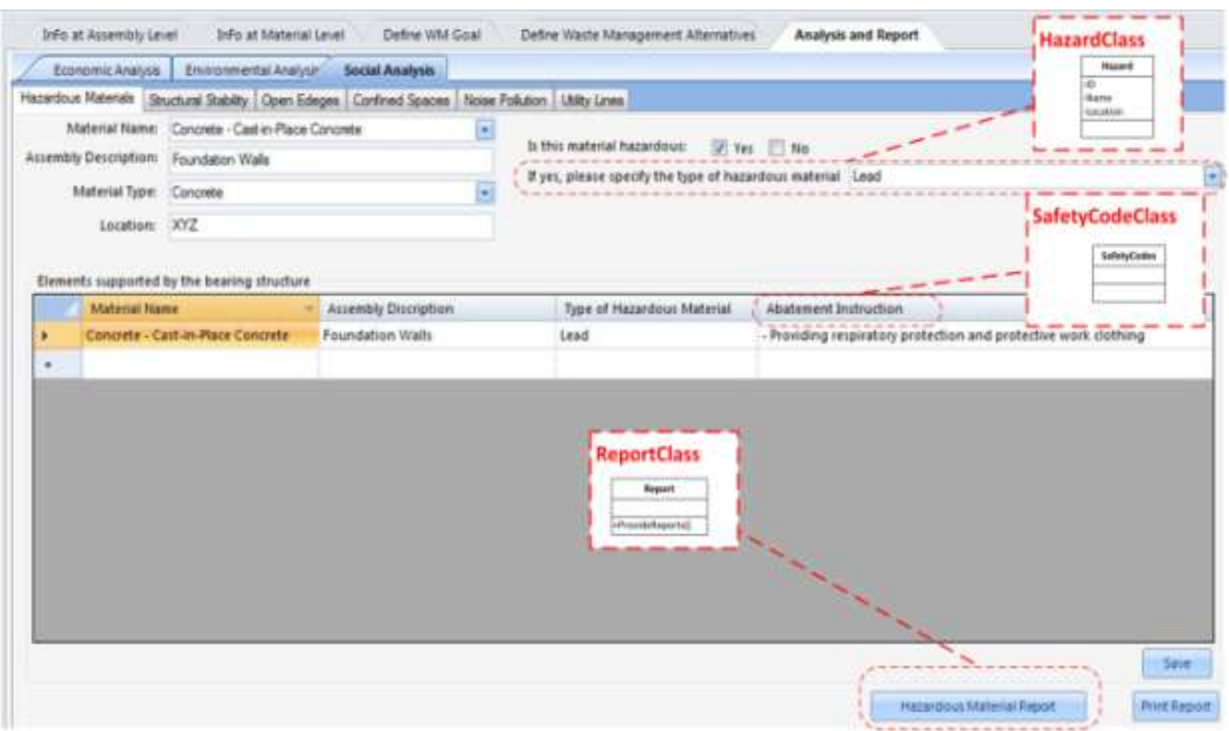

Figure 34: Hazardous Material Analysis - Case Study Analysis

The WM application helps the user enter information related to the hazardous materials within the hazardous material user interface (Figure 34). The information covers the material type, the assembly description, type of hazardous substance, and the location of the hazardous material. This information is stored into `Hazard` class. Furthermore, the OSHA safety instructions for each hazardous material are stored within the `SafetyCode` Class, which provides proper safety instructions for each hazardous substance type. For instance, if the concrete of the foundation wall with the location of XYZ is tested positive for the existence of lead-based painting materials, the OSHA safety instructions for lead-based materials are assigned to the concrete abatement, handling, and disposal. A report of the all hazardous materials along with their locations and safety instructions can be created by clicking on Hazardous Material Report at the bottom.

Structural Instability

Another critical safety concern at the end-of-life of a building is structural instability, which may result in the collapse of the building. The structural stability tests and assessments are also required to be conducted by certified engineers to make sure that all portions of the building are stable enough for the demolition and deconstruction processes.

The WM application provides the structural stability user interface to help the user to classify bearing elements/assemblies within the building (Figure 35). Furthermore, the maximum load capacities of the bearing assemblies are stored based on the structural stability on-site tests and assessments. If an assembly has a bearing function then the other assemblies/elements supported by this element need to be addressed.

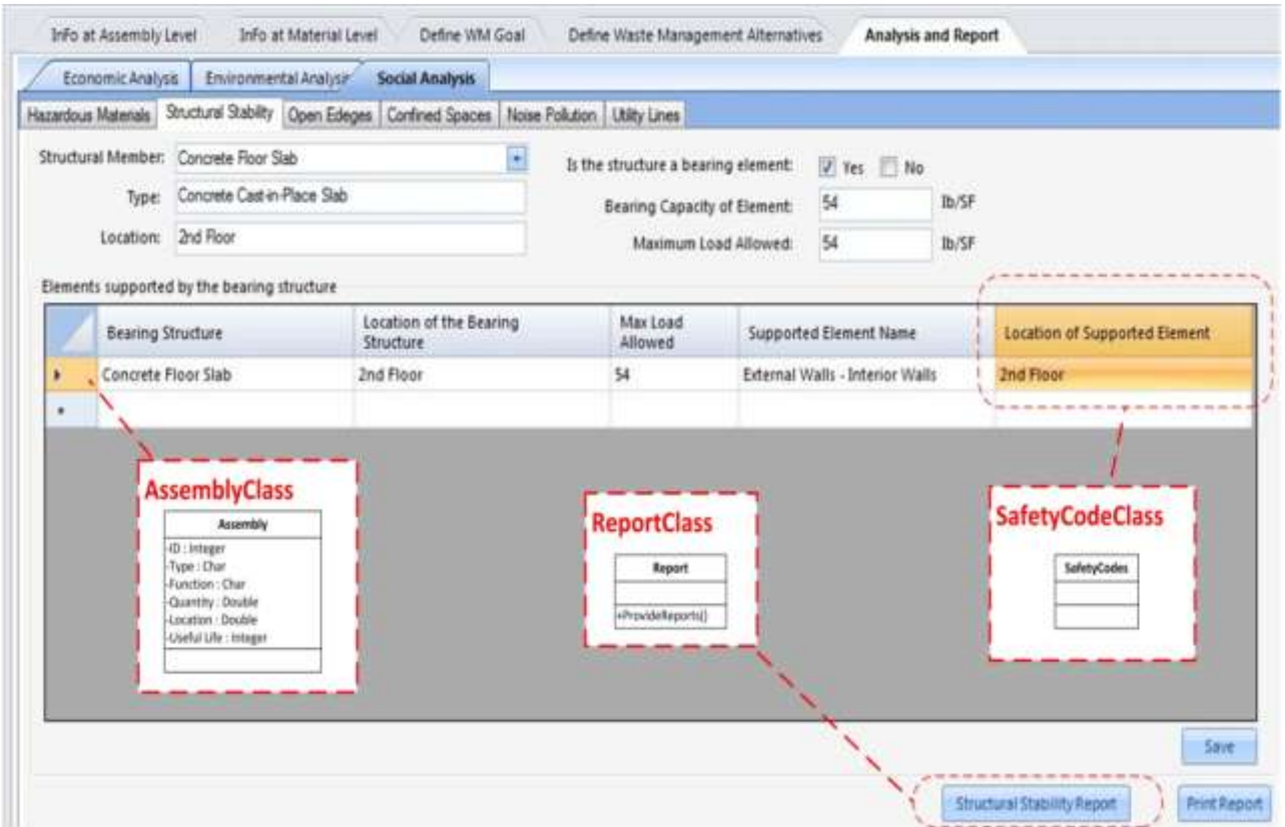

Figure 35: Structural Stability Analysis - Case Study Analysis

Open Edges

Falling from open edges is one of the other common hazards on a construction jobsite. The demolition contractor is required to conduct on-site assessments to identify open edges that may lead workers to fall from heights higher than 6'. The information on the open edges including name, location, and height can then be stored within the `Hazard` class via the `OpenEdges` interface (Figure 36). The OSHA safety instruction are also provided for the demolition contractor in the Open Edges report.

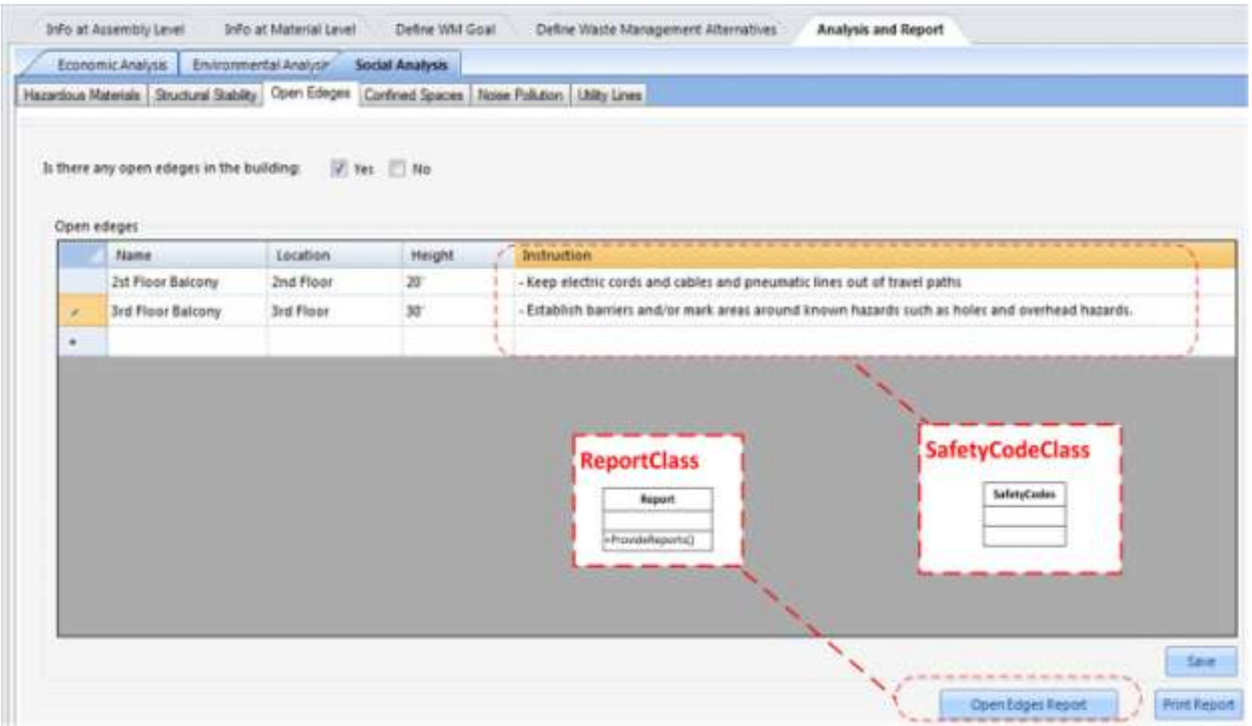

Figure 36: Open Edges Analysis - Case Study Analysis

Confined Spaces

A confined space includes any spaces, which has limited means of entry and exist. The confined spaces may contain physical (e.g., mechanical and electrical) and atmospheric hazards (e.g., airborne combustible dust and toxic substances). The demolition contractor is required to conduct on-site assessments to identify confined spaces with the building. The examples would be the boiler, drainage pits, furnace, and vent gas tank. The user can save the information on the confined spaces within the Confined Space user interface and get the proper OSHA safety instructions from the Confined Spaces report (Figure 37).

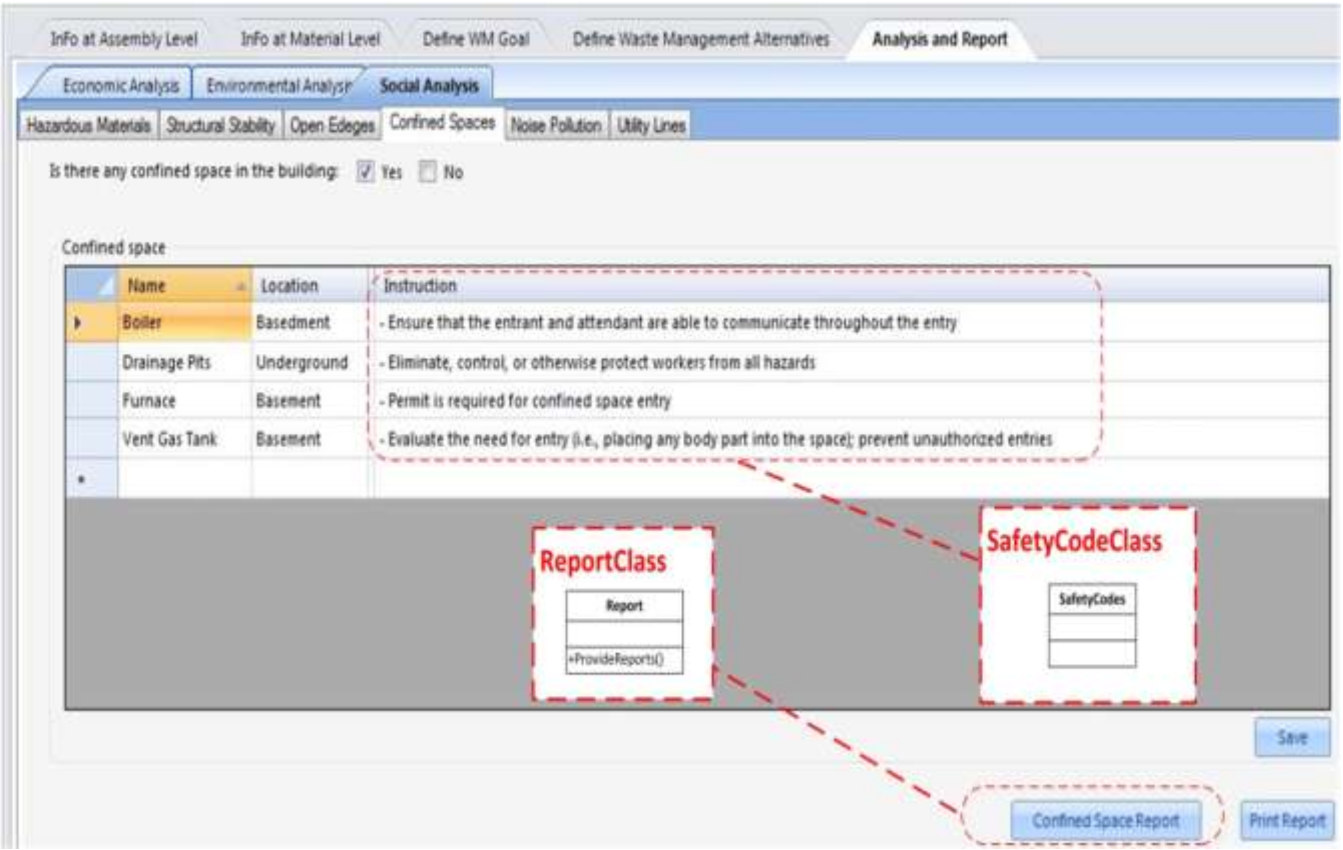

Figure 37: Confined Space Analysis - Case Study Analysis

Noise Pollution

Some equipment used during demolition and waste management may have a noise level higher than 90 dBA. Noise higher than 90 dBA may cause serious health problems for the workers on the jobsite. Therefore, an assessment needs to be done to identify equipment with a noise level higher than the safe threshold. The information on these types of equipment can be stored within the Noise Pollution interface and the required safety actions can be provided by the Noise Pollution report (Figure 38).

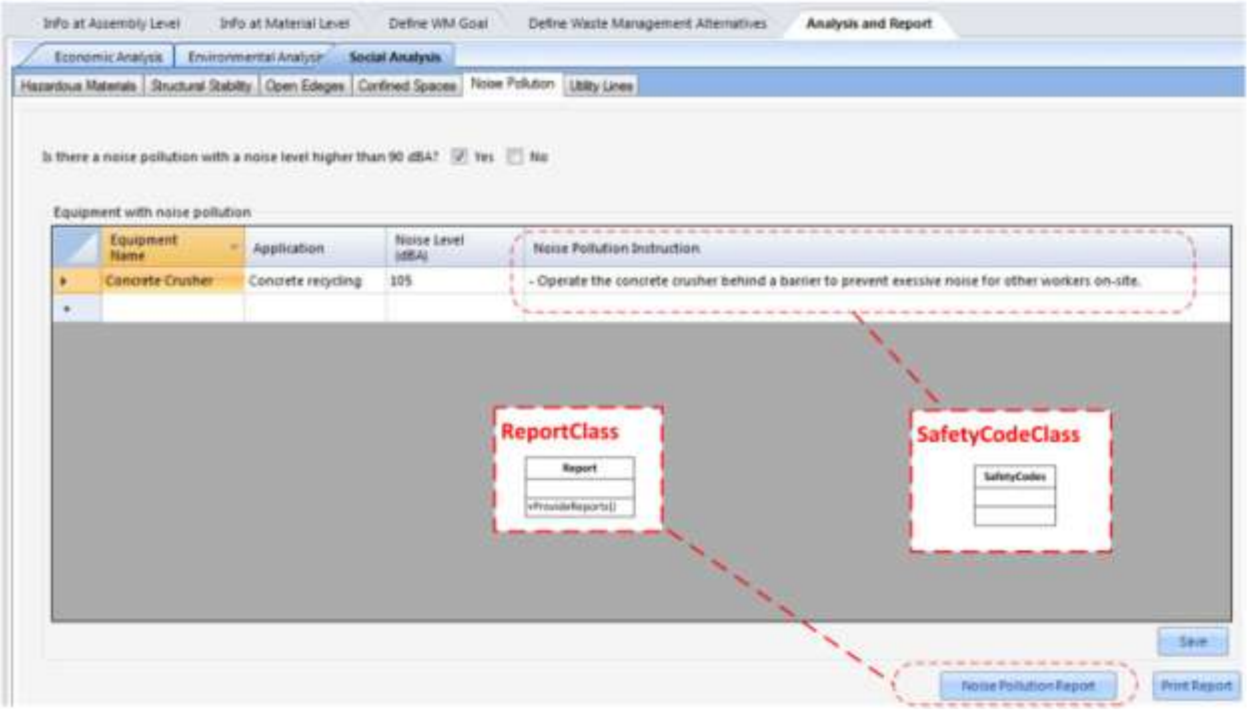

Figure 38: Noise Pollution Analysis - Case Study Analysis

Utility Lines

All utility lines should be discontinued before any demolition activity can start on the jobsite. However, some equipment needs to operate on site to provide required energy. For instance generators are used to provide electricity for deconstruction equipment. The WM application helps the demolition contractors to check if all utility lines are discontinued (Figure 39). In addition, the user can get OSHA safety instructions if he/she requires the use of equipment and utility lines within the job site. The report on all connected utility lines along with the safety instructions can be provided by clicking on Utility Lines report.

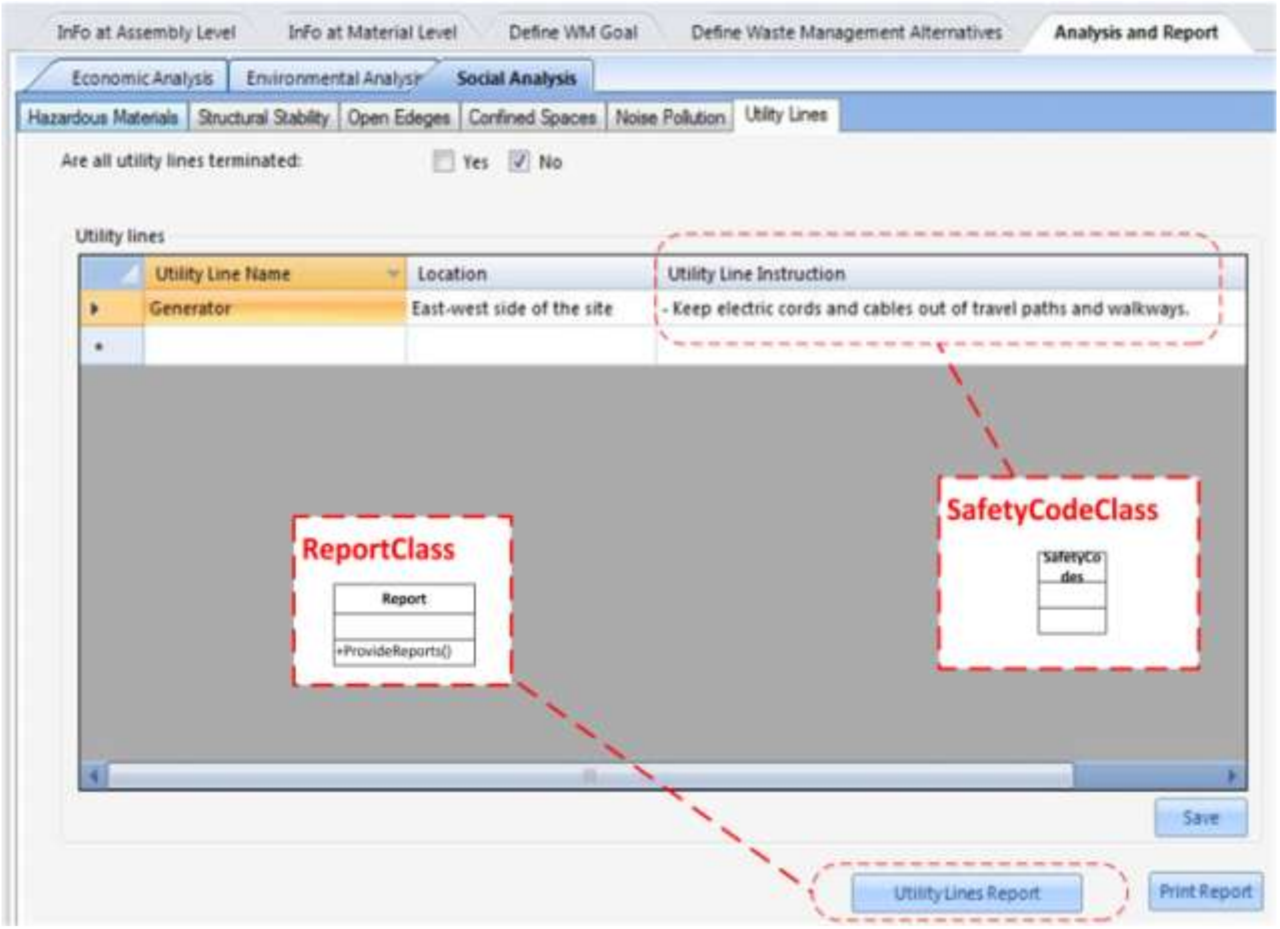

Figure 39: Utility Lines Analysis - Case Study Analysis

Surrounding Spaces

All surrounding spaces need to be identified before the actual demolition and waste management activities can start. The demolition contractor needs to identify the surrounding spaces in order to lay out the demolition and waste management activities. An example for the case study is the location of the hazardous materials dumpster that is in the backyard of the building. The related information on surrounding spaces and the possible lay out for activities are stored within the `SafetyCode` class. The reports on surrounding areas can be produced from the `Report` class (Figure 40).

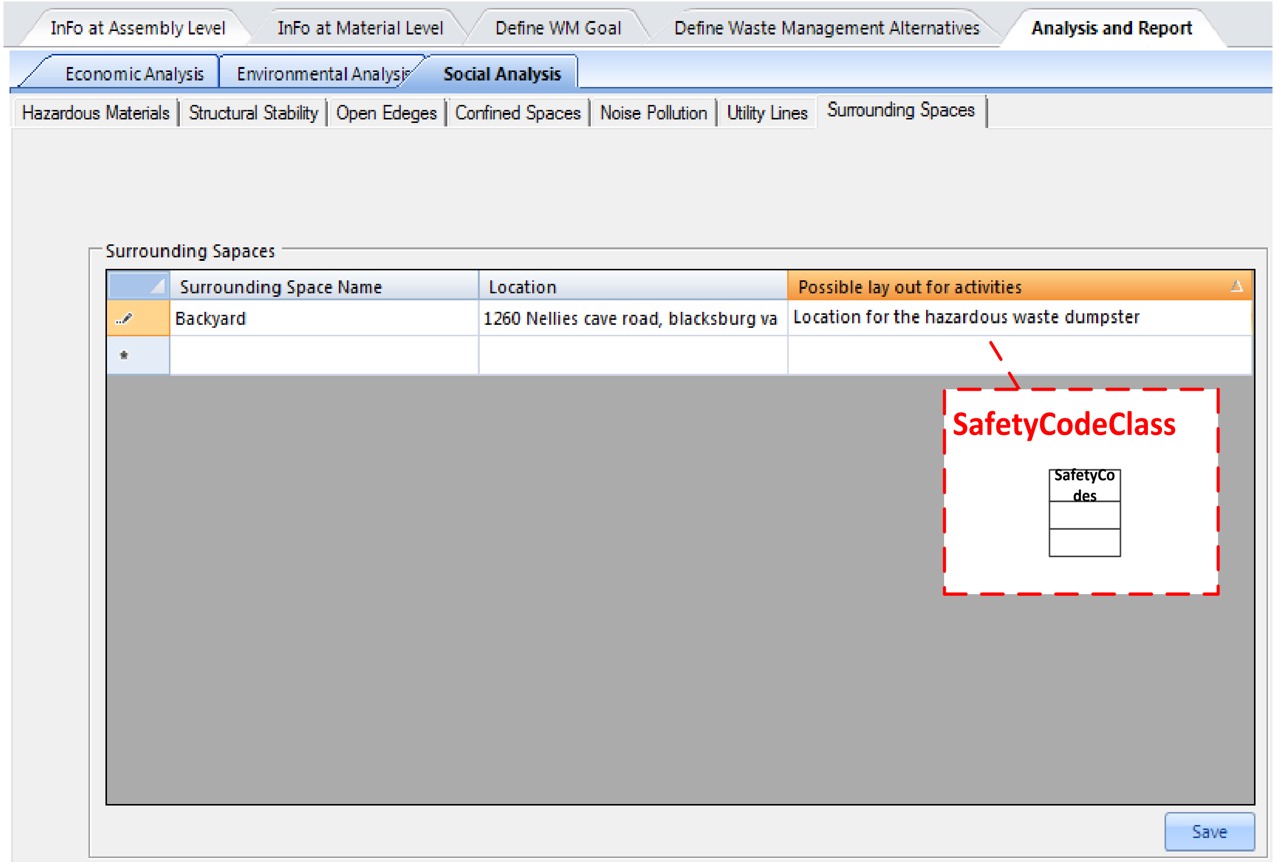

Figure 40: Surrounding Spaces Analysis - Case Study Analysis

Summary of Object-oriented Data Model Verification

The verification chapter explained the processes taken to verify the OODM. For this purpose, the scope, flexibility, and implementability of the model were verified using interviews and case study analysis. The scope of the OODM was verified by industry practitioners to make sure the OODM covers required information for sustainable demolition waste management decision making. The flexibility of the model for future changes was also verified by adding an instance class and its attributes to the model without disturbing the structure of the OODM. The implementability of the proposed OODM was further verified by developing the sustainable waste management application and conducting sustainable waste management analyses on a case study.

The next chapter summarizes the contribution of this study and potential benefits of the OODM. Limitations and future research works will be also discussed within the next chapter.

6. Conclusion and Future Research Work

Currently, sustainable demolition waste management is rarely practiced in the construction industry. This is mainly because the decision-making process for sustainable demolition waste management is a very resource-demanding and time-consuming task in terms of data collection and data management. The decision-making process should analyze possible waste management scenarios from an economic, environmental, and social perspective. Such analyses requires waste managers to deal with huge amounts of data at the end-of-life of a building.

The identified research problem is that the sources of information, which can provide the required information are fragmented and not properly managed at the end-of-life. Hence, the process of acquiring and managing information would be very time-consuming and costly.

To overcome the identified problem, this study developed an object-oriented data model to propose an integrated database structure that is able to store all required information in one integrated source of data. The proposed model helps waste managers more efficiently manage information at the end-of-life phase. Furthermore, a sustainable demolition waste management prototype application was developed to demonstrate how the required information is captured from different sources of data, stored within defined OODM classes, and retrieved from the integrated database. Finally the scope, flexibility, and implementability of the OODM were verified to demonstrate the potential application of the model within end-of-life operations.

This chapter summarizes the process of developing the OODM, the verification of the model, sustainable waste management prototype application, and the case study. Furthermore, a list of contributions and benefits of the conducted research is also included with identified weaknesses and how they can be overcome through future research work.

Object-oriented Data Model

The object-oriented data model aims at providing all information required for sustainable demolition waste management decision making in one integrated source of data. In doing so, the first step was to identify all required information. This was achieved by studying economic, environmental, and social impacts of different waste management alternatives proposed by the EPA (2013). The identified information was further classified based on its sources of origin into four main categories including Information Protocols (e.g., IFC and COBie), Life Cycle Inventory Databases (e.g., USLCI Database), Regulatory Codes and Standards (e.g., Local

Codes, OSHA), and End-of-Life Quoting Information Sources (e.g., Demolition and Abatement Contractors, Salvage and Material Markets, and Recycling Facilities). In the next step, three use case diagrams were developed to illustrate interactions between the proposed object-oriented data model, sources of information, and end users.

After identifying all required information as well as creating the use cases, the structure of the object-oriented data model was developed as a UML Classification. The classification consists of multiple classes, which encapsulates all the required information. Furthermore, the sequence diagrams were developed to indicate how the UML classes as well as objects within the object-oriented data model interacts with each other. Each sequence diagram illustrates the processes involved within the sustainable demolition waste management decision making process. For instance, a sequence diagram was developed to indicate how an economic analysis of the generated waste is conducted through the interactions of UML classes within the object-oriented data model.

A sustainable demolition waste management prototype application was further developed to illustrate how the user can interact with the object-oriented data model through the application's user interfaces. The user interfaces were created to illustrate how the required information can be either loaded from the external sources (e.g., Revit model, IFC, COBie, and LCI Database) or collected directly from the end user's enquiries from End-of-Life Information Sources (e.g., Demolition and Abatement Contractors, Salvage and Material Markets, and Recycling Facilities).

Finally, the potential application of the OODM was verified by verifying three characterizations of the model including 1) scope, 2) flexibility, and 3) implementability. To verify the scope of the model, the OODM information coverage was validated by three interviews with industry experts. The flexibility of the model was discussed by elaborating the adaptability characterization of the object-oriented data modeling approach and tested by using an example. Furthermore, to demonstrate the implementability of the model two steps were taken, a) develop a prototype application that allows the user to interact with the OODM, and b) conduct economic, environmental, and social analyses for the case study.

6.1. Contributions and Benefits

The major contribution of this research is the object-oriented data model that provides waste managers and demolition contractors with the information required for sustainable demolition waste management decision making. The object-oriented data model captures the required information collected from external sources and stores them in one integrated source. By combining the fragmented sources of data, the data model addresses the identified problem of data collection and data management at the end-of-life phase. Furthermore, the object-oriented data model serves as the core information structure for the proposed sustainable waste management application presented in Chapter 5.

In order to identify potential benefits of the OODM, the sustainable waste management prototype application was introduced and presented to three practitioners within the construction industry. Though all three interviewees were involved in multiple demolition projects and waste management activities, the following benefits need to be further investigated through future studies. The potential benefits of the sustainable waste management application include:

- A potential to decrease waste management time at the end-of-life phase.
    - The interviewees addressed that since the application helps them deal with one source of data, the time needed for data collection and decision making would be significantly decreased.
- A potential to decrease waste management cost at the end-of-life phase.
    - Reducing the cost was the main concern of the interviewees. They addressed that the sustainable waste management application has this potential to streamline the decision making process for evaluating different waste management alternatives from the economic perspective.
- A potential to encourage waste managers to pursue sustainable demolition waste management practice.
    - The interviewees were asked if the proposed model can encourage them to pursue the sustainable demolition waste management practice. The answer was that "if practicing sustainable waste management does not add additional cost, we will be willing to follow this practice within our company. In this case, practicing sustainable waste management would be a great strategy for advertising our green value within the construction industry."

Assumptions

The following statements address some assumptions for application of the OODM developed within this study:

1) This study assumed that a BIM-based model is available at the end-of-life of a given building, and used the model as one of the information sources. That being said, the user interface, which acts as the interaction bridge between the user and the OODM, was designed in a way to let the user enter information from other sources such as drawings and on-site surveys. For instance, if there is no BIM-based model or if the model does not represent the as-built conditions of the building, the user can refer to drawings and conduct on-site surveys to collect required building information (e.g., material types and material quantities). The user can then enter new information or update the existing information within the OODM using Setting Form user interface. The capability of entering and changing information using the sustainable waste management application was presented in Chapter 5, under the Implementability Section.

2) As it was discussed in Chapter 3, the OODM was developed based on information collected from OSHA Demolition Codes under 1926 Subpart T - Demolition Standard (OSHA, 2014), the LCA guidelines developed according to ISO 14040 (ISO 14040, 2006) and ISO 14044 (ISO 14044, 2006), and the demolition and waste management guidelines addressed in this document. That being said, the user should consider potential discrepancies if he/she intends to use other information sources and guidelines for conducting sustainable waste management analyses. This limitation is further addressed within the Limitation Section.

3) The OODM proposed by this study is intended to be used for data collection and data management at the end-of-life of buildings. However, the data collection and data management within the OODM can be started at early stages of the building, and continued throughout the building lifecycle. For instance, the user can collect information such as material types and quantities at the design phase and store the information within the OODM. This approach was discussed with two practitioners from the construction industry. Both interviewees have been involved in multiple construction projects from concept phase to demolition stage. Though they approved that collecting and managing data at early stage of a building would help to streamline data management at the end-of-life, they expressed potential following obstacles that may exist in data collection at the early stages.

- From owners' perspective, this approach may not be financially feasible to allocate budget for collecting data, which might be used at the end-of-life of the building.
- Even if the owner has sustainable and green values, he or she is less willing to allocate time and budget for data collection at the early stages of the building due to concerns on the continuous ownership of the building.
- From general contractors' perspective, it is almost unlikely to consider extra work that is not mentioned within the contract in order to prevent any extra cost.

6.2. Limitations

Four limitations are identified in completing this study:

Limitation #1: The focus of this study is limited to the building construction industry. However, the same research approach could be applied to extend the application of the OODM to be used for any type of construction including bridges, transportations, and industrial facilities.

Limitation #2: The identified information that is covered by the proposed OODM was collected from OSHA Demolition Codes under 1926 Subpart T - Demolition Standard (OSHA, 2014), the LCA guidelines developed according to ISO 14040 (ISO 14040, 2006) and ISO 14044 (ISO 14044, 2006), and the demolition and waste management guidelines that were addressed in this document. That being said, the proposed OODM may not cover all information from other codes, standards, and guidelines that may differ from the sources that were used in this study.

Limitation #3: Two impact categories affected by demolition waste management activities were not considered for this study due to the complexity of quantification and reliability of local variables. These factors include potential employment opportunities and environmental cost. Employment and job opportunities will be created if the generated waste goes to salvage markets and recycling facilities rather than landfills (Yuan, 2012). Environmental cost is referred to as a penalty enforced by local authorities for any illegal waste dumping (Yuan, et al, 2011). These two factors are dependent on multiple variables, such as local economic status, existence of local markets for salvaged materials, and availability of information on illegal waste dumping. Therefore, these variables will be out of the scope of this research.

Limitation #4: This work used a case study to illustrate the implementability of the proposed OODM and the Sustainable Waste Management Prototype Application. In addition, three cognitive walkthrough interviews were conducted with demolition contractors to address the coverage of the OODM and the application in regards to sustainable demolition waste management decision making. Though the coverage of the proposed model was verified by the interviewees, this study did not examine the large scale usability and robustness of the OODM.

6.3. Future Research Work

In addition to the objectives of this study, future research tracks can be extended from this work to overcome the weaknesses and limitations of this study. These future research tracks include:

Expansions of the Coverage of the Object-oriented Data Model

Before the OODM can be piloted effectively, the coverage of the model needs to be further examined, and ultimately expanded. The identified information that is covered by the proposed OODM was collected from OSHA Demolition Codes under 1926 Subpart T - Demolition Standard (OSHA, 2014), the LCA guidelines developed according to ISO 14040 (ISO 14040, 2006) and ISO 14044 (ISO 14044, 2006), and the demolition and waste management guidelines addressed in this document. That being said, there needs to be future works that study other standards, codes, and guidelines from different cities in the U.S. and even worldwide to examine and expand the coverage of the proposed model. Document analysis can be one approach to identify information covered within other standards, codes, and regulations. The identified information can then be compared with the information addressed within the OODM. By comparing theses two sets of information, the information coverage of the proposed OODM can be examined, and ultimately expanded.

Expansions of the Object-oriented Data Model to Support Other Types of Constructions

This study demonstrated the implementability of OODM through conducting a case study of a single family residential building. However, as it was mentioned in Chapter 5, the proposed model has this flexibility to be extended to support sustainable demolition waste management decision making for other construction types including bridges, roads, industrial facilities, etc. This requires identification of waste management practice as well as any regulations and codes that are applicable for these types of constructions. Furthermore, as it was discussed within

Chapter 5, Section 5.2, objects, attributes, and operations can be added, changed, and removed to the proposed OODM without disturbing the structure of the model.

System Validation

Though the implementability, flexibility, and the coverage of the proposed model was verified by conducting a case study and interviews with the industry practitioners, there needs to be overall information validation and test-case studies to validate the robustness of the OODM. The system validation will examine the validity of inputs and outputs from the OODM to make sure that the model complies with the industry standards.

To achieve this goal, multiple actual case studies should be observed throughout different regions. The case studies should look for two main characterizations of the model: 1) information coverage of the OODM (inputs) and 2) usefulness of analysis reports (outputs).

Each pilot study needs to be observed to examine the information coverage of the model. All standards, codes, and regulations that are applicable to each region need to be further analyzed to make sure the OODM covers the required information to support sustainable waste management analysis. All discrepancies that are identified throughout conducting the case studies need to be documented and used for expansions of the model.

In addition, the sustainable waste management analysis reports, which are considered the outputs of the OODM, need to be further investigated for each case study to make sure that the produced results of the application covers all necessary information required for decision making.

Usability Studies

Future research works are needed to examine the usability of the OODM within the construction industry. The usability studies would make sure that the actual end-users of sustainable waste management application can interact with user interfaces. For this purpose, multiple cognitive walkthrough interviews with industry practitioners can be conducted. Some factors that these studies should look at are:

- Ability of the user to store information into the model
- Ability of the user to load data from external sources into the model

- Ability of the user to conduct economic, environmental, and social analyses using the application and retrieve desired results.

The goal of observing the usability level of the model is to identify possible weaknesses and drawbacks that may cause extra work load and overcomplicated implementation in practice. The user interfaces can be then changed to mitigate the identified weaknesses and drawbacks.

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