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Life Cycle Thinking Based Methodology for the Evaluation of Building Energy Retrofits

By

Rania Toufeili

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Life Cycle Thinking Based Methodology for the Evaluation of Building Energy Retrofits

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DECLARATION OF CO-AUTHORSHIP / PREVIOUS PUBLICATION

I. Co-Authorship

I hereby declare that this thesis incorporates material that is result of joint research. Chapters 2, 3 and 4 of this thesis were completed under the supervision of Dr. Edwin Tam and Dr. Rajeev Ruparathna. In all cases, the key ideas, primary contributions, designs, data analysis, interpretation, and writing were performed by the author, and the contribution of co-authors was primarily through the provision of feedback on refinement of ideas and editing of the manuscript.

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II. Previous Publication

This thesis includes three (3) original papers that have been previously published/submitted for publication in peer reviewed journals and conferences, as follows:

Thesis Chapter	*Publication title/full citation*	*Publication status*
Chapter [2]	Rethinking Energy Retrofit Evaluation: A Life Cycle Thinking Based Approach. *CSCE Annual General Conference* (2019)	Published
Chapter [3]	Life Cycle Assessment Methodology and Impact Database for Retrofit Evaluation	In Preparation
Chapter [4]	Building Energy Retrofit Evaluation Tool	In Preparation

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ABSTRACT

With current increasing climate change concerns, enhancing infrastructure sustainability is essential to the help mitigate greenhouse gas emissions. Today, 45% of Canada's greenhouse gas emissions can be attributed to the production of heat and electricity for buildings. Green building energy retrofits are useful to help decrease the energy consumption of a building and resulting emissions from a building. Before applying energy retrofits, evaluating their sustainability is important but can be challenging without the proper tools due to the many factors that need to be taken into consideration. Furthermore, life cycle thinking is crucial when making decisions on building retrofits implementation, and life cycle assessments are a valuable tool to help conduct sustainability evaluations. This research project aims to create a comprehensive methodology that will assess and compare building retrofits through life cycle thinking and the evaluation of environmental, economic, social and technical criteria. Appropriate key performance indicators are chosen for each criterion along with the development of a life cycle impact database. Overall, this research creates a comprehensive Microsoft Excel-based tool which may be used by building managers or stakeholders to determine the optimal energy retrofit.

DEDICATION

To my brother, Ali.

“You’re braver than you believe, and stronger than you seem, and smarter than you think.”

– Winnie the Poo

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I would like to thank my supervisors Dr. E. Tam and Dr. R. Ruparathna for their guidance, support and wisdom throughout my master’s degree. I have gained so much valuable knowledge from them and grown to be more independent because of their great help. I would also like to thank my committee members Dr. P. Henshaw and Dr. L. Miller for all their time and efforts which has helped me improve the quality of my work, as well as the University of Windsor and the Natural Sciences and Engineering Research Council of Canada (NSERC) for providing me with financial support. Additionally, I am grateful for the kindness and opportunities I have received from the University of Windsor’s Engineering Department faculty and staff.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background and Problem Statement

The Intergovernmental Panel on Climate Change (IPCC 2018) revealed that we have 12 years to limit climate change catastrophe. Climate change poses a serious global threat, with today's existing outdated infrastructure contributing to the overconsumption of depleting resources [1]. Climate change has been attributed to anthropogenic greenhouse gas emissions (GHG) primarily generated from fossil fuel use [2]. Buildings alone are estimated to contribute to 50% of the annual energy consumption and GHG emissions [1]. Thus, the greatest potential to reduce the environmental impact of energy consumption within the next 20-30 years lies within the building stock [3]. In order to address the growing concerns on climate change and environmental sustainability, the Canadian Government has invested $22 billion in the 2017 budget towards building green infrastructure, forming resilient communities and assisting with disaster mitigation and adaptation [4]. It is unrealistic and too costly to simply replace all existing building infrastructure; at the same time, inaction and accepting the status quo will lead to more financial and performance burdens, as well as increasing the risk to resident populations [5]. There is a global movement towards developing "environmental-friendly and sustainable, "green" and carbon reducing buildings" [6]. There is a clear need for the implementation of energy efficient building solutions for existing buildings as a climate change mitigation strategy [4].

The potential for sustainable development in the construction sector of developed nations lies "in the realm of building maintenance, repair, renewal, retrofit, adaptive re-use and recycling" [7]. Green retrofitting is an effective strategy to reduce energy consumption and improve the sustainability of a building [8]. Retrofitting can be defined as "a process that reaps the benefits of the embodied energy and quality of the original building in a dynamic and sustainable manner" [9]. Green retrofitting also presents many environmental, social and economic benefits when compared against replacing an existing building with a new one [1]. However, selecting the optimal energy retrofit for an existing building remains a dilemma.

Thus, evaluation of building retrofits can be challenging because of the complex relationship between buildings and their environment since many factors need to be considered including the economic, technical, social and ecological aspects [10]. Moreover, determining the embodied environmental impacts of retrofit alternatives remains uninvestigated. Building retrofit evaluation is a multi-criteria decision making problem. Previous researchers have used multi-criteria decision making (MCDM) such as multi-objective optimization (MOO), Analytical Hierarchy Process (AHP) and MAUT (Multi-Attribute Utility Theory) [11]. Software such as the Building for Environmental and Economic Sustainability (BEES) aid in economic and environmental evaluation of building products [12]. A comprehensive literature review of the existing building retrofit evaluation research revealed two critical knowledge gaps:

1) ***Existing decision aid methods are not complete and comprehensive:*** More sustainability criteria should be considered in order to properly evaluate retrofit selection. Despite the substantial research up to date, the technical, economic and environmental implications of green retrofitting have been studied by very few researchers. There is found to be a lack of established benchmarks and criteria for the assessment of environmental

significance of building retrofits [1]. Additionally, Si et al. (2016) revealed that much of the existing building retrofit evaluation decision-making processes focus on a single economic criterion, such as cost-benefit ratios [11]. Building energy retrofit evaluation criteria should consider economic, environmental, social and technical performance in the decision making process [11].

2) ***Life cycle impacts for varying sustainability criteria have been ignored:*** Life cycle thinking is crucial to develop superior and sustainable buildings and should be incorporated into the evaluation of building energy retrofit [13]. Therefore, incorporating life cycle thinking in the evaluation of building retrofits is critical. As Ingrao et al. (2018) discussed, the LCA decision-making "promotes stewardship by considering global, national, regional and local impacts on social and environmental problems such as human health, resource depletion, and ecosystem quality" [13]. Subsequently, conducting a social-LCA (S-LCA), environmental LCA, and life cycle costing (LCC) can all help in the determination of sustainability factors that are associated with building retrofit implementations throughout its life cycle.

The existing literature presents various decision-making methods however they do not address the two research gaps above. From the reviewed literature, Si et al. (2016) have developed a wholistic framework and criteria for the evaluation of green technology, however they do not consider life cycle thinking in their process. As a result, there remains the need for a retrofit evaluation method which incorporates life cycle thinking into its sustainability development measures. A comprehensive framework is developed to create a more holistic evaluation methodology which is useful to building managers as they select the appropriate retrofits for their buildings.

1.2 Objectives

This research tests the hypothesis that a user-friendly decision support framework should be able to assist building managers in determining the optimal retrofit alternative by considering a life cycle thinking lens. The main purpose of this research project is to develop a life cycle thinking based evaluation framework to compare building energy retrofits. A proposed methodological framework is developed as an easy-to-use decision support tool. The following are the specific objectives for this research to achieve the overall objective:

1. Determine key performance indicators (KPI) to evaluate the social, economic, environmental, and technical performance of building energy retrofits.
2. Develop a life cycle thinking based evaluation framework to compare building energy retrofits.
3. Develop a life cycle impact database of innovative and proven energy retrofits by conducting life cycle assessment (LCA), life cycle costing (LCC) and social life cycle assessment (S-LCA).
4. Develop an Excel-based energy retrofit evaluation tool by utilizing the developed evaluation framework and the database.
5. Conduct a case study to outline how the results from objectives 1 through 4 above will be implemented.
6. Propose implementation guidelines and best management practices (BMPs) for the developed evaluation method.

1.3 Literature Review

Infrastructure sustainability has become a crucial part of the development towards global sustainability. This research utilizes a life cycle thinking based approach for the development of an evaluation framework that will consider varying social, economic, environmental and technical criteria of building retrofit implementation.

The following literature review will:

1. Discuss the need for action against climate change.
2. Discuss sustainable buildings along with commonly installed building retrofits.
3. Review the various decision-making methods available to evaluate building retrofits.
4. Discuss the significance of life cycle assessments in building sustainability.

1.3.1 Climate Change

Today climate change is cause for major concern as it is responsible for significant changes in global temperatures, leading to threatening natural disasters. There are ongoing global discussions on ways to reduce the harmful greenhouse gas (GHG) emissions that are causing climate change which require serious and immediate action [14]. In 2015, countries in the United Nations Framework Convention on Climate Change (UNFCC) signed the Paris Agreement, which aims to deter the effects of GHG and keep global temperatures at a safe level. This includes putting in place efforts to ensure that the global increase in temperature is limited to less than 1.5 degrees Celsius [15]. This is crucial as a global temperature increase of one single degree of heat could make the difference between life-or-death for organisms on the planet [16]. Furthermore, the IPCC have released a

Special Report in 2018 detailing the drastic changes that would take place if the temperatures continue to rise at the current rate in the hopes that the global response to the threat of climate change will strengthen. These changes include the "risks to health, livelihoods, food security, water supply, human security, and economic growth" [2]. Canada is one of 196 parties at the UNFCC to participate in the Paris Agreement, with 1.95% of world greenhouse gases but has yet to ratify the agreement [15].

However, with the move towards a more sustainable future there are still some challenges to overcome as the United States, the world's second largest emitter of carbon, plans to pull out of the Paris Accord under the Trump administration. This is primarily due to the economic setbacks that the President believes the agreement will have on the United States [17]. Furthermore, Ontario's current Premier Doug Ford has eliminated the carbon tax and cap-and-trade, which many believe are the best ways towards a sustainable future [18]. There are clear challenges in relation to the mitigation of climate change effects however, there are still many productive initiatives that are helping counter the rise in GHGs. A very important component of this global climate change adaptation and mitigation movement includes improving infrastructure and building energy performance.

1.3.2 Buildings and their Sustainability Impacts

Buildings present a wide range of varying impacts throughout their lifespan. These impacts can be global or local and affect many different types of people [11, 19]. Existing literature has discussed a variety of impacts and their implications. Table 1-1 summarizes some of these various impacts presented by buildings for their triple bottom line categories of environmental, economic and social as listed by Si et al (2016) and Sev (2009) for building energy use and construction respectively.

Table 1-1: Building Sustainability Impacts

Impact	Environmental	Social	Economic
Raw material extraction and consumption, related resource depletion	*		*
Land use change, including clearing of existing flora	*	*	*
Energy use and associated emissions of greenhouse gas (GHG)	*		*
Other indoor and outdoor emissions	*		*
Aesthetic degradation		*	
Water use and wastewater generation	*		*
Increased transport needs, depending on the site	*	*	*
Waste generation	*		*
Opportunities for corruption		*	*
Disruption of communities, through inappropriate design and materials		*	*
Health risks on worksheets and for building occupants	*		*
Occupant wellbeing and comfort		*	
Job creations		*	*
Community engagement			*

1.3.3 Towards Sustainable Built Environment

The built environment is essential as it is “a spatial material and cultural product of human activities that combines physical elements and energy to support living, working and playing” [13]. Furthermore, buildings are a very important part of human daily life as people spend on average 90% of their lives indoors [20]. According to Industry Canada (2011), buildings consume 50% of extracted natural resources and 33% of the country’s energy use. In addition, buildings produce 25% of the landfill waste, 10% of airborne particles, and 35% of GHG emissions [21]. However, of the varying factors contributing to the climate change phenomenon, building energy consumption is one of the largest. Buildings are responsible for 40% of global energy use and 30% of GHG emissions [22]. Because of this significantly large contribution, there is a search for more efficient and innovative ways to improve the energy consumption of buildings. The current challenge also lies in improving the sustainability of entire building stocks as opposed to a narrow group of already sustainable buildings [1]. Implementing green technologies and sustainable measures can improve building performance and in turn help a building operate with less energy usage. Reducing building energy consumption is crucial in tackling climate change, as the operation of a building is accountable for a major percentage of its overall environmental impact [23]. There are worldwide efforts towards the betterment of infrastructure sustainability through implementation of green technologies. Moreover, Canada aims to develop a nationwide “net-zero energy ready” model building code by the year 2030 [24]. The US Department of Energy defines net-zero energy buildings as buildings that produce enough renewable energy to meet their energy consumption, which in turn reduces the consumption of fossil fuels [25]. Net-zero energy ready buildings are those which are prepared to be net zero ready in the future but may not have the means to produce on site energy for the time being [26].

The sustainable building actions taken by the government will "save Canadian money and help make homes, businesses and other buildings more comfortable, healthy and environmentally friendly" [24]. All building stakeholders should be looking at reducing GHG emissions within the building stock to mitigate climate change and global warming [27]. A significant reduction in global energy consumption and GHGs can be achieved using green retrofitting [1].

1.3.4 Importance of Green Retrofitting

The United State Green Building Council (USGBC) defines green retrofits as "any type of upgrade at an existing building that is wholly or partially occupied to improve energy and environmental performance, reduce water use, improve comfort and quality of space in terms of natural lighting, air quality and noise, all done in a way that it is financially beneficial to the owner" [28]. Thus, the implementation of green retrofitting can result in a wide variety of benefits. Hence, benefits of retrofitting may be economic (e.g., lower operating costs), environmental (e.g., reducing GHGs) or social (e.g. increase in comfort). This is why, according to Si et al., it is important to consider sustainability criteria when evaluating different retrofits through the assessment of the environmental, economic and social performance [11]. Retrofitting is also found to be more favorable than the demolition and reconstruction of buildings [29]. The rate of replacement of existing buildings is significantly low, and so retrofitting has been identified as "having a greater potential to improve energy efficiency and reduce GHG emissions than improving standards of new buildings" [11]. Retrofitting as opposed to reconstruction also results in a decreased pressure created on landfills as well as the decrease in construction waste and materials [1]. Furthermore, the cost of refurbishment is often found to be less than that of re-construction [3]. Consequently, the use of green building retrofits must be amplified or "building design and construction will have little responsibility in tackling global warming" as existing buildings are remaining in operation for 50-100 years because of their long lifespans [30]. Canada has invested over one billion dollars in 2018-2019 for the increase in energy efficiency of residential, commercial and institutional buildings. This includes the implementation of a variety of deep, major and minor retrofits. Collaboration on Community Climate Action has also invested $350 million that will go to municipalities for the green retrofitting of large and small community buildings [31]. With green retrofits being a vital component to sustainable development it's important to explore the different types and methods, to make an informative decision on the appropriate selection.

1.3.5 Green Retrofitting Types

There are a wide variety of green retrofits available to meet the needs of different infrastructure systems. Ma et al. outlines the major possible retrofit technology types with some of the most common ones including changes in thermal insulation, lighting, heating and cooling controls and solar panels [32]. Furthermore, these varieties of building retrofits may be installed in differing building categories such as office buildings, schools and multi or single-family homes [32]. The type of retrofits used in a building is dependent on many factors as multiple criteria exist and interrelate [11]. Ma et al. also discusses that retrofit technologies may be categorized into three groups: "supply side management, demand side management and change of energy consumption patterns". The supply side management focuses on retrofits which can provide energy to building (e.g., solar voltaic cells) while demand side management focuses on reducing the energy consumption (e.g., thermal insulation) [32].

Furthermore, there are three retrofitting categories as outlined by the Government of Canada; minor, major and deep retrofitting. These retrofitting types are outlined in Table 1-2 below. This table is adapted from data provided by the Government of Canada on Retrofitting [33].

Table 1-2: Minor, Major and Deep Energy Retrofits Descriptions - Adapted from the Government of Canada

Type of Retrofit	Description	Examples
Minor	Minor retrofits are modifications that are low-cost, easy to implement and that offer good value for the money and effort invested.	• Sealing with caulking or spray foam • Adding insulation • Upgrading lighting systems
Major	With major retrofitting a more holistic approach is taken, which is minimally disruptive to building occupants.	• Replacing window glazing and doors • Updating inefficient heating and cooling systems • Installing low-flow faucets with sensors and automatic shut-offs • Installing sub-metering
Deep	Deep retrofits require an extensive overhaul of your building's systems that can save you up to 60 percent in your energy costs. These types of retrofits can be disruptive to your building's occupants.	• Significantly reconfiguring the interior • Replacing the roof • Adding or rearranging windows for increased daylight • Replacing the heating, ventilation and air-conditioning system with a renewable technology like a ground-source heat pump

With a wide variety of green retrofits available it is important to evaluate their different benefits and impacts to decide on which ones to implement.

1.3.6 Retrofit Decision-Making Methods

A range of existing research touches on methods for energy retrofit selection of existing buildings [1]. Gore et al. have described a general procedure for decision making with the involvement of the following steps: setting objectives, defining the problem, searching for alternatives, evaluating the alternatives, making a choice and implementing [34]. This general method appears to be the basis for the various decision-making techniques available for the evaluation of building retrofits. Jafari et al. created an "optimization framework for building energy retrofits" focusing primarily on optimization of cost savings [29]. Ma et al. provided "a systematic approach" to cost-effective retrofit selection [32]. Furthermore, Si et al. uses the Analytical Hierarchy Process (AHP) as a MCDM method for the selection of technologies to retrofit existing buildings, taking in a variety of sustainability criteria [11]. Antipova et al. used a "mixed-integer linear program" for retrofitting by means of environmental LCA principles [23]. In addition, Menassa presents a "quantitative approach to determining the value of investment in sustainable buildings" focusing on life cycle costs and perceived benefits of investment [35]. Collier et al., utilized the Multi-Attribute Value Theory for roofing retrofit selection and the development of more comprehensive criteria [36].

The National Institute for Environmental and Economic Sustainability has also developed BEES, a software which aims to help with the selection of environmentally-preferred, cost-effective building products [12]. Athena Impact Estimator for Buildings is also useful for the evaluation of primarily environmental impacts presented by building assemblies. Athena Impact Estimator is created by the Athena Sustainable Materials Institute [37]. Facility Energy Decision System (FEDS) is another tool, developed in partnership with the US Department of Energy, that is used to determine optimal retrofits to install based solely on life cycle costing results. The FEDS tool is also able to provide emission data for six pollutant types as they relate to the energy decrease from retrofit installation [38]. Most developed decision-making methods to date do not include all three pillars of sustainability in their criteria consideration. Much of the decision-making process surrounding building retrofitting is based on a single economic or environmental criterion [11]. Additional decision-making models should be developed to maximize the energy retrofit benefits, including economic, environmental and social [29]. Furthermore, a critical consideration in the development of retrofit decision-making models includes life cycle thinking [13]. From all existing decision-making methods, life cycle assessments are not always used and if so, they are often limited to evaluation of criteria related to environmental or costing. Table 1-3 shows the criteria and life cycle thinking (LCT) considerations in existing literature pertaining to building energy retrofit selection.

Table 1-3: Retrofit Selection Literature Criteria Considerations

Authors	***Economical***	***Environmental***	***Technical***	***Social***	***LCT***
Miller et Buys (2008)				✓	
S.E. Chidiac (2010)	✓				✓LCC
Asadia et al. (2011)	✓	✓	✓		
C. Menassa (2011)	✓				✓LCC
Ma et al. (2012)	✓				
Antipova et al. (2014)	✓	✓			✓LCA
Si et al. (2016)	✓	✓	✓	✓	
Jafari et al. (2017)	✓				✓LCC

Dirutigliano et al. (2018)	✓			✓	
Liu et al. (2018)	✓	✓			✓LCC
Wang et al. (2018)	✓	✓	✓	✓	
Bragolusi (2019)	✓	✓	✓	✓	

1.3.7 Life Cycle Thinking and Retrofit Evaluation

Life cycle assessments allow for the testing and improvement of innovations in terms of their environmental, economic and social contributions. LCAs are considered to be valuable tools for the development of sustainable solutions, in which the solutions should involve a good cost to benefit ratio, result in social benefits, and minimize negative environmental effects [13]. There is currently not enough reliable data and methodology to undertake life cycle economic, energy and environmental analysis for sustainable building elements, such as retrofits, for the refurbishment of existing buildings [3]. Some research has focused on the life cycle assessment of specific types of criteria areas, i.e. on either environmental, economic or social criterion. Antipova et al., conducts an environmental LCA along with multi-objective optimization to present a systemic tool that considers economic and environmental criteria [23]. Menassa uses life cycle costing to evaluate sustainable building retrofits, focusing on the value of investment in sustainable retrofits [35]. Thomas et al., focus heavily on life cycle energy analysis in their study to evaluate net zero energy building efforts [39]. With all the incorporations of life cycle thinking into retrofit evaluation, there appears to be a lack of combination of environmental, economic, technical and social criteria. It is important to consider all of these criteria when comparing retrofits as the environmental, economic and social impacts occur throughout the life cycle of buildings; from raw material acquisition, construction, operation, demolition and disposal [40]. In general, social and economic impacts aspects are not generally considered in the literature concerning life cycle assessments of building refurbishments, and more studies are needed in this area [41].

1.3.8 Life Cycle Sustainability Assessment

In order to balance the triple bottom line of sustainability, life cycle thinking with regards to the built environment should encompass the three following stages; life cycle assessment (LCA) (environmental and social) and life cycle costing (LCC) [15]. A combination of these three assessments and sustainability pillars results in the Life Cycle Sustainability Assessment (LCSA). The United Nations Environmental Programme (UNEP) introduces this concept while acknowledging and combining the life cycle initiatives and methodologies of other organizations [42]. The International Standards Organization (ISO) can be referred to when conducting retrofit LCAs as it has two standards, ISO 14040 and 14044, that fit into building refurbishment scenarios [41]. These standards focus on life cycle assessments concerning environmental performance, however this established life cycle methodology and approach presented by ISO 14044 can be extended to economic or social aspects of a product [43]. Therefore, sustainable life cycle assessments in the built environment can evaluate multiple criteria using an LCA (for environmental and social aspects) and an LCC (for economic aspects). According to the ISO 14044 standard, "LCA studies shall include the goal and scope definition, inventory analysis, impact assessment and interpretation of results" [44].

The goal and scope definition include identifying the preliminary assumptions and purpose of the study, along with the boundaries of the system. Some of the options available to select the system boundaries include; cradle-to-cradle, cradle-to-grave, cradle-to-gate and gate-to-cradle. The life cycle inventory (LCI), is concerned with the quantification of the mass and energy flows. The life cycle impact assessment (LCIA) is where the indicators are used for assessing the environmental impact or modified to social or economic impact. Finally, the life cycle interpretation is completed to establish ways which can reduce the impacts presented by the system [43]. For LCAs, quantitative or qualitative information on emissions, material, and energy used in all phases is useful as it helps conduct a complete impact assessment.

1.4 Research Methodology

The aforementioned objectives are achieved using a simulation-based methodology. Four interrelated phases form the methodology for this project. These phases are outlined in the diagram in Figure 1-1 and further detailed in this section below. The chapters in which each phase work is covered are also indicated in the figure. This results in the thesis being six chapters long with one introduction chapter, four body chapters (one for each phase) and a final discussion and conclusions chapter.

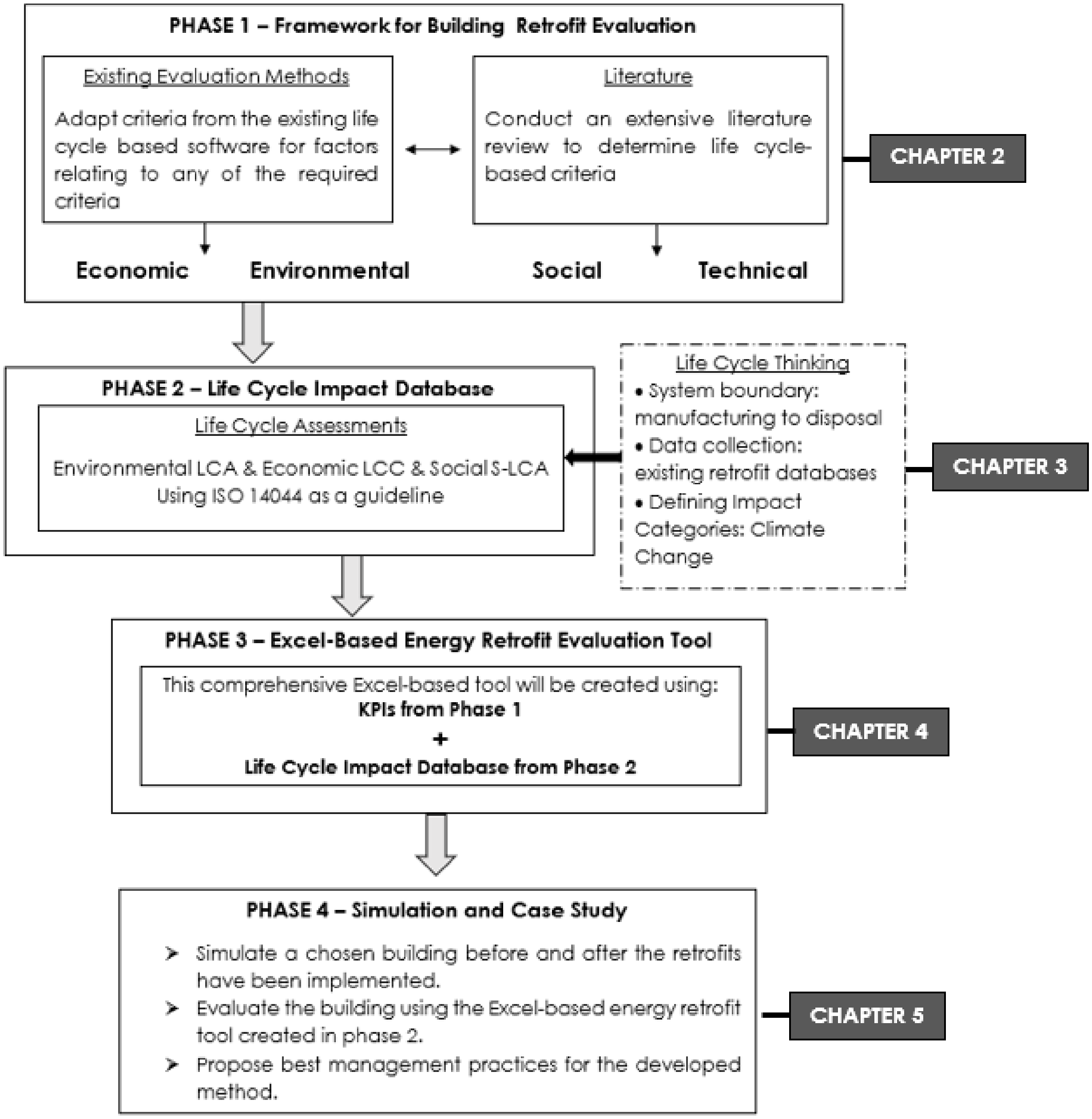

Figure 1-1: Research Methodology Overview

1.4.1 Phase 1 – Framework for Building Retrofit Evaluation

Phase 1 focuses on the determination of the key performance indicators (KPI). In order to develop the retrofit evaluation framework, the first step is to determine and develop a set of environmental, economic, social and technical key performance indicators. These KPIs are developed through an extensive literature review to incorporate the key aspects for each category. The Building for Economic and Environmental Sustainability (BEES) is useful towards the collection of the KPIs as it is developed by the National Institute of Standards and Technology (NIST) [12]. Although the BEES criteria are only related to economic and environmental aspects, they are developed using International Organization for Standardization (ISO) Life Cycle Costing and Life Cycle Impact Assessments [12]. Further software exists which assesses building sustainability such as Athena Sustainable Materials Institute, which focuses on building design evaluation using environmental LCA, and the Green Building Tool which is an environmental assessment tool [45]. Therefore, some of the environmental and economic KPIs can be collected through existing credible software assessments. The social and technical criteria will rely heavily on literature reviews and life cycle thinking. Existing research concerning the social life cycle of building elements will be taken into consideration for the development of the KPIs. The details of Phase 1 are explained and discussed in detail in Chapter 2.

1.4.2 Phase 2 – Life Cycle Impact Database

In Phase 2 a life cycle impact database is developed to help evaluate varying retrofits. This database is programmed on Excel to help define the assignable values for the KPIs while incorporating life cycle thinking. This database is created using existing life cycle sustainability assessment (LCSA) methodology. The LCSA is conducted according to the ISO 14044 standard [44]. The systems boundary for the assessments includes from the cradle-to-grave of the retrofit. This boundary encompasses the material and energy production chain and all processes from the raw material extraction through the production, transportation and use phase up to the product's end of life treatment [44]. Furthermore, data is collected from a variety of sources such as the RS Means for life cycle costing and the ecoinvent database for the collection of environmental values. This life cycle impact database is comprehensive enough to be modified for a variety of building retrofits that may need to be considered for a particular project.

These are evaluated and based on the following major criteria:

- Environmental: uses life cycle impact assessment (LCA) through software such as BEES and Athena
- Economic: uses life cycle costing (LCC) – using data from RS Means and the LCC formula
- Social: uses social life cycle assessment (S-LCA) – using Norris's SLCA methodology, calculating the difference between the year gain from economic growth and years lost from pollution to provide a result on health impacts.

Combining these three life cycle assessments will bring a more holistic evaluation to the selection of building retrofits. The development of the life cycle impact database will help bridge the methodology onto Phase 3 to develop the retrofit evaluation tool. Details of this methodology are outlined and detailed in Chapter 3.

1.4.3 Phase 3 – Retrofit Evaluation Tool

Once the KPIs from Phase 1 and the life cycle impact database from Phase 2 are complete, they are combined in Phase 3 to develop an Excel-based energy retrofit evaluation tool. The evaluation framework is structured with the information and definitions gathered for the KPIs in Phase 1. Firstly, this framework has the four major categories of: social, economic, environmental and technical. Then under these categories there are the associated subcategories as determined by the KPIs. This developed framework is shown and discussed in Chapters 1 and 4.

This framework utilizes a weighted sum method (WSM), with the breakdown and description of categories and subcategories. The weighted sum method is used for its comprehensibility, straightforwardness and simplicity [46]. This method follows an additive unity assumption to make the "best" decision. Although the WSM is one of the most basic and commonly used methods, it provides similar results when compared to other methods with accurate data [47]. A normalization scheme must be applied for the variables in the framework to apply the WSM. The following general formula is used for the weighted sum method:

$$A_{WSM-score} = max \sum_{j=i}^{n} a_{ij} w_j$$

Equation 1-1

where $A_{WSM-score}$ is the WSM score of the preferred alternative, n is the number of decision criteria, $a_{ij} w_j$ is the actual value of the i-th alternative in terms of the j-th criterion and w_j is the weight if the importance of the j-th criterion [48]. This framework will help create a scoring chart for the retrofits that will be evaluated.

Next, the life cycle impact database from Phase 2 is connected into the evaluation framework. LCA, LCC and SLCA data stored in the database will assist the life cycle thinking based evaluation. When using the tool, the weights for each of the four categories will be assigned based on the stakeholder's preference and valuation of the criteria for their needs. This will result in a value analysis of the retrofits using indicator scores multiplied by value weights [49]. This subjective weighting scheme is used as there is a lack of widespread agreement for weighting criteria [50].

1.4.4 Phase 4 – Case Study

Finally, in Phase 4 a case study will be used to demonstrate the frameworks abilities with select retrofits from the database. A chosen building will be modelled using HOT2000 software. This model will demonstrate the energy consumption changes that can be applied to the tool and help in the selection of the most appropriate retrofit.

The basis of this simulation case study will be to serve as a detailed example of the way the comprehensive Excel-based evaluation tool can be applied. Furthermore, implementation guidelines and best management practices can be determined and discussed with regards to the use of the tool, along with its limitations.

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CHAPTER 2

RETHINKING ENERGY RETROFIT EVALUATION: A LIFE CYCLE THINKING BASED APPROACH

2.1 Introduction

Building retrofits have a complex relationship with their environment making criteria development a crucial aspect of the decision making process [1-3]. Studies suggest that many factors should be taken into account, including the economical, technical, social and ecological aspects [4, 5]. Researchers have also found life cycle thinking incorporation to be important in achieving sustainable outcomes [6, 7]. Despite the amount of research to date on retrofit selection tools, there is a lack of established benchmarks and criteria [8]. Thus, a wholistic energy retrofit evaluation framework is required for the selection decision making process. There are a variety of existing decision-making methods available to aid in selecting building retrofits. These methods include multi-criteria decision making (MCDM), multi-objective optimization (MOO), Analytical Hierarchy Process (AHP) and Multi-Attribute Decision Making (MAUT) [1]. Furthermore, there are different software available to help evaluate sustainable building products such as Building for Environmental and Economic Sustainability (BEES) which focuses solely on environmental and economic criteria [9].

This chapter's main objective is to develop a life cycle thinking based methodological framework for building energy retrofit selection. The methodology incorporates holistic evaluation criteria by developing a set of environmental, economic, social and technical key performance indicators (KPI).

2.2 Methodology

The methodology for this framework is conducted in two parts. The first part deals with determining a set of KPIs for the environmental, economic, social and technical categories. These KPIs were determined through existing software, literature and content analysis.

The “Compendex Engineering Village” database was used to obtain journal articles. Key word searches were used to obtain relevant publications related to the research. The combination of key works in this project included: “green”, “building”, “retrofit”, “sustainability”, “indicator”, “decision making” and “energy”. From the output articles, the list was narrowed down by analyzing the abstracts and if found to be potentially relevant, it was followed by reviewing the content of the articles. Furthermore, the KPIs were developed through the evaluation of existing building materials selection and evaluation tools.

The second part of the methodology develops the framework to compare and evaluate the energy retrofits. Existing MCDM methodologies which deal with building materials selection and retrofits were reviewed. These methods are evaluated based on existing literature to determine which is deemed most appropriate for the purposes of this research project. After selecting the MCDM method for this framework, the determined list of KPIs was established and normalized. Finally, a set of equations was developed to apply the framework.

2.3 Key Performance Indicators

The content analysis methodology discussed in the previous section was used in order to choose the key performance indicators for four criteria categories: environmental, economic, social and technical. A content analysis is a "powerful data reduction technique", which is beneficial for research as it can narrow down a large amount of data, in this case available literature, through the compression of many words of text into fewer content categories based on explicit rules of coding [10]. The collected studies were narrowed down by analyzing the abstracts and if found to be potentially relevant, they were followed by reviewing the contents of the articles. Furthermore, the KPIs were developed through the evaluation of existing building materials selection and evaluation tools.

The second part of the methodology develops the framework to compare and evaluate the energy retrofits. Existing MCDM methodologies which deal with building materials selection and retrofits are reviewed and discussed. These methods were evaluated based on existing literature to determine which were deemed most appropriate for the purposes of this research project. Then, a MCDM method is selected to incorporate these four criteria which should be considered when selecting green technologies, such as in energy retrofits [11]. The sustainability requirements for the building sector are becoming more prevalent making it is essential for the decision makers to consider the triple bottom line criteria, which address environmental, economic and social performance [1]. Furthermore, technical criteria are important in building material selection decision making as many studies focus heavily on them to meet functional requirements [11]. Technical factors are an important part of the decision making process as the new components that are introduced in building energy retrofitting bring in challenges with the existing system interactions [12]. The selection of the varying criteria for the four impact categories is detailed in the respective sections below.

2.3.1 Environmental Performance Indicators

Environmental impacts are one of the most widely discussed topics in green building energy retrofitting. This research focusses on developing key performance indicators that incorporate life cycle thinking. Two credible North American life cycle assessment tools are popularly used to select building materials: 1) Building for Environmental and Economic Sustainability (BEES), and; 2) Athena Impact Estimator for Buildings [9, 13, 14]. BEES has indicators for environmental and economic criteria, while Athena focusses on only environmental impacts through life cycle assessments (LCA). BEES was developed by the National Institute of Standards and Technology (NIST) while ATHENA was developed through Athena Sustainable Institute. Both utilize the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) metrics to develop their environmental indicators, and therefore present many similarities.

Athena and BEES both account for: global warming potential, acidification, human health, ozone depletion, smog potential, fossil fuel depletion and eutrophication. One difference is that Athena accounts for primary and non-renewable energy consumption while BEES does not. Energy consumption will later be discussed as a technical indicator in Section 3.4 and thus removed from the environmental category. Furthermore, BEES examines indoor air quality, habitat alteration, water intake, criteria air pollutants and ecological toxicity. Athena explains that water use and habitat alteration are highly site specific and therefore are not be used in their LCA analysis. Thus, the more complete set of indicators from BEES will be adapted for the environmental KPIs in the framework because they cover a wider range of criteria. Human health is, however, removed from the environmental category and used as a social criterion as discussed in Section 3.3.

2.3.2 Economic Performance Indicators

The economic criteria for this framework were based on the requirements of a life cycle costing (LCC) evaluation which is covered in BEES. BEES has two economic criteria which are calculated in order to provide an economic analysis for a building product, being first cost and future costs. The BEES software follows the American Society for Testing and Materials (ASTM) method for LCC, starting at product purchasing and ending at some end date of product ownership [9]. These can be combined into one KPI of total cost, which can be determined using the LCC approach.

2.3.3 Social Performance Indicators

There are various social life cycle assessment methodologies available, such as the most popular methods by Dreyer, Norris, Hunkeler and Weidema [15]. Human well-being is found to be the basis for all social life cycle assessments (SLCAs). SLCA differs from environmental LCAs or LCC as it is “based on the way business affects human well-being” [16]. Dreyer et al. have developed a method for which corporate social responsibility is key, focusing on a company’s management of social issues. Norris has developed a method to quantitatively model the social impacts of a product across its lifecycle through one end point indicator, being human health impact. Hunkeler’s involves the calculation of labour hours, giving a focus on the employees at a production company and the benefits created by the industry. Weidema developed a method which relates human life-years lost during a products life cycle to social impacts, taking a damage-oriented approach to the SLCA [17]. Of all these popular SLCA methods that were reviewed, Norris's SLCA was adopted to determine the end point social KPI within the framework. The focus of the framework is to analyze a particular retrofit involving its product materials and processes. This contrasts with other SLCA approaches that examine company involvement in product manufacturing in conjunction with a company's ability to manage social issues, such in Dreyer's SLCA. Hunkeler's SLCA focuses on the labour hours and employment. Weidema's SLCA requires identifying social issues and damage categories which are highly variable. Norris was influenced by Weidema's SLCA, and integrates social and economic impacts together [16].

The health impact endpoint indicator in Norris's SLCA is developed by analyzing the economic life cycle and the human life expectancies in the countries where the products are produced and supplied [18]. Thus, the KPI for the social category becomes human health impact which is determined through socio-economic pathways.

2.3.4 Technical Performance Indicators

One article published in 2016 by Si et al. specifically dealt with retrofit decision-making selection considering criteria which are categorized as environmental, economic, social and technical [1]. Interestingly, this research article did not consider life cycle thinking for the development of their framework, as is considered throughout this project for environmental, social and economic KPIs. The technical criteria used by Si et al. (2016) are compatibility, reliability, efficiency, durability and flexibility. These criteria are pertinent to the framework for this project and are therefore included. Other technical criteria, beyond those found in Si et al.'s (2016) research, are also deemed to be important and added to the framework. These criteria were found through a literature review of articles which dealt with renewable energy technologies.

Although there was not much literature pertaining directly to selecting technical indicators for building energy retrofits, there is a substantial amount of research geared towards selecting indicators for renewable energy and storage technologies as well as improving sustainability of industrial systems. Much of this existing research to date varies in terms of the types of technical indicators and categories. Some of the developed indicators however are repetitive and commonly found throughout the literature. Karunathilake et al. (2019) determines a set of technical indicators that relates to renewable energy assessment criteria by extracting the key findings from other published sources [7]. These technical criteria include feasibility, risk, reliability, maturity, safety, performance and capacity. Wimmler et al. (2015) has also discussed the varying technical indicators that can be found throughout literature for multi-criteria decision-making methods that are applied to technology selection [19]. Furthermore, Ibáñez-Forés, Bovea, and Pérez-Belis (2014) put together a table that outlines the technical criteria indicators selected by researchers dealing with improving the sustainability of industrial systems [20]. The five most commonly mentioned indicators mentioned in these articles (in over 15% of them) include performance/efficiency, maturity, reliability, compatibility and lifespan, which present some overlap with the indicators presented by Si et al. (2016) [1].

These additional indicators (maturity and lifespan) were thus added to the technical KPI list for the framework. Maturity is mentioned in the research by Si et al. (2016) to be important but not included in their proposed framework. Both maturity and lifespan are deemed to be important to consider as they play a role in the life cycle of an energy retrofit.

2.3.5 Content Analysis Results Summary

Table 2-1 gives a summary of the KPIs for the four criteria categories along with the literature sources used for their selection.

Table 2-1: KPI Selection References

CATEGORY	KPI	REFERENCES
ENVIRONMENTAL	Global Warming Potential	[9, 13, 21]
	Acidification	[9, 13, 21]
	Eutrophication	[9, 13, 21]
	Fossil Fuel Depletion	[9, 13]
	Indoor Air Quality	[9, 21]
	Habitat Alteration	[9]
	Water Intake	[9]
	Criteria Air Pollutants	[9, 21]
	Smog	[9, 13, 21]
	Ecological Toxicity	[9, 21]
	Ozone Depletion	[9, 13]
ECONOMIC	Total Life Cycle Cost	[9, 22]
SOCIAL	Human Health	[18]
TECHNICAL	Performance	[5, 7, 19, 20, 23]
	Maturity	[7, 19, 20, 23-25]
	Reliability	[5, 7, 19, 20, 23-26]
	Compatibility	[5, 20, 24]
	Lifespan	[19, 20]
	Durability	[5, 24]
	Flexibility	[5, 20, 24]

2.4 Retrofit Evaluation Framework

There are 20 KPIs in total; eleven in environmental, one in economic, one in social and seven in technical. In order to apply the 20 KPIs determined and discussed above a multi criteria decision making method was chosen to structure the framework. The hierarchical framework is shown in Figure 2-1. The weighted sum method was chosen and discussed in detail in the following section along with an illustrative case study to demonstrate the use of the framework in Section 4.

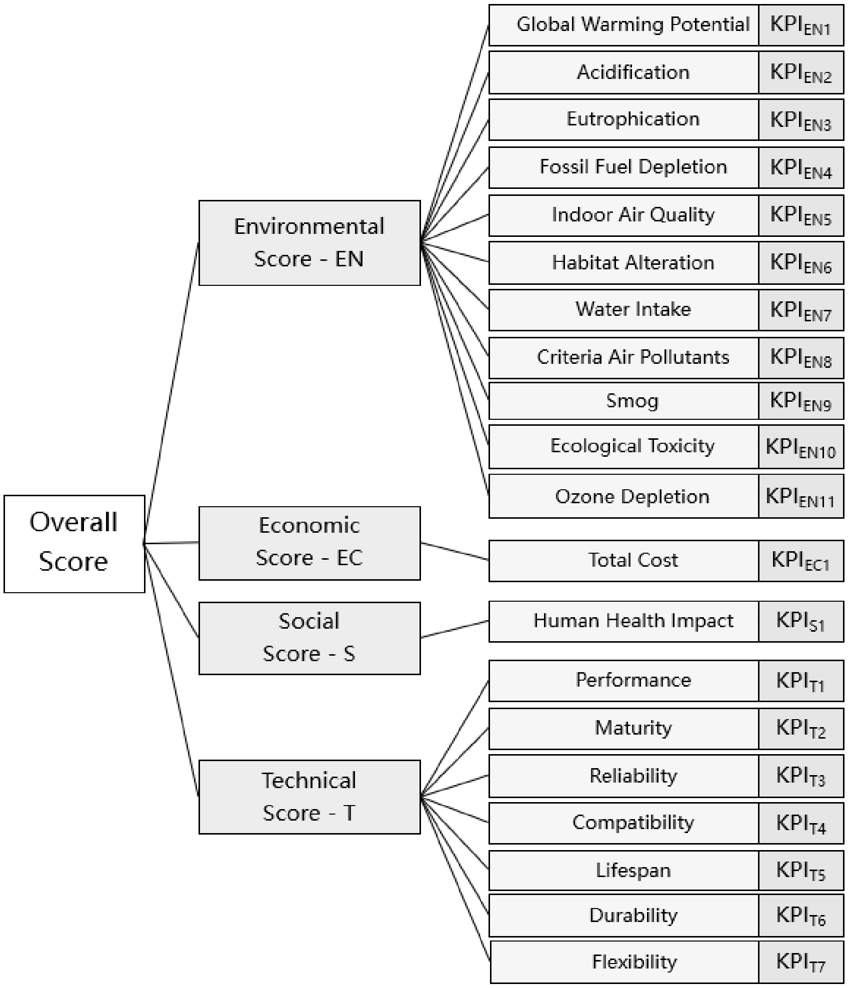

Figure 2-1: Hierarchical Framework

2.4.1 Aggregation of KPIs using MCDM

There are several commonly used models that are used for MCDM including; weighted sum method, analytical hierarchy process, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Elimination et Choice Translating Reality (ELECTRE) [1]. The analytical hierarchy process creates a pairwise comparison based on assigned importance from a decision maker. This technique is useful when designing an alternative rather than for selection. TOPSIS works by choosing the alternative that has the shortest distance from the ideal solution and the farthest distance from the negative-ideal solution. This method is rated below average in terms of understanding by decision makers. ELECTRE uses the concept of an outranking relationship and consists of an elaborate and length procedure [27]. Table 2-2 shows descriptions and a summary of the MCDM methods considered for this framework.

Table 2-2: MCDM Methods

Methods	Description
Weighted Sum Method (WSM)	• The overall score of an alternative is computed as the weighted sum of the attribute values. • Simple and fast understandable methods for people who are not familiar with the multi-criteria decision support methods. • Can provide similar results when compared to other more complex methods.
Analytical Hierarchy Process (AHP)	• Pairwise comparison is used comparing each criterion against the other based on importance assigned from the decision maker. • More useful for designing an alternative rather than selection.
Technique for Order Preference by	• The chosen alternative should have the shortest distance from the ideal solution and the farthest distance from the negative-ideal solution.

Similarity to Ideal Solution (TOPSIS)	• Found to be rated a 2/5 in terms of understanding by decision makers.
Elimination et Choice Translating Reality (ELECTRE)	• The concept of an outranking relationship is used, which says that even though two alternatives do not dominate each other mathematically, the decision maker accepts the risk of regarding one alternative as surely better than the other. • Very lengthy and elaborate procedure. • Can eliminate a set of alternatives to then work with other lower alternatives but will need to determine an elimination threshold.

The framework for this research utilizes a weighted sum method (WSM), with the breakdown and description of categories and subcategories. The weighted sum method will be used for its comprehensibility, straightforwardness and simplicity [28]. This method follows an additive unity assumption to select the preferred alternative. Although the WSM is one of the most basic and commonly used method, it provides similar results when compared to other methods with accurate data [29]. To apply the WSM, a normalization scheme must be applied for the variables in the framework. Normalization ensures all values in the framework are on the same scale so that weights can be applied. The reference values that will be used for the normalization includes the inputs for a given alternative retrofit that has the highest beneficial value or the lowest non-beneficial (cost) value for each KPI [30]. Steps and formulas for this application are detailed in Section 4.2.

2.4.2 Weighting and Normalization

In order to score and compare each of the retrofits, values will be acquired and normalized for each of the established KPIs. Data will be collected through a variety of sources such as other tools and frameworks or literature to calculate the values of each KPI.

For the environmental, economic and social criteria this will be done by conducting life cycle assessments (LCA, LCC, SLCA). Technical criteria, however, can be determined by using content analysis or manuals for a particular product or company which provides the retrofit materials. Because many of the technical criteria are qualitative, the decision makers will need to make defensible and reasonable assumptions to choose and justify the values of the criteria.

The WSM determines the overall score of each energy retrofit relative to all the alternatives. Each of the four major criteria categories (environmental, economic, social and technical) has its own weights which will be selected by the user. This subjective weighting scheme will be used for these four categories as there is a lack of widespread agreement for weighting criteria [20]. A decision maker in this framework can emphasize a select aspect by changing the values of those weights in the overall scheme. There will be a predetermined category weight set for the KPIs. It is lengthy to have a user determine the weights for each individual KPI because there is a relatively large total of 20 KPIs. Furthermore, the weight of each KPIs is not meant to be changeable as the user may lack the appropriate knowledge or full in depth understanding of the impact from each KPI in its category.

The weights for the environmental category were determined through BEES, which has a set of relative importance weights based on an Environmental Protection Agency Science Advisory Board Study [9]. As discussed above, human health was not considered as it fell into the social criteria, therefore its weight in BEES was equally distributed amongst the other environmental categories. The economic and social criteria stand alone as total cost and human health impact respectively and are therefore each weighted as 100%

for the appropriate score. Not many weighting schemes are found through the literature pertaining to technical KPIs. Therefore, all technical KPIs were assigned equal weights. This method of assigning equal weights is the most popular in sustainable energy decision making and has been found to produce results that are nearly as defensible as those using optimal weighting methods [23]. All KPI category weights, along with the KPI units, can be seen in Table 2-3 below.

Table 2-3: Weights for Key Performance Indicators

Category	Notation	KPI	Units	Category Weight (%)
Environmental (EN)	KPI_{EN1}	Global Warming Potential	g CO_2 equiv.	18
	KPI_{EN2}	Acidification	g SO_2 equiv.	5.6
	KPI_{EN3}	Eutrophication	g N	5.6
	KPI_{EN4}	Fossil Fuel Depletion	MJ surplus energy	5.6
	KPI_{EN5}	Indoor Air Quality	TVOCs	12.4
	KPI_{EN6}	Habitat Alteration	T&E count	18
	KPI_{EN7}	Water Intake	L of water	3.4
	KPI_{EN8}	Criteria Air Pollutants	microDALYs	6.7
	KPI_{EN9}	Smog	g O_3 equiv.	6.7
	KPI_{EN10}	Ecological Toxicity	g 2,4 – D equiv.	12.4
	KPI_{EN11}	Ozone Depletion	g CFC-11 equiv.	5.6
Economic (EC)	KPI_{EC1}	Total Cost	CAD $	100
Social (S)	KPI_{S1}	Human Health	Years	100
Technical (T)	KPI_{T1}	Performance	Energy savings (%)	14.3
	KPI_{T2}	Maturity	Score out of 5	14.3
	KPI_{T3}	Reliability	Score out of 5	14.3
	KPI_{T4}	Compatibility	Score out of 5	14.3
	KPI_{T5}	Lifespan	Years	14.3
	KPI_{T6}	Durability	Score out of 5	14.3
	KPI_{T7}	Flexibility	Score out of 5	14.3

The formulas for normalizing the KPI values are shown in Equation 2-1 and Equation 2-2. The min-max linear normalization process is used. It is found that this method can better distinguish between candidate alternatives compared to other MCDM methods [31]. This method results in a higher normalized KPI value representing a higher performance for the indicators. If a KPI is beneficial (such as durability or maturity), each alternative KPI unit value $r_{alt,i}$ will be normalized by subtracting the smallest alternative value from it, r_{alt}^{min}, and diving that result by the difference between the highest and lowest alternative to calculate the normalized value $KPI_{alt,i}$ as shown in Equation 2-1. If a KPI value is disadvantageous (such as CO_2 emissions or cost), the alternative KPI unit value $r_{alt,i}$ will be subtracted from the largest unit value, r_{alt}^{max}, and that result will be divided by the difference between the highest and lowest alternative to calculate the normalized value $KPI_{alt,i}$ as shown in Equation 2-2.

$$KPI_{alt,i} = \frac{r_{alt,i} - r_{alt}^{min}}{r_{alt}^{max} - r_{alt}^{min}}$$

Equation 2-1

$$KPI_{alt,i} = \frac{r_{alt}^{max} - r_{alt,i}}{r_{alt}^{max} - r_{alt}^{min}}$$

Equation 2-2

Equation 2-3 shows the formula that is used to determine the total category score, $Score_{CATEGORY}$, based on the KPIs in each criteria category (environmental, economic, social, technical) of each alternative retrofit, where $KPI_{alt,i}$ is the normalized value of the i-th KPI in terms of the alternatives normalization, n is the number of decision criteria in the respective criteria category and is the weight if the importance of the i-th KPI.

$$Score_{CATEGORY} = \sum_{i=1}^{n} KPI_{alt,i} * w_i$$

Equation 2-3

Equation 2-4 is used to calculate the overall score for each alternative energy retrofit, $Retrofit\ Score$, where $W_{CATEGORY}$ is the weight of the major categories. The sum of all the weights together equates to 100%. The retrofit with the largest overall score will determine which alternative is best.

$$Retrofit\ Score = Score_{EN} * W_{EN} + Score_{EC} * W_{Ec} + Score_S * W_s + Score_T * W_T$$

Equation 2-4

2.5 Summary

Buildings, one of the largest contributors of greenhouse gas emissions, can benefit from energy retrofit implementation. Existing retrofit selection decision aid tools need to be more holistic and consider the life cycle aspects of the products. The framework in this research is developed with a comprehensive life cycle perspective and considers comprehensively the environmental, economic, social and technical impacts of a retrofit. Key performance indicators are selected through literature, databases and content analysis which fall into the four impact categories. This framework consists of 20 indicators total. Furthermore, the weighted sum method is used in order to calculate a total score for each retrofit with respect to all alternatives. Each KPI has its own pre-determined weight value, however the weights for the environmental, economic, social and technical categories are chosen by the decision maker to suit their needs. Furthermore, values for the KPIs are normalized in order to apply the framework.

2.6 References

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CHAPTER 3

LIFE CYCLE SUSTAINABILITY ASSESSMENT OF BUILDING ENERGY RETROFIT ALTERNATIVES

3.1 Introduction

A life cycle assessment (LCA) is an important tool to help determine the impacts of a product not only through the most commonly examined operational phase, but through its entire life from cradle-to-grave [1]. Life cycle assessments also allow for the testing and improvement of innovations in terms of their environmental, economic and social contributions. LCAs are considered to be valuable tools for the development of sustainable solutions, in which the solutions should involve a good cost to benefit ratio, result in social benefits, and minimize environmental effects [2]. The life cycle impacts for economic and social criteria are not always considered when evaluating the effects of green building initiatives such as energy retrofits [2, 3]. Furthermore, if life cycle impacts are considered, there is typically a focus on only one of the criteria areas, i.e. solely on either environmental, economic or social criterion.

This chapter develops a life cycle impact database (LCID) to conduct a sustainability assessment for proven building energy retrofits. The LCID is developed using the varying requirements of the International Standards Organization along with their outlined phases which are required to conduct LCAs. For this life cycle sustainability assessment environmental, economic and social impacts will be considered. A list of key performance indicators (KPIs) for the triple bottom line categories, from Chapter 2, will be used throughout the assessment. Furthermore, data for the LCID is collected from a variety of life cycle centered resources such as Building for Environmental and Economic Sustainability (BEES), Athena Impact Estimator, RS Means and different energy retrofit product manuals.

3.2 Methodology

The methodology followed for this research is adapted from the International Standards Organization (ISO) guidelines for life cycle assessments. ISO has developed two standards which may be adopted to conduct and structure LCAs: ISO 14040 LCA Principles and Framework and ISO 14044 LCA Requirements and Guidelines. These standards state that "LCA typically does not address the economic or social aspects of a product, but the life cycle approach and methodologies described may be applied to these other aspects" [4]. Three different life cycle assessment methodologies can be used to cover all of these areas. An environmental LCA examines the potential impacts relative to the environment through the life cycle processes such as the "extraction of resources, transportation, production, use, recycling and discarding of products"; life cycle costing (LCC) examines the cost implications for the life cycle for a product; and social life cycle assessment (S-LCA) assesses the social consequences throughout a products lifecycle [5]. In order to conduct the life cycle sustainability assessment (LCSA), the information for the LCA, LCC and SLCA must be determined and brought together into a cohesive unit. Furthermore, ISO outlines the four phases in an LCA study which are the goal and scope definition phase, the inventory analysis phase, the impact assessment phase and the interpretation phase. It is also important to note that this research will only focus on the life cycle and assessment of the evaluated retrofits and will not consider the end of life of the materials which need to be removed to install these retrofits.

Thus, each of the categories (environmental, economic and social) is addressed separately to outline the sustainability assessments. For each of the three assessments the four steps, as shown in Figure 3-1: Life Cycle Assessment FrameworkFigure 3-1, are followed:

1. *Goal and Scope Definition*: addresses the aim of the study and other preliminary information such as the functional unit and boundaries of the system.
2. *Life Cycle Inventory*: relates to the collection of data required to meet the goals of the study.
3. *Impact Assessment*: assessing the impacts of the product through the use of indicators.
4. *Life Cycle Interpretation*: discussing and evaluating the significance of the results for the product. This part of the assessment is done in conjunction with the first three steps.

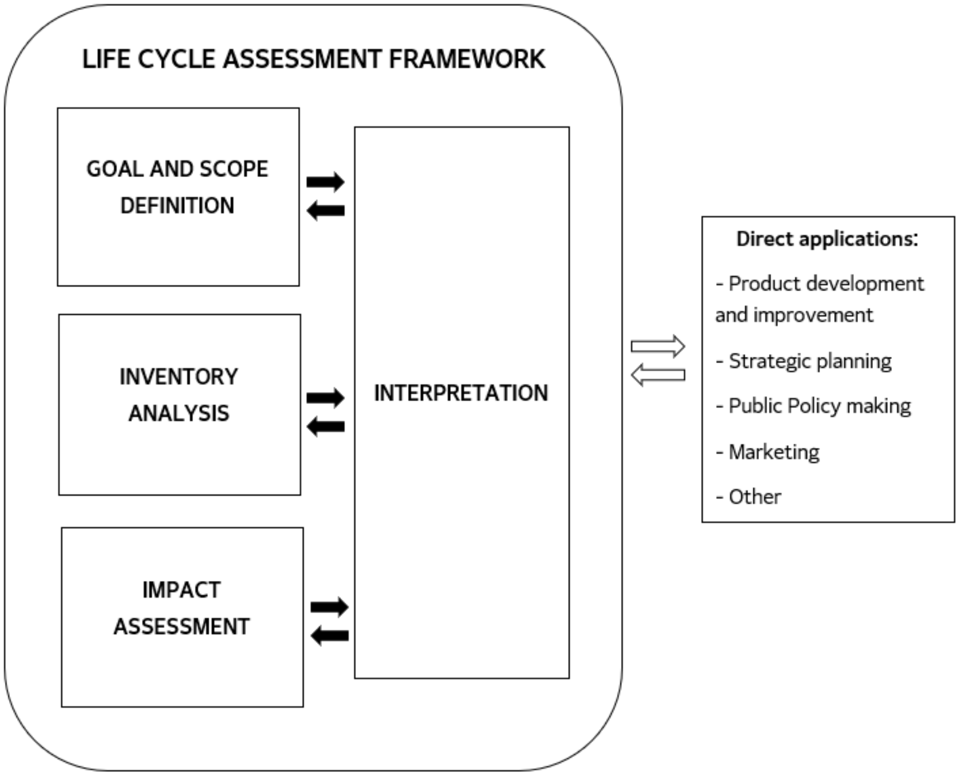

Figure 3-1: Life Cycle Assessment Framework Adapted from ISO 14040

The fourth step is primarily completed throughout the Chapters 4 and 5. The primary focus of the LCID is to set up the indicators and information required to conduct an LCSA of a building energy retrofit. Therefore, after all steps 1, 2 and 3 are followed the LCID is created.

3.3 Goal and Scope Definition

The first step, according to the ISO 14044, is to conduct an LCA is to define the goal and scope. The three LCA studies in this study (environmental LCA, LCC and SLCA) present one combined goal and scope. For the purposes of this research, the goal of these life cycle assessments is to aggregate the environmental, economic and social impacts presented by building energy retrofits through the analysis (KPIs). The outputs of the LCAs can then be further combined and weighted in order to help building managers in decision making when they are selecting retrofits for their buildings. Thus, the final results from these LCAs will be used to make comparisons between multiple alternative building energy retrofits. Building energy retrofits present many environmental, economic and social and impacts and thus conducting the LCAs will help better determine which retrofit is most appropriate for a building. The KPIs shown in Table 3-1 will be used as part of the impact assessment. The system boundary of these LCAs is from cradle-to-grave, and thus the unit processes of the energy retrofit products will be included in the analysis “from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal” as per ISO 14044 guidelines [3]. Cradle-to-grave is most fitting for this study as it covers the entire life cycle of the retrofits as opposed to the growing concept of cradle-to-cradle, which is regarded with a high degree of skepticism in the academic environment [6]. Cradle-to-cradle involves a biomimetic approach to design products to have a circular life cycle which follows the principles of reuse and recycling, putting it outside the scope of this research [7].

The end goal of the LCSA is to have an overall score for each energy retrofit to compare the alternatives. The functional unit for the assessment will change depending on the retrofit being evaluated. Many retrofits are highly variable in size and nature, and energy savings are different for each building in which they are applied. The purpose of the LCSA is to determine the life cycle sustainability impacts of applying a quantity of a retrofit in a building, which will provide data for the decision making framework. The application of the LCSA will be building specific to help compare the retrofit applications in different numbers and sizes required to service a building. Thus, this database is being developed with applicability to varying buildings. It is important to note that there are technical KPIs in consideration for the decision making framework, which are further discussed throughout Chapters 2 and 4. A life cycle assessment methodology is not applicable to the technical indicators shown in Chapter 2 and they will therefore be excluded from the LCAs discussed in this study.

Table 3-1: KPIs for Sustainability Criteria

Life Cycle Assessment	Criteria	Key Performance Indicators
Environmental Life Cycle Assessment	Environmental	• Global Warming Potential (g CO_2) • Acidification (g SO_2) • Eutrophication (g N) • Fossil Fuel Depletion (MJ surplus energy) • Indoor Air Quality (TVOCs) • Habitat Alteration (T&E count) • Water Intake (L of water) • Criteria Air Pollutants (microDALYs) • Smog (g O_3) • Ecological Toxicity (g 2,4-D) • Ozone Depletion (g CFC-11)
Life Cycle Costing	Economic	• Life Cycle Cost (CAD $)
Social Life Cycle Assessment	Social	• Human Health (Years)

The data to be collected for the KPIs will be valid for current and commercially available building energy retrofits product systems. These KPI values will be a combination of quantitative and qualitative data for a more complete analysis. This range in data will help achieve representativeness, consistency and reproducibility as per ISO 14044 [4]. However, with highly variable data there is some uncertainty and limitations. All of the KPI data is not collected from the same source as some LCA software only focus on specific types of retrofits. It is important to recognize that a variety of sources may be needed to gather all the required information and values for the KPIs. Furthermore, this

LCSA will be conducted for applicability in Canada, hence the Canadian dollars costing for the LCC. The values, however, may be converted or determined for use in other geographic locations by following the methodology applied in this study. Seven retrofits will be included in the LCID, and more may be added to the life cycle impact database if the methodology is followed and repeated.

3.4 Environmental LCA

3.4.1 Inventory Analysis

The system boundary shown in Figure 3-2 is the basis for the collection of inventory data for the environmental LCA. This includes the cradle to grave life cycle for a building energy retrofit, generalized into the following unit processes: raw material acquisition, production, use and operation and end of life. Thus, the summation of the outputs for each of the KPIs in each of the unit process will be the overall contribution of a retrofit with respect to that indicator. Data will be collected from a variety of sources in order to provide values for the environmental KPIs. Data sources include existing LCA software such as BEES or Athena. Furthermore, product manuals or company environmental reports will be useful to find information pertaining to a specific energy retrofit. Credible sources are used, in that they follow applicable standards and an appropriate methodology to collect and characterize their data. Information for each retrofit may however be collected from a different source, as some software or literature may have proper data that is only pertinent to one type of retrofit.

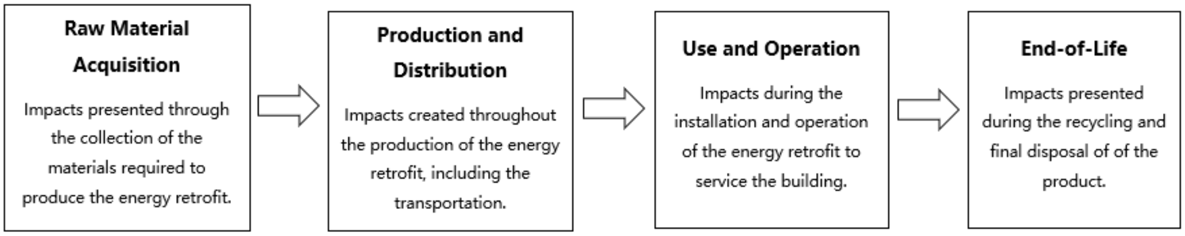

Figure 3-2: Unit Process Flow for System Boundary of LCA

3.4.2 Impact Assessment

The impact assessment phase addresses the selection of the impact categories as well as their characterization. Characterizing the indicators is needed to calculate the category indicator results. The category endpoints and definitions are available in Table 3-2 which is used to further describe the properties and significance of each of the chosen KPIs for the environmental category. Descriptions in Table 3-2 are adapted from the descriptions provided in BEES [8]. Furthermore, the characterization factors are show in the table, representing the units of each indicator. The units for some of the indicators are taken from ATHENA Sustainable Institute rather than BEES because they are more readily available for retrofit data collection that is required in the LCID.

Table 3-2: Environmental KPI descriptions

Category Indicator	**Characterization Factor**	**Environmental Relevance and Endpoints**
Global Warming Potential	Grams of carbon dioxide equivalents	There is an increase in global temperatures through the absorption of heat through GHG emissions. This alters the atmospheric patterns and results in many damaging global ecological changes.
Acidification	Grams of sulphur dioxide equivalents	Acidic compounds may dissolve in ecosystems through hydrological transportation. This is affecting trees, soil,

		buildings, animals and humans. This process is quantified through hydrogen ions as a reference substance.
Eutrophication	Grams of nitrogen	An addition of minerals is transported into existing ecosystems and producing a negative effect on species, an increase in algae growth and in turn a lack of oxygen.
Fossil Fuel Depletion	Surplus megajoules per kilogram	Fossil fuel is a finite resource and its depletion is measured for flows of coal, natural gas and oil.
Indoor Air Quality	Total volatile organic components	A product may be volatile and present direct health impacts through exposure. Some products may be “possible carcinogens”.
Habitat Alteration	Threatened and Endangered Species Count	Species may be displaced through the landfilled waste, product installation, replacement and end of life of a product.
Water Intake	Liters of water	Water is a crucial human and animal need. It is becoming a scarce resource globally and needs to be conserved.
Criteria Air Pollutants	Micro disability-adjusted life years	Air pollutants in the form of solids and liquids are resulting in some severe respiratory symptoms and diseases.
Smog	Grams of trioxides equivalents	Photochemical smog may be developed through air emissions that are trapped at the ground level.
Ecological Toxicity	Grams of 2,4-dichlorophenoxy-acetic acid	Harmful chemicals present negative effects on terrestrial and aquatic ecosystems, through flows to air and water.
Ozone Depletion	Grams of trichlorofluoromethane	Without the ozone layer harmful ultraviolet light will not be absorbed which can result in negative ecosystem and agriculture changes.

In order to evaluate the final indicator results in the life cycle interpretation phase, a normalization process is used to weigh in the relative magnitude for each indicator. It is important to note that this normalization process is completed for the environmental indicators together only; economic and social indicators also being normalized separately. A weighting scheme will be discussed in the results section of this chapter.

3.5 Economic LCC

Life cycle costing determines the entire costs that will be incurred on the owner of the product throughout the products lifecycle, including the cost for purchasing, installation, operation and disposal. No cost is incurred on the owner during the raw material acquisition and production, thus the boundary for the LCC falls between purchasing to end-of-life. Figure 3-3 shows the system boundaries of the life cycle costing assessment. The life cycle costing method used in this research follows the American Society for Testing and Materials (ASTM) standards for LCC. The ASTM is an international standards organization that has a practice for measuring the life-cycle costs of buildings and building systems. Information for costing of building materials is widely available through a variety of software, product manuals and books. R.S. Means Green Building Costs 9th edition was used to determine the purchasing and installation costs of associated with implementing a retrofit[9].

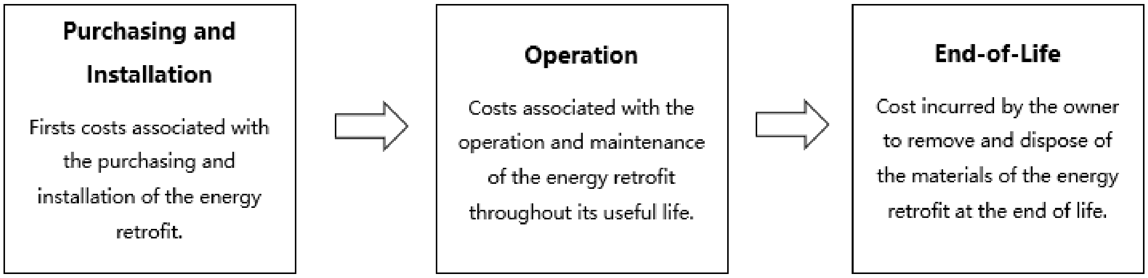

Figure 3-3: Unit Process Flow and System Boundary of the LCC

Thus, the costs associated with retrofit selection can be generalized as first and future costs. Costing is an important aspect of a retrofit selection, as the lowest cost possible is most desired: minimizing cost allows for the investments and purchasing of other valuable products. In order to fulfil the requirements of a life cycle sustainability assessment, cost considerations are considered together with environmental and social impacts. The carbon costs associated with energy, such as the cost of carbon emissions, are not considered in this life cycle costing analysis as they are highly variable and constantly changing over the life cycle of retrofits.

The following equation is used in order to determine the present value life cycle cost of a product:

$$\mathrm{LCC_j} = \sum_{\mathrm{t}=0}^{\mathrm{N}} \frac{\mathrm{C_t}}{(1+\mathrm{d})^{N}}$$

Equation 3-1

where: LCC_j = total life-cycle cost in present value dollars for alternative j; C_t = sum of all relevant costs, less any positive cash flows, occurring in year t; N = number of years in the study period; d = discount rate used to adjust cash flows to present value [8]. The framework is being created for Canadian locations but may be extended to other regions. Thus, the costing unit will be measured in Canadian Dollars (CAD). Costing data is available in American Dollars and therefore must be converted. The current conversion rate stands at approximately 1.32 CAD for 1 USD [10]. Calculations in the LCID used this rate for the collected data.

3.6 Social-LCA

A previously developed SLCA was used for this research, known as Norris's SLCA methodology. The European Office of the World Health Organization states that "people who are less well off have substantially shorter life expectancies and more illnesses than the rich" [11]. Norris's SLCA methodology considers the socio-economic pathways to the human health endpoint [12]. Norris has developed a set of equations that are used to quantify the human health effects caused by a product. This process looks at a country's GNP and life expectancy year gain against the year lost.

The following two equations are used in order to calculate the human health impact:

$$\text{Year Gain} = \text{b} * \text{Population}^{\text{c}+1}[\text{GNP}_0^{-\text{c}} - (\text{GNP}_0 + \Delta\text{GNP})^{-\text{c}}]$$

Equation 3-2

$$\text{Health Impacts} = \text{Year Gain} - \text{Year Loss}$$

Equation 3-3

The parameters a, b and c are model parameters to estimate life expectancy which were developed by Norris using data for mean life expectancy at birth in relation to per capita gross national product. Following the calculation of the Year Gain, the Year Loss will be determined from the criteria air pollutants indicator from the environmental KPIs. This will determine the years lost based on the disability-adjusted life-years (DALYs). These are impacts of "respiratory inorganic emissions and the potential health consequences of global warming" [13]. The difference between the Year Gain and the Year Loss will result in the endpoint of health impacts.

The data required to calculate endpoint result of health impacts from a product's life cycle includes the population of a country, the GNP of a country with and without the money generated through the product's manufacture. These values can be determined through a content analysis of government databases and company's information. Furthermore, the negative health consequences relating to years lost is determined through the DALYs created by the life cycle of the products in question. Thus, the endpoint result for the social impact is for a unit amount of retrofitting material, but rather it is based on a production company's profits and the total emissions that are produced is making a product.

3.7 Results

3.7.1 LCSA Results

Three insulation types are used in order to demonstrate the use of the LCID. These three retrofits are found through the Athena Sustainable Institutes software which had most of the available data for the environmental criteria. No available data was found for the habitat alteration in the Athena software; however, BEES included this data for insulation as zero. The economic total life cycle costing per square foot was determined using RS Means Green Building Costs 2019 [9]. The GNP for companies which sold the insulation products were used to calculate the social impact using Equation 3-2 and Equation 3-3, along with the other factors considered in Section 3.6 covering the S-LCA calculations. The three chosen insulation retrofits are Generic Cellulose R-13, Generic Fiberglass R-13 and Generic Mineral Wool R-13. The collected data is shown in Table 3-3 for these retrofits. The environmental and economic values correspond to the emissions or costing per 1 m^2 of material, while the social value corresponds to a human health impact based on the overall production of the material and the production company's profits.

Table 3-3: Insulation Data for Life Cycle Sustainability Assessment for 1m^2 of Material

Units	**KPI**	**Generic Cellulose R-13**	**Generic Fiberglass R-13**	**Generic Mineral Wool R-13**
ENVIRONMENTAL				
g CO_2 equiv.	Global Warming Potential	2480	2640	3920
g SO_2 equiv.	Acidification	34.6	33.9	45.7
g N	Eutrophication	2.13	2.27	2.53
MJ surplus energy	Fossil Fuel Depletion	36.6	40.2	56.4
TVOCs	Indoor Air Quality	1.17	1.39	2.55
T&E count	Habitat Alteration	0	0	0
L of water	Water Intake	1.78	5	7.04
microDALYs	Criteria Air Pollutants	0.15	0.59	0.59
g O_3 equiv.	Smog	1130	1160	1230
g 2,4 – D	Ecological Toxicity	7.03×10^{-4}	9.26	11.36
g CFC-11	Ozone Depletion	1.46×10^{-6}	2.36×10^{-5}	3.0×10^{-5}
ECONOMIC				
CAD $	Total Cost	8.95	19.04	13.61
SOCIAL				
Years	Human Health	701.36	20364.92	20083.46

The life cycle impact database would contain the values shown in Table 3-3 for the insulation types provided along with data for the window glazing types as per Appendix B. Furthermore, additional energy retrofits could be added to the LCID list for future comparisons, as long as each KPI value is determined.

3.8 Summary

The LCSA assessment described in this chapter is useful to obtain values for environmental, economic and social factors of an energy retrofit, as shown in Table 3-3. The procedures for each category life cycle assessment were used as described in Sections 3.4, 3.5 and 3.6. In order to determine the environmental indicators, the data must be available in the units for each indicator or a unit that can be converted appropriately. The economic and social data relies on the collection of data and then further calculations are per Equation 3-1, Equation 3-2 and Equation 3-3.. It is significant to emphasize that although there are more environmental indicators than economic and social, the importance of the categories depends on the user’s preference. An overall score is populated for each category which can then be evaluated (traded off) against each other.

3.9 References

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CHAPTER 4

BUILDING ENERGY RETROFIT EVALUATION TOOL

4.1 Introduction to Building Energy Retrofit Evaluation Tools

Building stakeholders or managers may have limited knowledge about sustainability and life cycle assessments when implementing new products into their infrastructure [1]. Today there are some tools which aid in the selection of building energy retrofits and materials that are lacking the inclusion of important selection factors and criteria. Building for Environmental and Economic Sustainability (BEES) is primarily used for selecting building material products and does not include data for energy saving retrofits other than insulation. Furthermore, BEES only focuses on the environmental and economic aspects, neglecting the social and technical implications [2]. Athena Impact Estimator for Buildings focuses only on the environmental life cycle analysis of building materials and products [3]. The Facility Energy Decision System (FEDS), used to select retrofit alternatives for buildings, aids with decision making based solely on life cycle costing results [4]. There is a need for the incorporation of more factors in existing resources to create “sustainability assessment tools” rather than single criterion tools [5].

As discussed in previous chapters, life cycle thinking and a wholistic set of criteria is crucial for the decision making process in the selection of building energy retrofits [6, 7]. Therefore, the development of an inclusive energy retrofit selection tool could assist building managers in analyzing and selecting the most appropriate retrofits for their buildings. This resource should be easy to use, comprehensive and accessible to ensure that it is a viable option. This chapter discusses the development of the Building Energy Retrofit Evaluation Tool (BERET).

4.2 Methodology

The Building Energy Retrofit Evaluation Tool (BERET) is a Microsoft Excel-based tool which is comprehensive and user-friendly. Visual Basic for Applications (VBA) is used within Microsoft Excel to create the tool. A series of user forms were created on multiple sheets within the Excel file in order to process the data selected by the user. The three life cycle assessments used in this tool for data collection are the environmental LCA, economic LCC and social LCA, all which have been discussed in detail in Chapter 3 and are available within the LCID which is imbedded into the tool. This LCID contains a set of values for different proven energy retrofits, for which data was available.

4.3 Overview of the Tool

The process of the proposed BERET tool is shown in Figure 4-1:

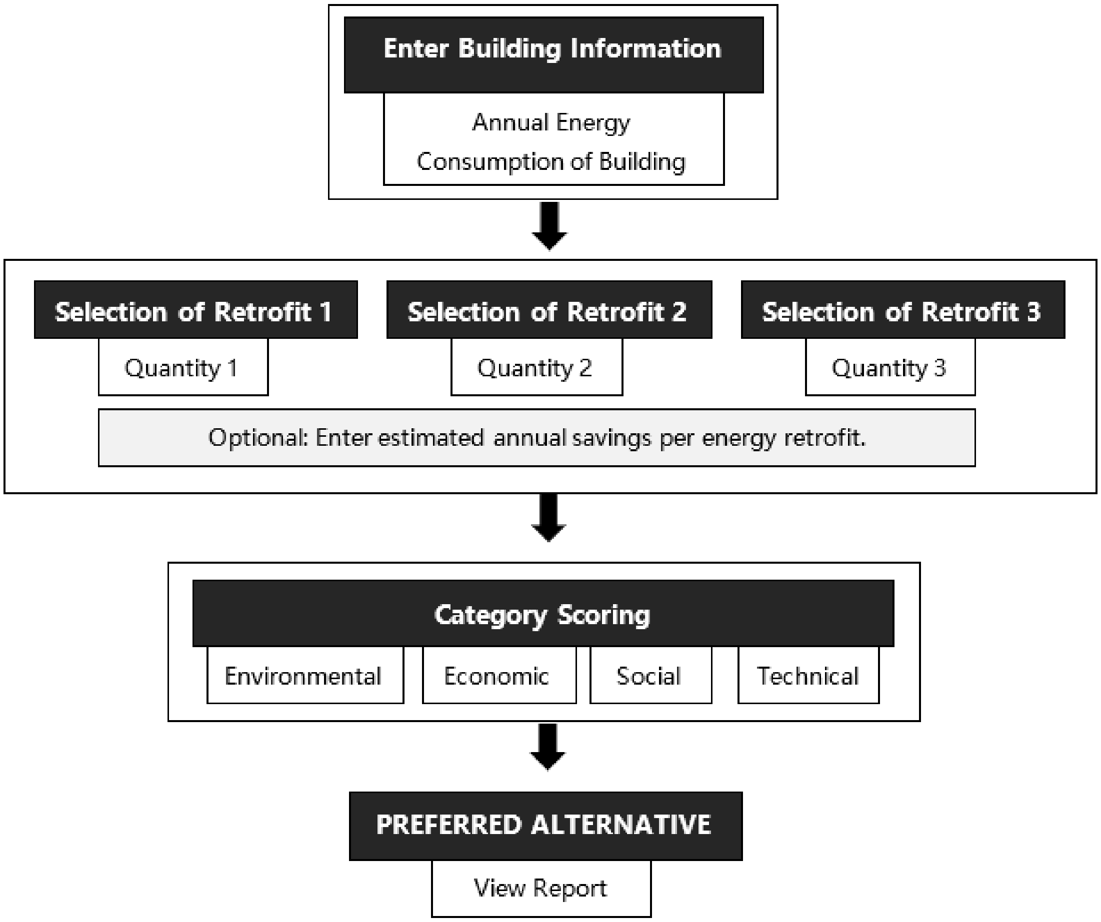
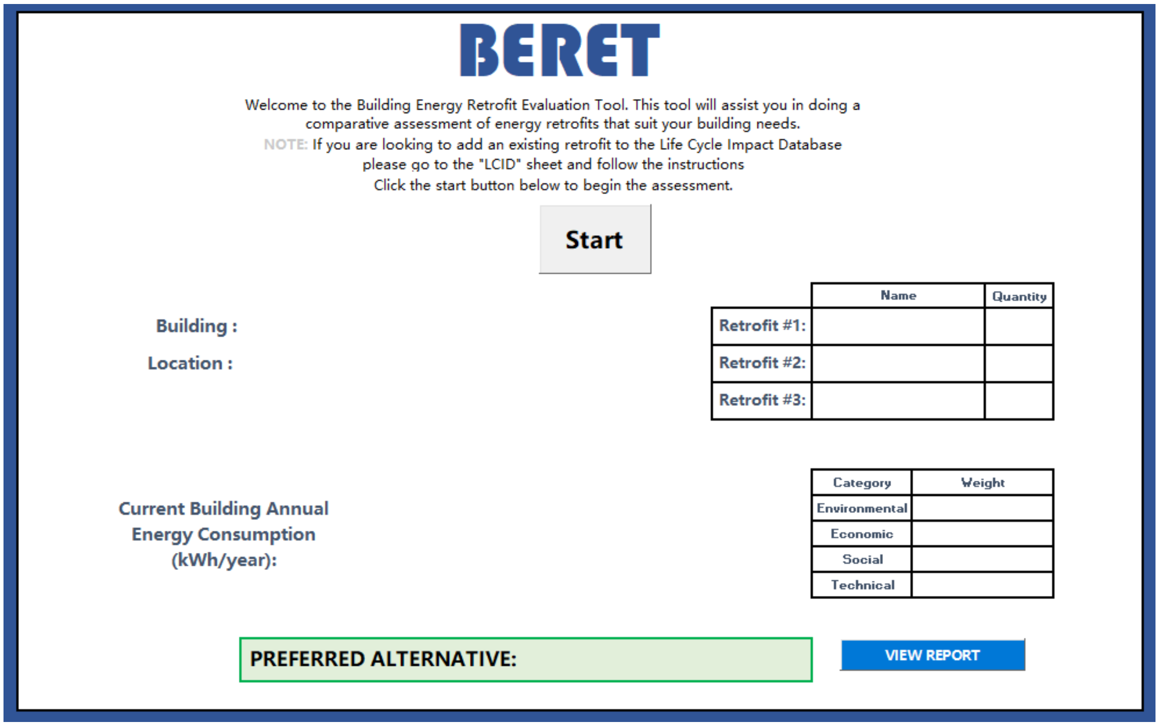


Figure 4-1: Information and Data Flow for BERET

The user will be greeted by the user interface, Figure 4-2, that contains a layout of required information and blank cells. The user will need to click the start button to initiate the series of user forms, as indicated at the top of the interface. The information required on the opening page includes the building name, location, the annual energy consumption of their building, the three retrofits they want to select, and their four weights for the criteria categories.



Welcome to the Building Energy Retrofit Evaluation Tool. This tool will assist you in doing a comparative assessment of energy retrofits that suit your building needs.
NOTE: If you are looking to add an existing retrofit to the Life Cycle Impact Database please go to the "LCID" sheet and follow the instructions
Click the start button below to begin the assessment.

Building :
Location :

	Name	Quantity
Retrofit #1:		
Retrofit #2:		
Retrofit #3:		

Current Building Annual Energy Consumption (kWh/year):

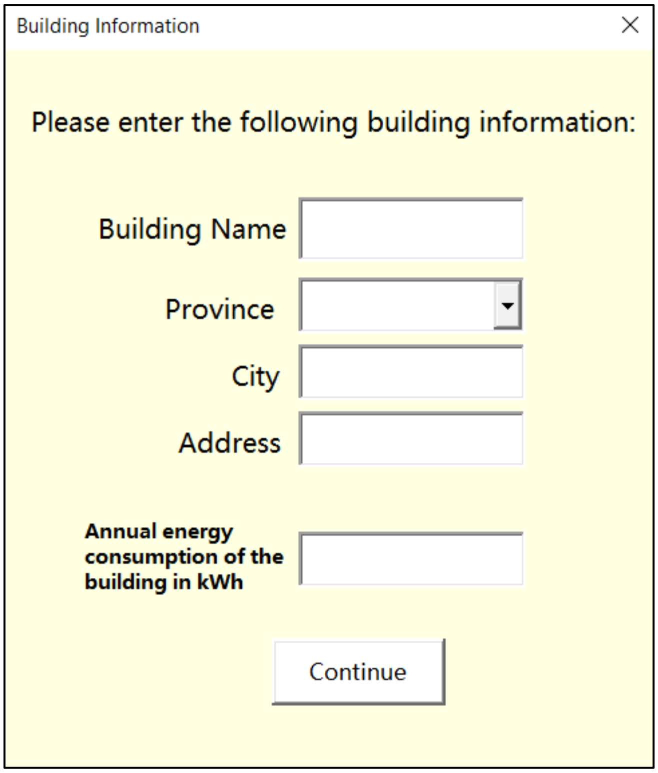
Category	Weight
Environmental	
Economic	
Social	
Technical	

PREFERRED ALTERNATIVE:

Figure 4-2: BERET Main Interface

The first user form, the Building Information User Form, that will open upon clicking the “Start” button asks for the building name and location within Canada as shown in Figure 4-3. The Canadian province selected is important as the reduction of CO_2 emissions is calculated based on the energy savings from the addition of the retrofit. This is because provinces have varying electricity generation sources that all emit different quantities of CO_2. This is further discussed in the calculation process Section of this chapter, Section 4.3. Furthermore, the user will need to know the current energy consumption of their building to enter the user form. This can be calculated through an energy simulation or if the building manager has energy records. It is important to note that BERET is primarily useful for buildings which consume energy through electricity for their buildings, including for heating and cooling. Approximately one third of buildings in

Canada use electricity for their heating and cooling [8]. This tool is not useful for building that solely rely on natural gas to provide energy. However, the tool is useful for buildings which rely partially on natural gas, provided the user is looking to only analyze the electricity savings in their building.



Building Information

Please enter the following building information:

Building Name

Province

City

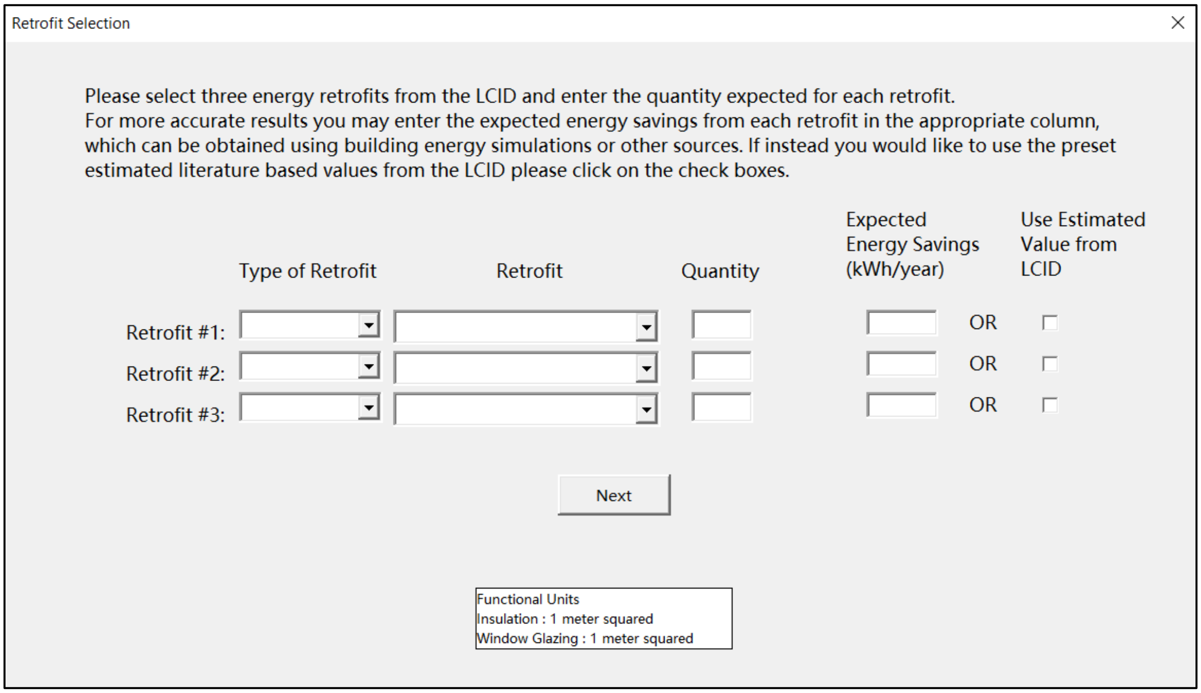
Address

Annual energy consumption of the building in kWh

Figure 4-3: Building Information User Form

The second user form, Retrofit Selection User Form, asks for the selection of three retrofits in drop down format from the life cycle impact database and quantity of each retrofit that will be used in the building as shown in Figure 4-4. Firstly, the user will need to select the retrofit type and based on their selection the available retrofits will be available from the dropdown menus. Furthermore, quantities will need to be entered for each retrofit that is selected. This is important for the calculation of the environmental, economic, social and technical KPIs. The functional units are placed on this second user form for the existing retrofits which are in the database. Thus, modifications would need to be made when a variety of different retrofits will continuously be added to the LCID.

For the energy performance data, the first KPI for technical criteria, there will be a literature based expected percentage of energy savings available within the database. This value is important as it is used to calculate the decrease in CO_2 emissions as well as the decrease in annual costs. Thus, for more accurate results, the user may input their expected energy savings from the retrofit (in kWh/year) that they have gathered from an energy simulation or their own sources.



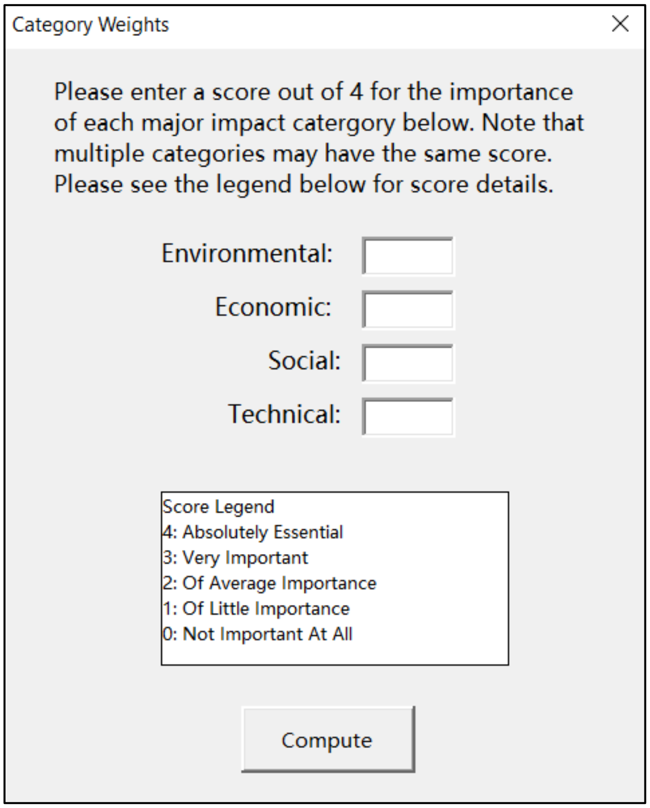
Please select three energy retrofits from the LCID and enter the quantity expected for each retrofit.
For more accurate results you may enter the expected energy savings from each retrofit in the appropriate column, which can be obtained using building energy simulations or other sources. If instead you would like to use the preset estimated literature based values from the LCID please click on the check boxes.

	Type of Retrofit	Retrofit	Quantity	Expected Energy Savings (kWh/year)		Use Estimated Value from LCID
Retrofit #1:					OR	☐
Retrofit #2:					OR	☐
Retrofit #3:					OR	☐

Functional Units
Insulation : 1 meter squared
Window Glazing : 1 meter squared

Figure 4-4: Retrofit Selection User Form

The final and third user form, Category Weights User Form, asks for a rating score (out of 4) that is chosen for each of the four criteria categories; environmental, economic, social and technical (Figure 4-5). This rating system follows that of the Likert's scale, which is a "psychometric scale that has multiple categories from which respondents choose to indicate their opinions, attitudes, or feelings about a particular issue" [9]. This type of scale is also a universal method used to collect data, and useful when qualitative data needs to be translated into quantitative measures [10]. The rating choices will then be weighted to give a percentage of importance out of 100% for each of the categories. If the value of 0 is selected for any of the criteria categories, this category will be omitted from the analysis.



Please enter a score out of 4 for the importance of each major impact catergory below. Note that multiple categories may have the same score. Please see the legend below for score details.

Environmental:
Economic:
Social:
Technical:

Score Legend
4: Absolutely Essential
3: Very Important
2: Of Average Importance
1: Of Little Importance
0: Not Important At All

Figure 4-5: Category Weights User Form

To move from one user form to another it is required that all the boxes are filled with the appropriate values. The user will receive a message if they attempt to move to the next user form without filling in the boxes appropriately. The quantity and energy saving boxes in user form 2 must be a numeric value greater than zero. The retrofits also must be available in the LCID and shown in the drop-down menu, which will be discussed in Section 4.2. Also, three different retrofits must be selected for the user to continue. The values for the scores in user form 3 must be values between 0 to 4 as shown in the legend of the Category Weights user form. Once all user forms have been filled, the compute button is activated on user form 3 the preferred alternative will be shown in the green box on the main interface.

The values filled into these user forms will be placed onto the main interface once the user completes the series. If a user wishes to view the details of the scoring and data for all three retrofits, they can click the “VIEW REPORT” button after all the forms are filled and the preferred alternative is shown.

4.4 Additional Features of the Tool

BERET is linked with the LCSA database described in Chapter 3.

4.4.1 Life Cycle Impact Database

As discussed in Chapter 3, a life cycle impact database (LCID) is created in this research to simplify and conduct the life cycle sustainability assessments. This impact database generates outputs for all the KPIs discussed; for environmental, economic and social impacts. This database is meant to help generate inputs for the framework which will eventually be weighted to generate the output for energy retrofit selection and comparison. The LCID is modifiable so that a user can add more retrofits to the database. Furthermore, the LCID is created using Microsoft Excel which will compute comparative scores for the retrofits being evaluated. The LCID is therefore able to collect data from a user and assign it to an energy retrofit, which can later be used for a valuation against other retrofits.

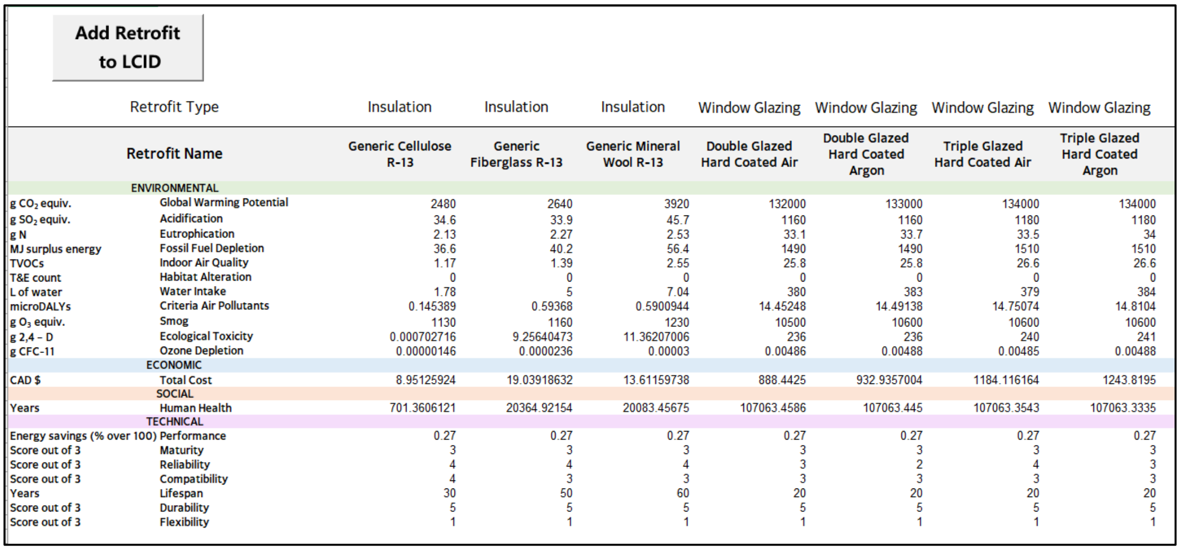
In order to access the LCID, the user will need to go to the next tab (sheet) in the workbook. This instruction is shown on the top of the primary interface in Figure 4-2. For simplicity, the LCID sheet includes all the life cycle data for the environmental, economic and social life cycle analyses but also the values for the technical scores that are not life cycle related. There are already some pre-selected proven and effective retrofits for which data has been collected. These added retrofits include three types of wall insulations and four types of window glazing.

Insulation and window upgrades are common retrofit technologies that are useful in decreasing the energy consumption of a building [11]. Jagarajan et al. (2017) and Zhenjun Ma et al. (2012) outline many of the major retrofit technologies used in buildings[12, 13]. Building envelope improvement, specifically increasing the vertical wall insulation, is an effective and commonly used technology for energy savings and retrofitting. Furthermore, window replacement and changing the glazing is a popular retrofitting technique. Therefore, these retrofits are selected to be a part of the LCID with their values. The uniqueness of the KPIs also resulted in some data collection difficulties which only allowed for the inclusion of these two retrofit types.

For the environmental data, the Athena Impact Estimator was used for all seven retrofits in the LCID. For economic data, the RS Means Green Building Costs 2019 included the data available for the purchasing and installation. For disposal, literature has shown that there is a variability in costing and methods of disposal for end of life materials. Furthermore, it is shown that a majority of construction waste ends up in landfills [14]. The retrofits in the database were assumed to be landfilled with a disposal cost of zero, given that tipping fees in Canada are low and at times not even charged or minimal for lightweight materials such as insulation or windows [15]. The disposal cost is modifiable within BERET if the user chooses to include a different charge. Social data was collected through literature sources by searching product details. Technical data was collected by reviewing literature and product sources for each type of retrofit. Further details on the selection of technical data is provided in Section 4.4.3. Part of analysis also includes the cost savings and CO_2 emission savings based on the energy consumption decrease from the retrofits. The energy savings incorporation is further discussed in Section 4.5. The raw data values for each retrofit are shown in Appendix B.

4.4.2 Adding Retrofits

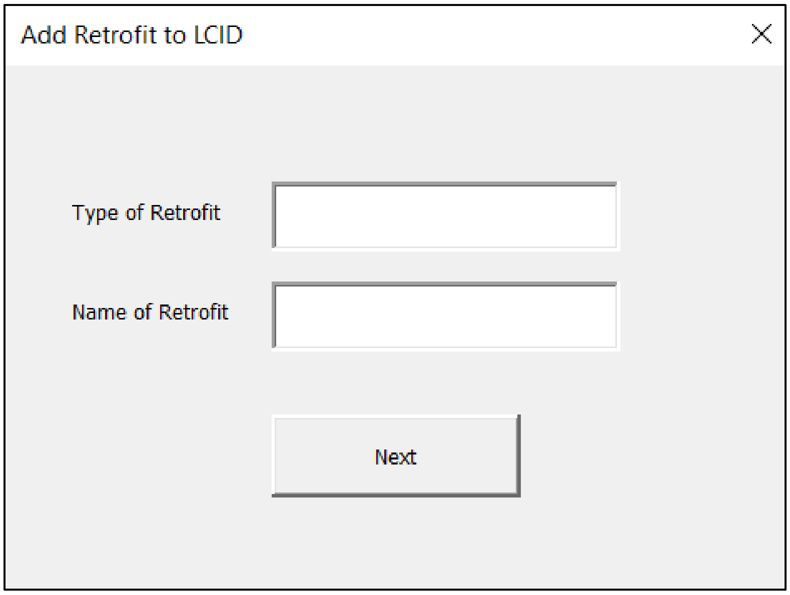
If a user would like to add their own retrofit in the LCID they will need to click the "Add Retrofit to LCID" button. This is important in the future if the user wants to expand their database with newer retrofits as technologies advance. They will then be prompted to add environmental, economic and social LCA data values. For technical data, life cycle assessment methodology is not included and therefore the user will need to score the values based on the technical indicator scoring chart which will be converted to numerical values and is further discussed in Section 4.4.3. Figure 4-5 shows the general layout of the LCID sheet, which contains retrofit data for the KPIs.



	Retrofit Type	Insulation	Insulation	Insulation	Window Glazing	Window Glazing	Window Glazing	Window Glazing
	Retrofit Name	**Generic Cellulose R-13**	**Generic Fiberglass R-13**	**Generic Mineral Wool R-13**	**Double Glazed Hard Coated Air**	**Double Glazed Hard Coated Argon**	**Triple Glazed Hard Coated Air**	**Triple Glazed Hard Coated Argon**
	ENVIRONMENTAL							
g CO_2 equiv.	Global Warming Potential	2480	2640	3920	132000	133000	134000	134000
g SO_2 equiv.	Acidification	34.6	33.9	45.7	1160	1160	1180	1180
g N	Eutrophication	2.13	2.27	2.53	33.1	33.7	33.5	34
MJ surplus energy	Fossil Fuel Depletion	36.6	40.2	56.4	1490	1490	1510	1510
TVOCs	Indoor Air Quality	1.17	1.39	2.55	25.8	25.8	26.6	26.6
T&E count	Habitat Alteration	0	0	0	0	0	0	0
L of water	Water Intake	1.78	5	7.04	380	383	379	384
microDALYs	Criteria Air Pollutants	0.145389	0.59368	0.5900944	14.45248	14.49138	14.75074	14.8104
g O_3 equiv.	Smog	1130	1160	1230	10500	10600	10600	10600
g 2,4 – D	Ecological Toxicity	0.000702716	9.25640473	11.36207006	236	236	240	241
g CFC-11	Ozone Depletion	0.00000146	0.0000236	0.00003	0.00486	0.00488	0.00485	0.00488
	ECONOMIC							
CAD $	Total Cost	8.95125924	19.03918632	13.61159738	888.4425	932.9357004	1184.116164	1243.8195
	SOCIAL							
Years	Human Health	701.3606121	20364.92154	20083.45675	107063.4586	107063.445	107063.3543	107063.3335
	TECHNICAL							
Energy savings (% over 100)	Performance	0.27	0.27	0.27	0.27	0.27	0.27	0.27
Score out of 3	Maturity	3	3	3	3	3	3	3
Score out of 3	Reliability	4	4	4	3	2	4	3
Score out of 3	Compatibility	4	3	3	3	3	3	3
Years	Lifespan	30	50	60	20	20	20	20
Score out of 3	Durability	5	5	5	5	5	5	5
Score out of 3	Flexibility	1	1	1	1	1	1	1

Figure 4-6: LCID Worksheet Layout

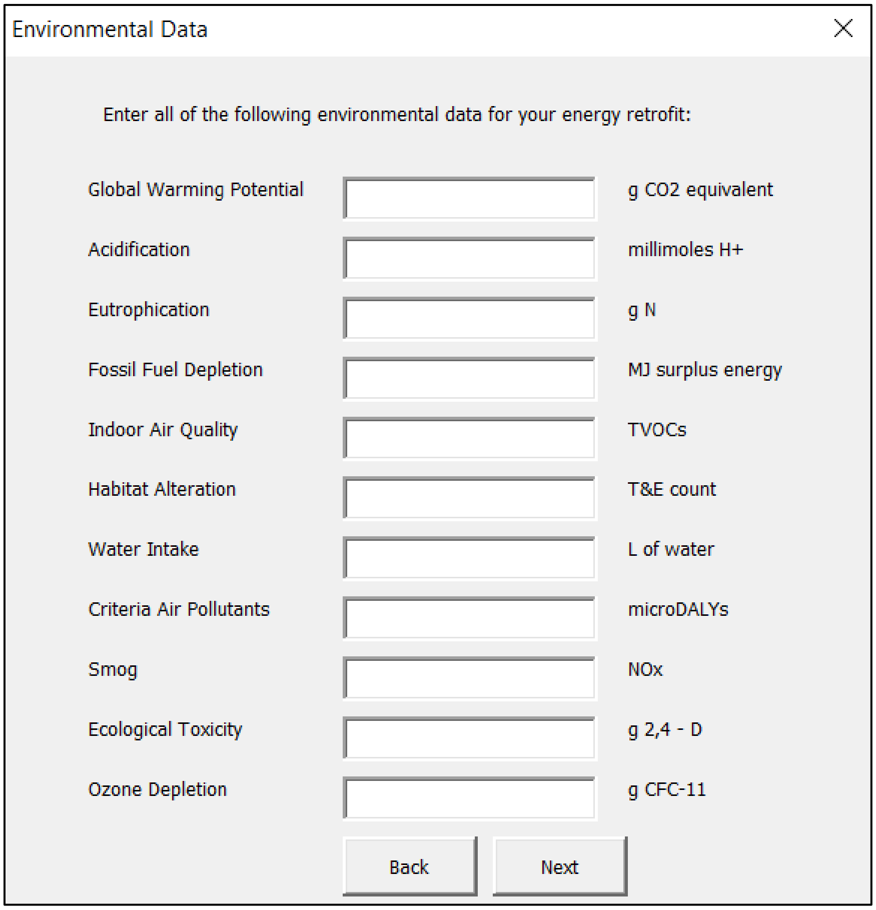
There are a series of five user forms that must be completed in order to add the retrofit to the database. The first user form asks for the type of energy retrofit and the name of that specific retrofit as shown in Figure 4-7. The second user form asks for the environmental LCA data which can be collected from the literature, other databases or resources as shown in Figure 4-8. The units are also included on the right hand side of each user form to show the user what units are required to ensure normalization is later properly completed when the retrofits are compared.


Add Retrofit to LCID

Type of Retrofit

Name of Retrofit

Figure 4-7: First User Form for Adding Retrofit to LCID

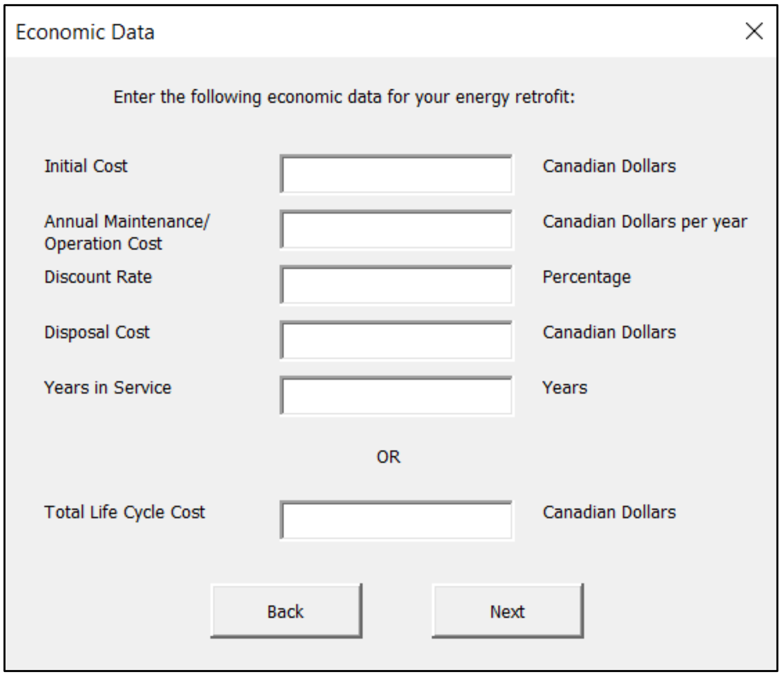

Environmental Data

Enter all of the following environmental data for your energy retrofit:

Global Warming Potential	g CO2 equivalent
Acidification	millimoles H+
Eutrophication	g N
Fossil Fuel Depletion	MJ surplus energy
Indoor Air Quality	TVOCs
Habitat Alteration	T&E count
Water Intake	L of water
Criteria Air Pollutants	microDALYs
Smog	NOx
Ecological Toxicity	g 2,4 - D
Ozone Depletion	g CFC-11

Figure 4-8: Adding Environmental Data into the LCID

The economic data user form gives the user two options for entering the data as shown in Figure 4-9. The data required to conduct the LCC analysis can be entered or the final total life cycle cost value. If the user chooses to enter the data that is needed for the LCC analysis, then the life cycle cost formula, Equation 3-1 in Chapter 3, will be used to calculate the value for the total life cycle cost of the retrofit.


Economic Data

Enter the following economic data for your energy retrofit:

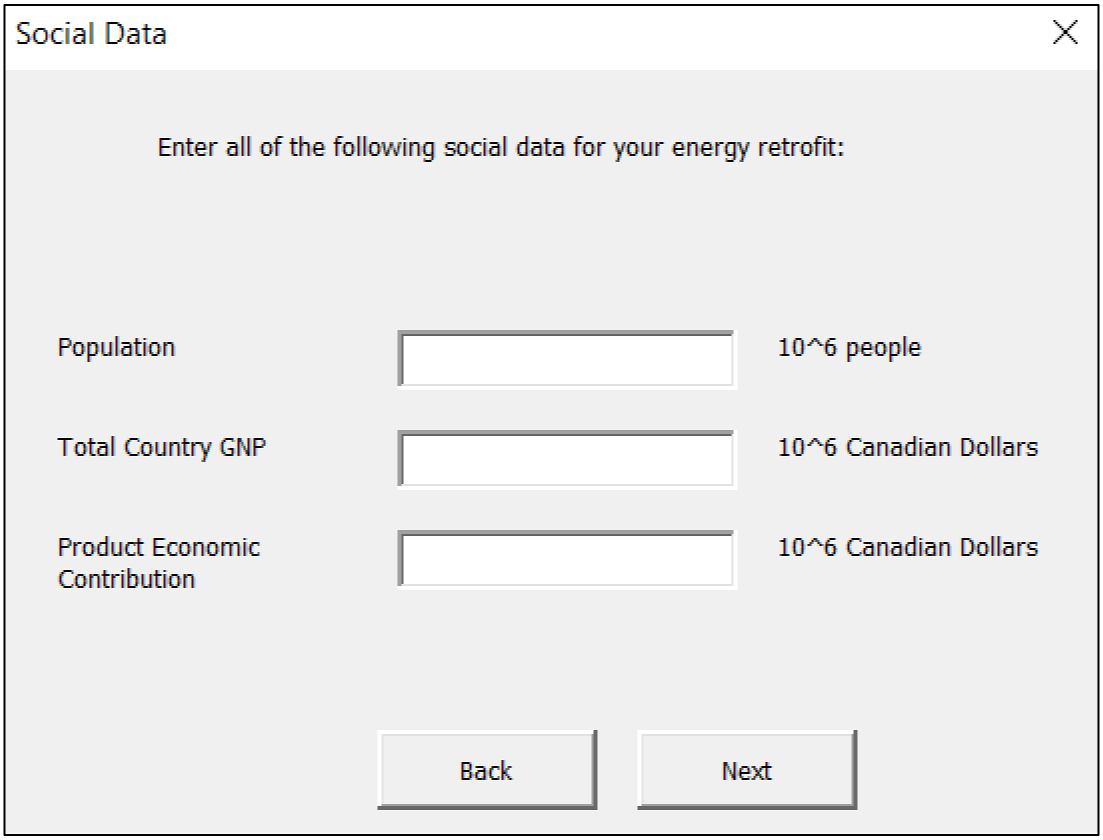
Initial Cost		Canadian Dollars
Annual Maintenance/ Operation Cost		Canadian Dollars per year
Discount Rate		Percentage
Disposal Cost		Canadian Dollars
Years in Service		Years

OR

Total Life Cycle Cost		Canadian Dollars

Figure 4-9: Adding Economic Data into the LCID

The social LCA data is required in the third user form as shown in Figure 4-10. The fourth user form is for the entry of the technical data as shown in Figure 4-11, which is both quantitative and qualitative. In this case the user must decide as to which qualitative scaled score they want to give for the differing technical key performance indicators. It is important to emphasize that the user form will only accept all numerical values in all these user form cases. Further details on the technical indicator data values is discussed in Section 4.2.1.


Social Data

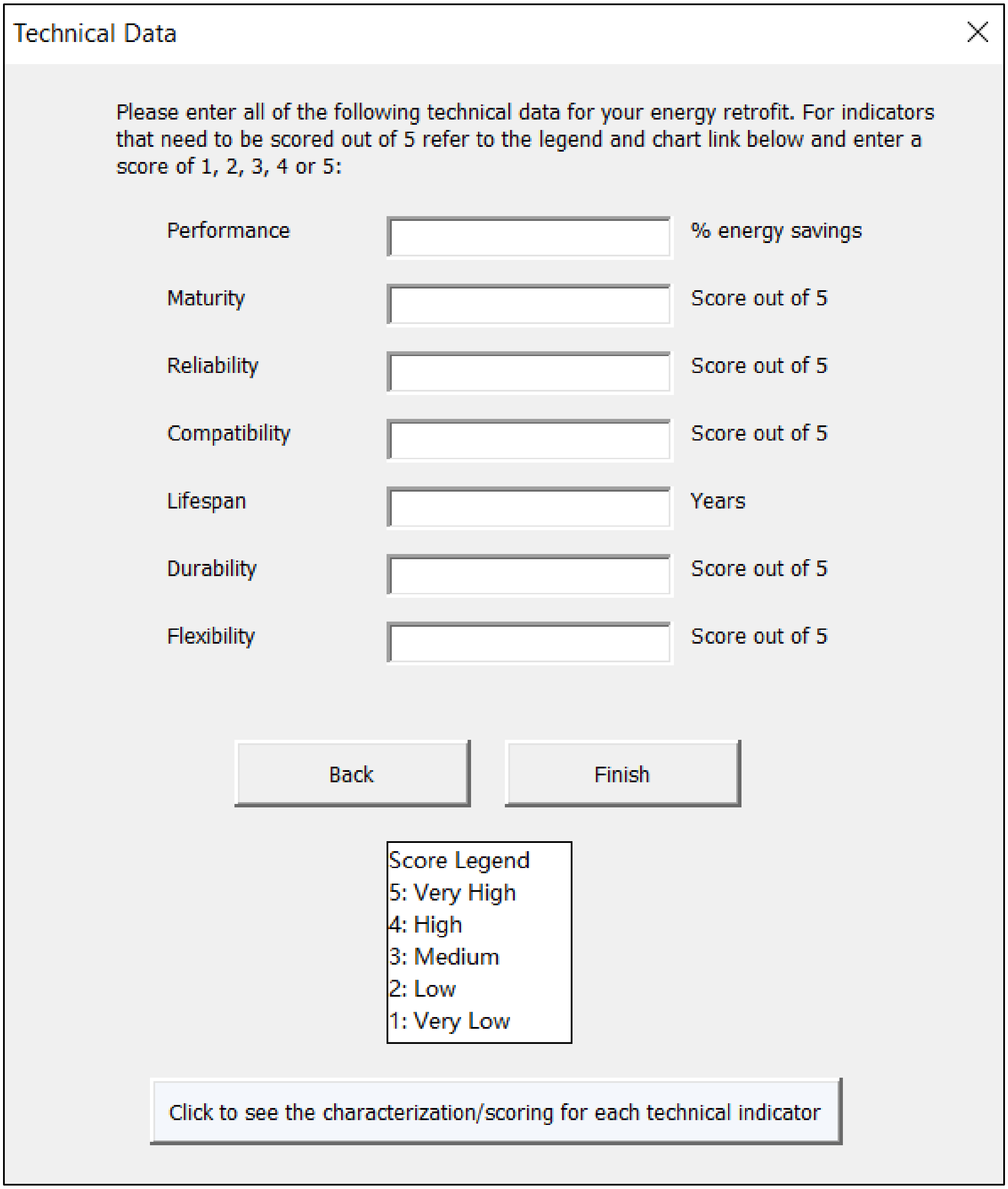
Enter all of the following social data for your energy retrofit:

Population 10^6 people

Total Country GNP 10^6 Canadian Dollars

Product Economic Contribution 10^6 Canadian Dollars

Figure 4-10: Adding Social Data into the LCID



Technical Data

Please enter all of the following technical data for your energy retrofit. For indicators that need to be scored out of 5 refer to the legend and chart link below and enter a score of 1, 2, 3, 4 or 5:

Performance		% energy savings
Maturity		Score out of 5
Reliability		Score out of 5
Compatibility		Score out of 5
Lifespan		Years
Durability		Score out of 5
Flexibility		Score out of 5

Score Legend
5: Very High
4: High
3: Medium
2: Low
1: Very Low

Figure 4-11: Adding Technical Data into the LCID

4.4.3 Technical Performance of Retrofits

The technical data in this analysis differs from the environmental, economic and social because a life cycle assessment methodology is not used to determine the values for the technical KPIs. In order to decide on the evaluation values for the technical data a five point Likert scale is used, as shown in the selection of category ratings from user form 3. However, the range is different for the scale of the indicators. Due to the impreciseness and unavailability of data the qualitative indicators will have to be determined using a score instead of an exact measurable quantitative value, such as through a five point Likert scale point system [16, 17]. It is important to note that the majority of the technical KPIs are qualitative and therefore their scoring will require some subjectivity as defined. Linguistic ratings have been commonly used throughout literature and converted into values to represent qualitative criteria [16, 18]. Thus, the Likert scale used relates the indicators to five levels being “very low”, “low”, “medium”, “high”, and “very high” with the “very high” rating equating to 5 on the scale, and the “very low” rating equating to 1. Table 4-1 shows the definition of each KPI along with the rating definition scale used for each of them based on existing rating scales determined through literature. The scores of 5, 3 and 1 are clearly defined while the scores of 4 and 2 establish the middle ground between these scores that a user may feel would better define the rating they would assign to the technical indicator of a particular retrofit.

Table 4-1: Technical Key Performance Indicators Characterization and Scoring

Technical KPI	Characterization	Scoring
Performance	Performance refers to the ability to reduce the amount of energy required to provide products and services [19]. Therefore, the unit will be in kWh saved. This will require an energy simulation for the building to determine the change in consumption.	Energy saved annually (measured in percentage, %) Note: There is also an option provided for the user to enter their simulated energy savings for each retrofit for more accurate results.
Maturity	Maturity refers to the years that a product has been in the market [16]. First generation technologies emerged from the industrial revolution at the end of the 19th century. Second generation technologies are those now entering the market and reflect revolutionary advancements in materials. Third generation technologies are still under development [20].	Very High (5) – First generation technologies
		Medium (3) – Second generation
		Very Low (1) – Third generation
Lifespan	The lifespan is the useful life of the energy retrofit given in years.	Years in service (measured in years)
Reliability	Reliability of energy systems may be defined to the capacity of a device or system to perform as designed; the resistance to failure of a device or system; the ability of a device or system to perform a required function under stated conditions for a specified period of time; or the ability of something to ‘‘fail well’’. It can be expressed in a qualitative scale or a number, such as realization time in [17].	Very High (5) – Very high reliability
		Medium (3) – Fairly reliable
		Very Low (1) – Very low reliability
Compatibility	Compatibility refers to the ability of two or more systems or their components to work together without user intervention or modification. This pertains to following categories as per the Architectural Compatibility Guide: theme, scale, form, articulation and fenestration [21].	Very High (5) – Fits well into the building without modification of the categories
		Medium (3) – Fits into the building with some modification to the categories
		Very Low (1) – Will require significant modification of the categories to fit into the building

Durability	Durability is the ability of a building or any of its components to perform its required functions in its service environment over a period without unforeseen cost for maintenance or repair. In the CSA Durability Standards there are 8 categories which are further grouped into 3 sections concerning the effects of failure caused relative to a building product's durability [22].	Very High (5) – No exceptional problems
		Medium (3) – Security compromised, interruption of building use, costly because repeated, costly repair
		Very Low (1) – Danger to health or ecological system, risk of injury, danger to life
Flexibility	Product flexibility can be defined as the amount of responsiveness (or adaptability) for any future change in a product design, including new products and derivatives of existing products [23]. The questions is asked of whether the technology is flexible for system upgrading and measured through the use of a scale [24].	Very High (5) –Very high flexibility
		Medium (3) – Fairly flexible
		Very Low (1) – Very low flexibility

The data scoring for technical indicators are reflected in the user form for technical values data entry. The user will have access to the scoring characterization to help them in determining which score of high, medium or low that their selected retrofit will fall into by clicking on the "Click to see the characterization /scoring for each technical indicator".

4.5 Energy Savings and Calculations

After the user enters their retrofit choices the scoring calculations take place for the three selected retrofits. A hidden sheet places the three selected retrofits KPI values from the main interface. Also, the four category scores that are provided on the main interface are placed into the calculation sheet. It then multiplies these KPI values by the entered quantity for each retrofit. A reduction in CO_2 emissions and energy costs are also taken into consideration based on the annual energy savings provided by each energy retrofit. The National Energy Board of Canada provides the grams of CO_2 per kilowatt hour per province which based on each province's power and electricity generation methods [25, 26]. The following equations are used to incorporate the energy savings:

$$\text{Global Warming Potential (g CO}_2\text{)} = \text{LCA GWP (g CO}_2\text{)} - \textit{CO}_2\textit{ Savings (g CO}_2\textit{)}$$

Equation 4-1

$$\textit{CO}_2\textit{ Savings (g CO}_2\textit{)} = \text{Annual Energy Consumed (kWh/year)}$$
$$* \text{ Expected Energy Savings (\%)} * \text{ Years in Service (years)}$$
$$* \text{ Provincial Energy Emission Rates (g CO}_2\text{/kWh)}$$

Equation 4-2

$$\text{Total Life Cycle Cost (\$)} = \text{Life Cycle Cost (\$)} - \textit{Cost Savings (\$)}$$

Equation 4-3

$$\textit{Cost Savings (\$)} = \text{Annual Energy Consumed (kWh/year)}$$
$$* \text{ Expected Energy Savings (\%)} * \text{ Years in Service (years)}$$
$$* \text{ Provincial Average Cost per kwh (cents/ kWh)} * \text{ Years in Service (years)}$$

Equation 4-4

Table 4-2 provides the energy saving values along with the average cost of electricity per kilowatt hour. This table also includes the breakdown of electricity generation sources in percentages. It is important to note that "Hydro, wind, solar, and nuclear, produce no CO_2 emissions directly during the generation of electricity, although lifecycle emissions are associated with building and decommissioning facilities and related infrastructure, and with maintenance and other generation-related activities" [27].

Table 4-2: Canadian Province Electricity Carbon Emissions and Prices

Province	Grams CO_2 per unit ($g\ CO_2$ / kWh)	Electricity Production Sources	Average Cost per unit (cents / kWh)
Quebec	1.2	Hydro: 95.0% Wind: 4.0% Biomass and geothermal: 1.0% Petroleum: Around 1.0% Natural gas: Around 1.0%	6.87
Manitoba	3.4	Hydro: 97.0% Wind: 2.0% Biomass or geothermal: Around 1.0% Coal and coke: Around 1.0% Petroleum: Around 1.0% Natural gas: Around 1.0%	7.9
British Columbia	12.9	Hydro: 88.0% Natural gas: 1.0% Petroleum: More than 1.0% Wind: 1.0% Biomass or geothermal: 9.0%	8.91
Prince Edward Island	20.0	Wind: 98.0% Petroleum: 1.0% Biomass or geothermal: Around 1.0%	16.9
Newfoundland and Labrador	32.0	Hydro: 95.0% Petroleum: 2.0% Natural gas: 2.0% Wind: Around 1.0% Biomass or geothermal: Around 1.0%	12.55
Ontario	40.0	Nuclear energy: 58.3% Natural gas: 6.2% Wind, solar and other alternative sources: 10.8% Hydro: 23.9% Other: 0.8%	14.17
Yukon	41.0	Hydro: 95.0% Natural gas: Around 1.0% Petroleum: 5.0% Wind: Around 1.0%	13.6
New Brunswick	280.0	Uranium: 30.0% Hydro, wave and tidal: 21.0% Wind: 6.0%	11.19

		Biomass and geothermal: 3.0% Coal and coke: 21.0% Natural gas: 15.0% Petroleum: 4.0%	
Northwest Territories	390.0	Petroleum: 52.0% Hydro: 34.0% Natural gas: 13.0% Wind: 1.0%	31.0
Nova Scotia	600.0	Coal and coke: 64.0% Wind: 11.0% Biomass and geothermal: 2.0% Natural gas: 13.0% Hydro, wave and tidal: 9.0% Petroleum: 3.0%	15.45
Saskatchewan	660.0	Coal and coke: 49.0% Natural gas: 34.0% Hydro: 13.0% Wind: 3.0% Biomass and geothermal: More than 1.0% Petroleum: More than 1.0%	13.15
Nunavut	750.0	Petroleum: 100.0%	32.0
Alberta	790.0	Coal and coke: 47.0% Natural gas: 40.0% Wind: 7.0% Hydro: 3.0% Biomass or geothermal: 3.0%	12.18

Following the inclusion of energy savings resulting in cost and environmental score changes, the values were normalized using Equation 2-1 and Equation 2-2 in Chapter 2. For two of the KPI values, Global Warming Potential and Total Life Cycle Cost, there is potential for a negative value to be obtained due to the subtraction of the savings in CO_2 emissions and Global Warming Potential. For example, if there are more energy cost savings in the lifetime of the retrofit that is equal to more than the costing to implement and maintain the retrofit, the value for the Total Life Cycle Cost would become a negative value. The min-max linear normalization in Equations 2-1 and 2-2 in Chapter 2 remain applicable and are used.

After the normalization of each KPI value for each retrofit, the normalized values are multiplied by the category percentage weight for each KPI as shown in Equation 2-3 of Chapter 2. Then each of the weighted values is added up for the individual four categories and the weighted sum method is used to provide an overall score for each criteria category, which are then multiplied by the environmental, economic, social and technical weights that are chosen by the user. This then provides an overall score for each retrofit, and the retrofit with the highest score is seen as the preferred alternative for this given situation. This tool is not primarily designed for considering a combination of retrofits together within a single building. Interestingly, the bulk of the literature reviewed reveals that most retrofits undertaken only involve a single type of retrofit, not a combination. However, the tool can be modified so that aggregate parameters for a combination of retrofits can be assessed. This would involve restructuring some of the internal calculations and structure of BERET. These modifications would not be difficult but are outside of the scope of this research agenda and will be included as a future consideration for additional research. Figure 4-12 shows a data flow diagram for the current calculation process.

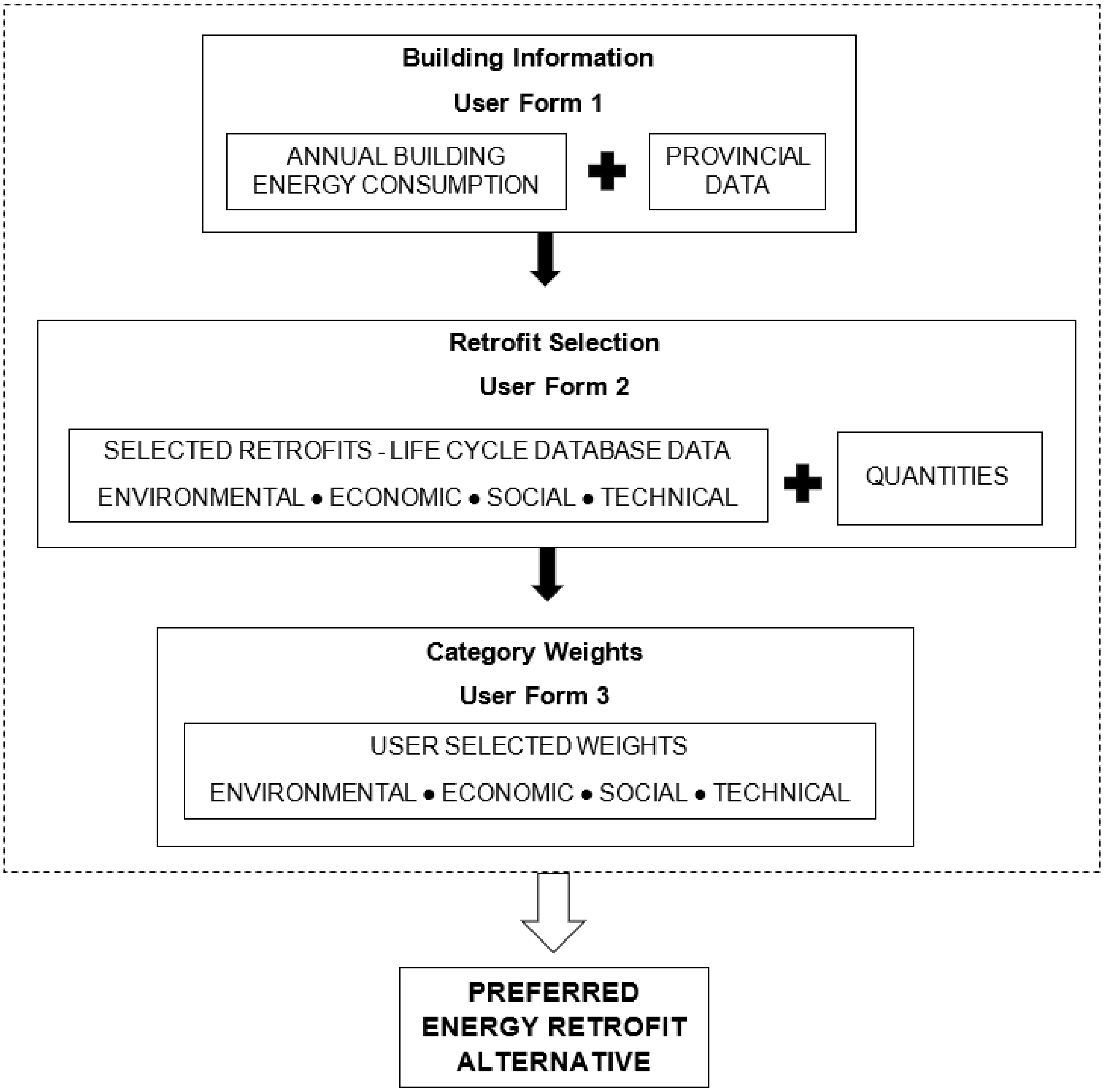
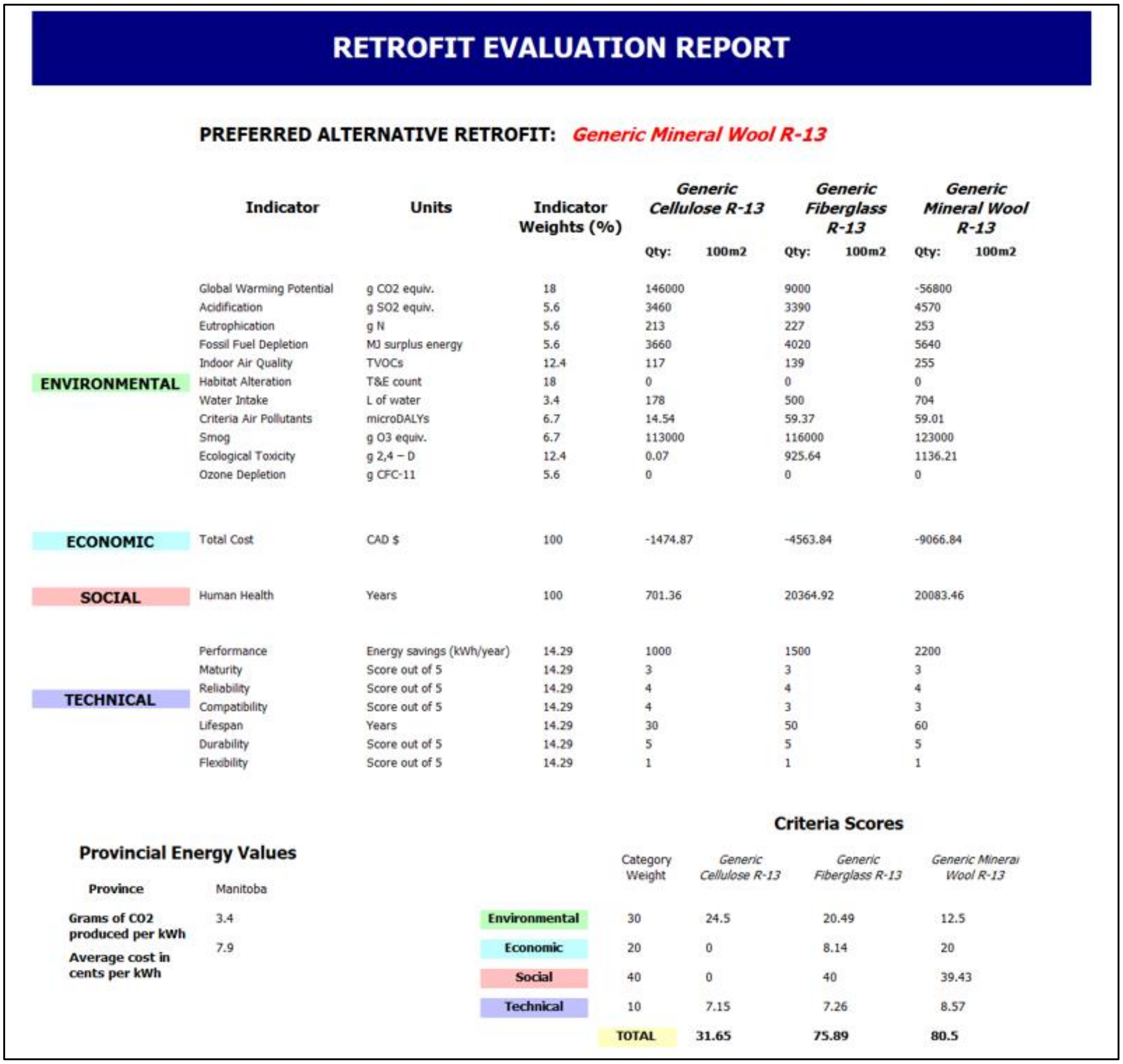


Figure 4-12: Data Flow Diagram

4.6 Final Report

After the calculation sheet has been populated based on the selected retrofits, quantity and location, the tool user will be able to generate a final report which will contain select data from the hidden calculation spread sheet. This report will show the data values with the quantity of retrofit units factored in for the environmental, economic, social and technical KPIs. It will then also show the normalized and weighted final values, along with the score that each retrofit received in each of the four criteria categories. This will help the user identify how retrofits perform relative to each other in categories that may be more favorable to the user. Figure 4-13 shows a template of the report using sample values from the LCID.



RETROFIT EVALUATION REPORT

PREFERRED ALTERNATIVE RETROFIT: ***Generic Mineral Wool R-13***

	Indicator	Units	Indicator Weights (%)	*Generic Cellulose R-13*	*Generic Fiberglass R-13*	*Generic Mineral Wool R-13*
				Qty: 100m2	Qty: 100m2	Qty: 100m2
ENVIRONMENTAL	Global Warming Potential	g CO2 equiv.	18	146000	9000	-56800
	Acidification	g SO2 equiv.	5.6	3460	3390	4570
	Eutrophication	g N	5.6	213	227	253
	Fossil Fuel Depletion	MJ surplus energy	5.6	3660	4020	5640
	Indoor Air Quality	TVOCs	12.4	117	139	255
	Habitat Alteration	T&E count	18	0	0	0
	Water Intake	L of water	3.4	178	500	704
	Criteria Air Pollutants	microDALYs	6.7	14.54	59.37	59.01
	Smog	g O3 equiv.	6.7	113000	116000	123000
	Ecological Toxicity	g 2,4 – D	12.4	0.07	925.64	1136.21
	Ozone Depletion	g CFC-11	5.6	0	0	0
ECONOMIC	Total Cost	CAD $	100	-1474.87	-4563.84	-9066.84
SOCIAL	Human Health	Years	100	701.36	20364.92	20083.46
TECHNICAL	Performance	Energy savings (kWh/year)	14.29	1000	1500	2200
	Maturity	Score out of 5	14.29	3	3	3
	Reliability	Score out of 5	14.29	4	4	4
	Compatibility	Score out of 5	14.29	4	3	3
	Lifespan	Years	14.29	30	50	60
	Durability	Score out of 5	14.29	5	5	5
	Flexibility	Score out of 5	14.29	1	1	1

Provincial Energy Values

Province	Manitoba
Grams of CO2 produced per kWh	3.4
Average cost in cents per kWh	7.9

Criteria Scores

	Category Weight	*Generic Cellulose R-13*	*Generic Fiberglass R-13*	*Generic Mineral Wool R-13*
Environmental	30	24.5	20.49	12.5
Economic	20	0	8.14	20
Social	40	0	40	39.43
Technical	10	7.15	7.26	8.57
	TOTAL	**31.65**	**75.89**	**80.5**

Figure 4-13: BERET Sample Report

4.7 Summary

The Building Energy Retrofit Evaluation Tool (BERET) uses a comprehensive approach to assess the environmental, economic, social and technical criteria for building retrofits. The tool's evaluation allows for the input of some user judgement and preference, as they can select their weighting for the four criteria categories. The highest scored retrofit will be selected as the preferred alternative for the building. The tool can also provide an overview of how each retrofit performs against another in the four criteria categories and their KPIs. A user can input new retrofits into the tool and its LCID provided they have all the KPI values or life cycle assessment values required. Finally, a report can be generated by BERET to provide the user details about the scoring of the retrofits and the key performance indicator values that are normalized and calculated. This tool is comprehensive, and Microsoft Excel-based, making it accessible for building managers to implement, navigate and utilize.

4.8 References

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CHAPTER 5

RETROFIT EVALUATION OF THE KERR HOUSE AT THE UNIVERSITY OF WINDSOR: CASE STUDY

5.1 Introduction

A case study was conducted on a University of Windsor building using the Building Energy Retrofit Evaluation Tool. The Faculty Association building, also known as the Kerr House, is a low rise commercial office space used by the Windsor University Faculty Association. An energy simulation for the Kerr house is conducted using the HOT2000 software to collect more accurate energy saving values for the evaluation. Three retrofits are chosen from the existing life cycle impact database in BERET to be comparatively assessed for the Kerr House. The results of the case study indicate which retrofit is deemed as most appropriate for the selected building as well as the performance of the varying retrofits in each of the four criteria categories under consideration; environmental, economic, social and technical.

The main objective of this chapter is to demonstrate how BERET can applied, and to propose best management practices (BMP) for the tool. Furthermore, this chapter summarizes how this new developed methodology and framework can support building stakeholders with limited sustainability knowledge in their selection process by incorporating life cycle thinking and holistic evaluation criteria.

5.2 Methodology

In order to conduct the energy simulation, the HOT2000 software is used. This software was developed by Natural Resources Canada (NRC) to support energy efficiency initiatives for low-rise residential buildings [1]. The software is used for low-rise residential buildings and provided for free by NRC and is easily accessible for building owners. The building's annual energy consumption is calculated based on a combination of existing and assumed characteristics and properties for the building components. Information was provided for this case study by University faculty as well as site visits and examinations of the infrastructure. After the existing energy consumption was calculated, the energy consumption was calculated after the retrofits are implemented to determine the total energy savings which can be added into the scoring metrics for the assessment.

Three retrofits are selected from the Life Cycle Impact Database that was created in Chapter 3. These retrofits are fiberglass wall insulation, double glazed air filled windows and triple glazed argon filled windows. The HOT2000 database had these retrofit upgrades available within the tool in order to be applied to the Kerr House. Assumptions which were made on the original state of the building and existing conditions are discussed in this chapter as well.

5.3 Kerr Faculty House Building

This Kerr building, established in 1972, has been renovated into a commercial space that contains storage and office spaces for staff. Various existing Kerr House building characteristics were required in order to conduct the HOT2000 energy simulation. Due to these data restrictions, some assumptions were made about the existing properties and materials of building's the walls and windows prior to the energy upgrades. A front view of the Kerr Faculty House is shown in Figure 5-1 [2].

Figure 5-1: Kerr Faculty Association House

The building is located at 366 Sunset Avenue on the University of Windsor Campus, in Windsor Ontario. Some building data was found in a set of floor plans were provided by the university which were used to collect the required perimeter, area, wall and window measurements for the two story building. The building also has a full basement and sloped ceiling. There are 36 windows in total, 16 on the first floor and 20 on the second floor. There were no records provided by the university on the current insulation, windows or retrofit types within the building. As discussed in earlier chapters, BERET is best used for outdated buildings that have had no energy upgrades for the retrofits under evaluation.

Windows widths were found from the floor plans, and all assumed to be a height of 500 mm. They were also assumed to all be clear and made of single glazing. The walls in the building were assumed to have no insulation layers on both floors as well. University staff was also able to provide the average monthly utility cost for electricity which was used to calculate the daily energy consumption for the tool with the use of data from the

Ontario energy board website [3]. Table 5-1 shows the properties that were used for the building in the HOT2000 tool.

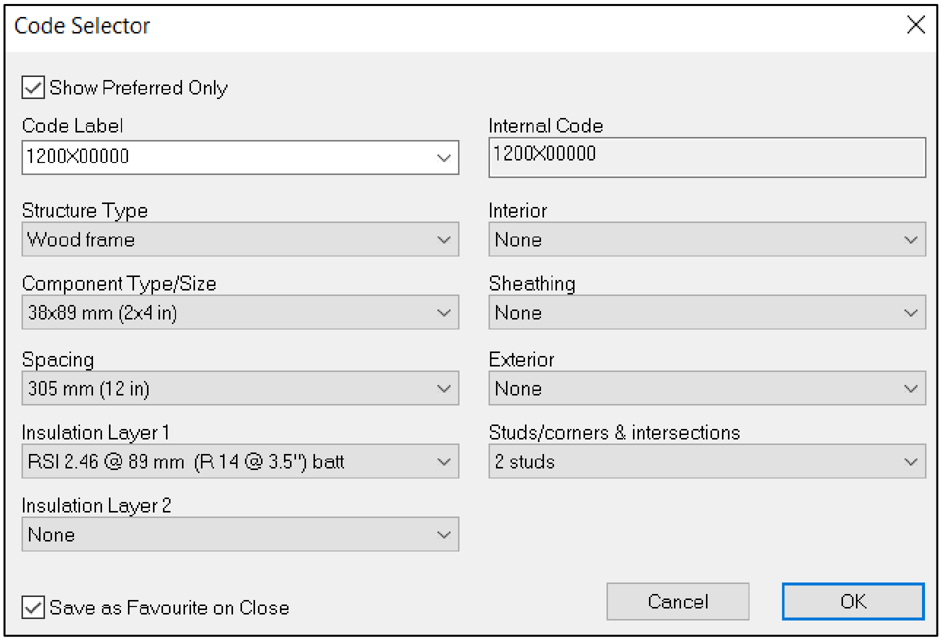
Table 5-1: Kerr House Simulation Properties

Property/Characteristic	**Data**
Perimeter	44.7 m
Area (floor)	124.0 m^2
Front Orientation	West
Wall Heights	2.25 m
Weather Data Location	Windsor, Ontario
Temperatures	Daytime Heating: 21°C Nighttime Heating: 18°C
Average Electricity Consumption	17.2 kWh/day

It is assumed that the current insulation in the building is basic fiberglass batt with an R value of 8 and 2.5 inches thick. Thus, the life cycle impact database retrofits are all considered to be more energy efficient than the existing conditions within the building.

5.4 HOT2000 Retrofit Upgrades

In order to conduct the HOT2000 energy simulation, the building properties in Table 5-1 were placed into the tool to create the Kerr faculty house energy profile. After this, the individual properties of each new retrofit were assigned through the energy retrofit upgrade feature. The energy retrofits that were selected from the LCID were also available in the HOT2000 software. Firstly, the properties of the wall insulation were assigned to the walls in both the upper and lower level of the building. The code selector for the fiberglass wall insulation with an R value of 14 and thickness of 3.5 inches is shown in Figure 5-2. The second upgrade code for the double glazed air filled window in shown in Figure 5-3 and the fourth upgrade code for the triple glazed argon filled window is shown in Figure 5-4.



☑ Show Preferred Only

Code Label: 1200X00000

Internal Code: 1200X00000

Structure Type: Wood frame

Interior: None

Component Type/Size: 38x89 mm (2x4 in)

Sheathing: None

Spacing: 305 mm (12 in)

Exterior: None

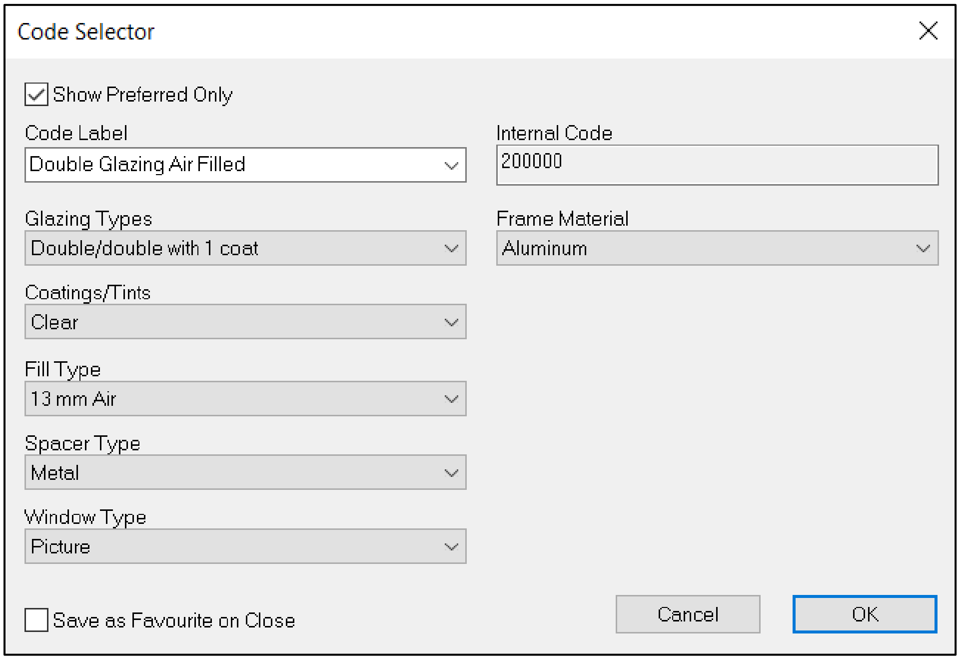
Insulation Layer 1: RSI 2.46 @ 89 mm (R 14 @ 3.5") batt

Studs/corners & intersections: 2 studs

Insulation Layer 2: None

☑ Save as Favourite on Close

Figure 5-2: Fiberglass Insulation Upgrade Code



☑ Show Preferred Only

Code Label: Double Glazing Air Filled

Internal Code: 200000

Glazing Types: Double/double with 1 coat

Frame Material: Aluminum

Coatings/Tints: Clear

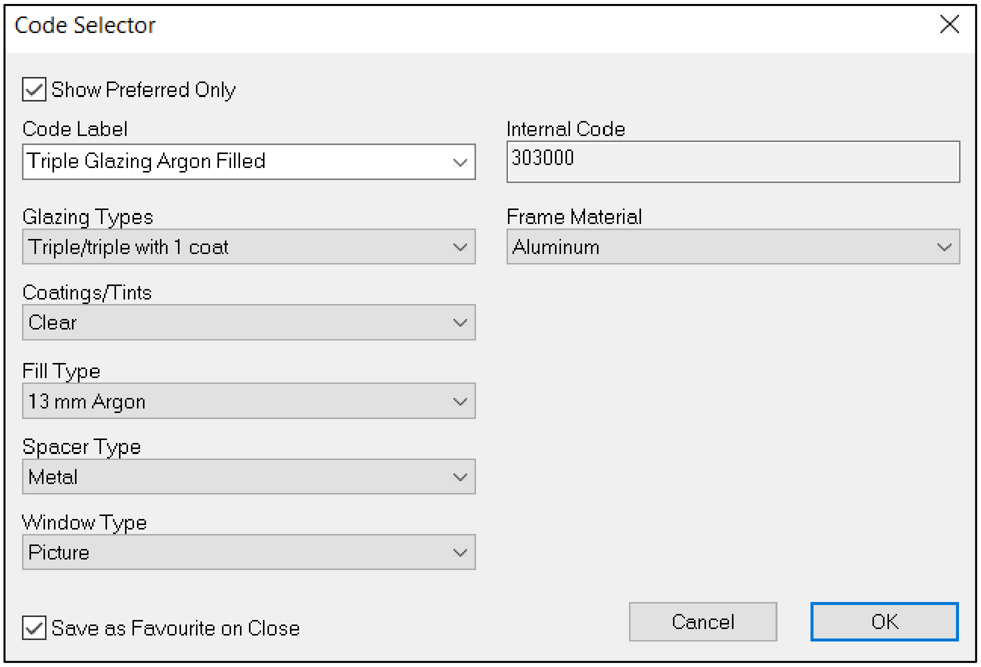
Fill Type: 13 mm Air

Spacer Type: Metal

Window Type: Picture

☐ Save as Favourite on Close

Figure 5-3: Double Glazing Air Filler Window Upgrade Code



Code Selector

☑ Show Preferred Only

Code Label: Triple Glazing Argon Filled

Internal Code: 303000

Glazing Types: Triple/triple with 1 coat

Frame Material: Aluminum

Coatings/Tints: Clear

Fill Type: 13 mm Argon

Spacer Type: Metal

Window Type: Picture

☑ Save as Favourite on Close

Figure 5-4: Triple Glazing Argon Filled Window Code Selector

The window retrofits upgrade had to be applied to each of the 26 windows individually. A report was generated for the energy savings of each upgrade and demonstrated the changed energy consumption in kilowatt-hours. The energy savings from each individual retrofit is shown in Table 5-2. The energy upgrade which saved the most electricity per year is the triple glazed argon filled windows, followed by the double glazed air filled windows and finally the fiberglass insulation upgrade. Once the energy saving data was gathered BERET was used to comparatively evaluate the preferred option for the Kerr building.

Table 5-2: Energy Savings from HOT2000 Energy Upgrades

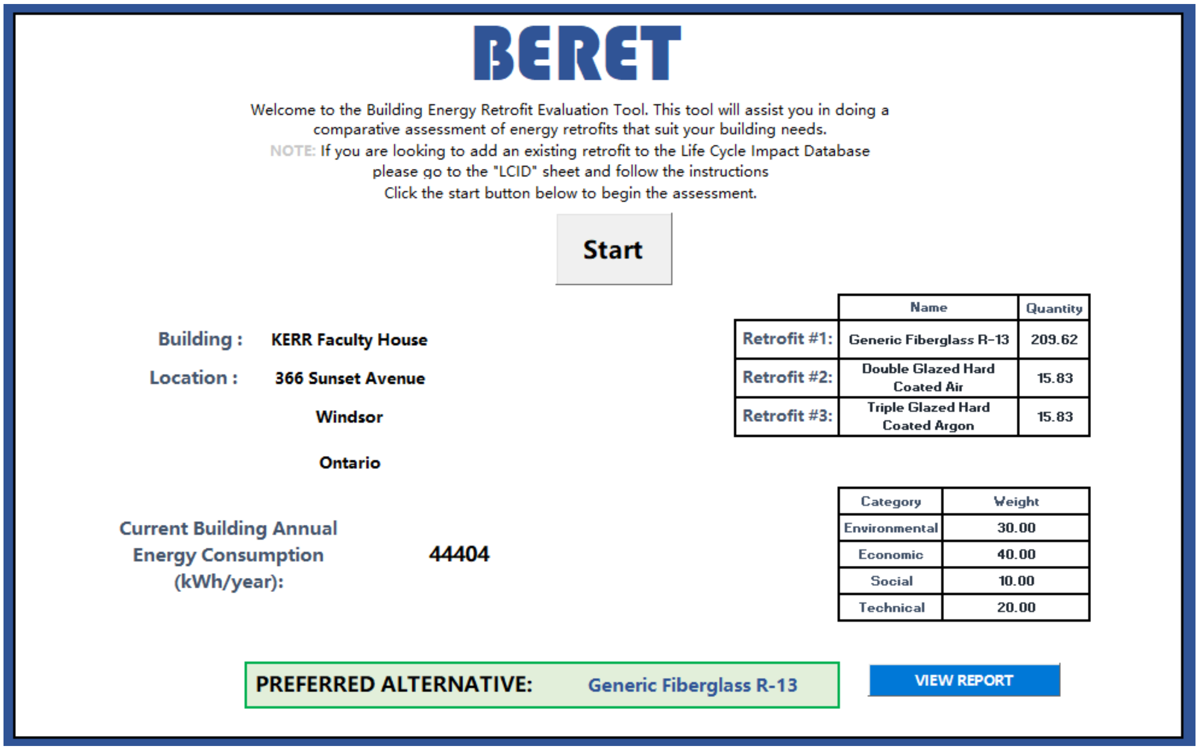
Energy Retrofit Upgrade	Building Energy Consumption (kWh/year)	Amount of Energy Saved (kwh/year)
No upgrades	44400	---
Fiberglass Insulation R-14	42300	2140
Double Glazed Air Filled Windows	41900	2490
Triple Glazed Argon Filled Windows	41100	3270

5.5 Results

BERET was used in order to evaluate the three retrofit upgrades against each other in terms of their environmental, economic, social and technical indicators. The user forms for the main interface shown in Figure 4-2 of Chapter 4 were filled out according to the properties and selected retrofits in the simulation. Scores out of 4 were chosen for the importance rating for the four major criteria categories; environmental was given a score of 3, economic was given a score of 4, social was given a score of 1 and technical was given a score of 2. The environmental category was given a 3 because it is regarded as important for the university's green initiatives and being highly ranked for its environmental commitment. The economic category was given a score of 4 because of the budget constraints and constraints on public funding that come with a renovation project. Social was given a score of 1 because it was not found to be of high priority for the university but is still a factor to be considered. And finally, technical was given a score of

2 because the technical parameters are not found to be of a huge concern with the university having its own maintenance department for their infrastructure.

Furthermore, the total quantities are required for each new retrofit so that the calculations can be made. Based on the HOT2000 simulation these values can be determined; the total window area is 15.83 m^2 and the total wall areas is 209.62 m^2. Figure 5-5 shows the BERET main screen after the three user forms have been filled out. The preferred alternative is shown at the bottom in the green box, being Generic Fiberglass R-13 insulation.



Welcome to the Building Energy Retrofit Evaluation Tool. This tool will assist you in doing a comparative assessment of energy retrofits that suit your building needs.
NOTE: If you are looking to add an existing retrofit to the Life Cycle Impact Database please go to the "LCID" sheet and follow the instructions
Click the start button below to begin the assessment.

Building : KERR Faculty House
Location : 366 Sunset Avenue
Windsor
Ontario

Current Building Annual Energy Consumption (kWh/year): 44404

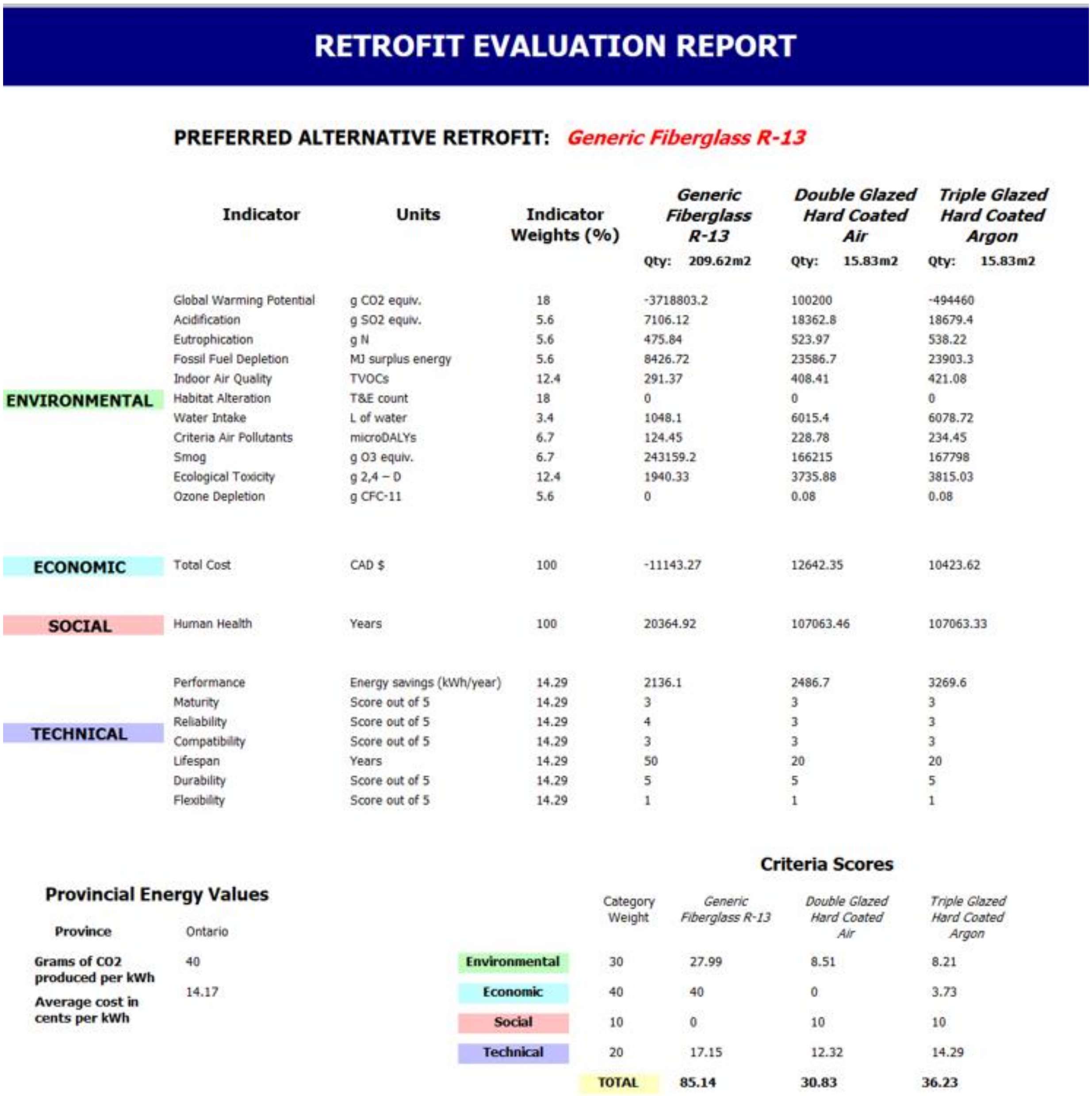
	Name	Quantity
Retrofit #1:	Generic Fiberglass R-13	209.62
Retrofit #2:	Double Glazed Hard Coated Air	15.83
Retrofit #3:	Triple Glazed Hard Coated Argon	15.83

Category	Weight
Environmental	30.00
Economic	40.00
Social	10.00
Technical	20.00

PREFERRED ALTERNATIVE: Generic Fiberglass R-13

Figure 5-5: Kerr House BERET Information

The final report and results are also shown in Figure 5-6. The report also shows the category scores for each retrofit. A user will be able to look in which categories the retrofits outperformed each other.



RETROFIT EVALUATION REPORT

PREFERRED ALTERNATIVE RETROFIT: ***Generic Fiberglass R-13***

	Indicator	Units	Indicator Weights (%)	*Generic Fiberglass R-13* Qty: 209.62m2	*Double Glazed Hard Coated Air* Qty: 15.83m2	*Triple Glazed Hard Coated Argon* Qty: 15.83m2
ENVIRONMENTAL	Global Warming Potential	g CO2 equiv.	18	-3718803.2	100200	-494460
	Acidification	g SO2 equiv.	5.6	7106.12	18362.8	18679.4
	Eutrophication	g N	5.6	475.84	523.97	538.22
	Fossil Fuel Depletion	MJ surplus energy	5.6	8426.72	23586.7	23903.3
	Indoor Air Quality	TVOCs	12.4	291.37	408.41	421.08
	Habitat Alteration	T&E count	18	0	0	0
	Water Intake	L of water	3.4	1048.1	6015.4	6078.72
	Criteria Air Pollutants	microDALYs	6.7	124.45	228.78	234.45
	Smog	g O3 equiv.	6.7	243159.2	166215	167798
	Ecological Toxicity	g 2,4 – D	12.4	1940.33	3735.88	3815.03
	Ozone Depletion	g CFC-11	5.6	0	0.08	0.08
ECONOMIC	Total Cost	CAD $	100	-11143.27	12642.35	10423.62
SOCIAL	Human Health	Years	100	20364.92	107063.46	107063.33
TECHNICAL	Performance	Energy savings (kWh/year)	14.29	2136.1	2486.7	3269.6
	Maturity	Score out of 5	14.29	3	3	3
	Reliability	Score out of 5	14.29	4	3	3
	Compatibility	Score out of 5	14.29	3	3	3
	Lifespan	Years	14.29	50	20	20
	Durability	Score out of 5	14.29	5	5	5
	Flexibility	Score out of 5	14.29	1	1	1

Provincial Energy Values

Province	Ontario
Grams of CO2 produced per kWh	40
Average cost in cents per kWh	14.17

Criteria Scores

	Category Weight	*Generic Fiberglass R-13*	*Double Glazed Hard Coated Air*	*Triple Glazed Hard Coated Argon*
Environmental	30	27.99	8.51	8.21
Economic	40	40	0	3.73
Social	10	0	10	10
Technical	20	17.15	12.32	14.29
	TOTAL	**85.14**	**30.83**	**36.23**

Figure 5-6: Report for Kerr Faculty House BERET Evaluation

The report above demonstrates that the fiberglass insulation performed best in terms of the environmental, economic and technical score although it is the retrofit with the least energy savings for the Kerr building as shown above in Table 5-2. Triple glazing of the windows is the most energy centric retrofit however it scored second and relatively low in comparison to the insulation. It is known that the weights are an important part of the calculation process and if modified can significantly change the final score of each retrofit. It is also important to discuss that contrary to the expected rational outcome, the retrofit with the most energy savings will not always result in the greatest overall score.

As explained throughout this thesis, energy savings are considered throughout the analysis, but it does not factor into all the key performance indicators. The energy savings directly affect the values for global warming emissions, costing and technical performance. When looking at the data values for this case study in Figure 5-6 it is seen that the life cycle costing value is negative for the fiberglass insulation, meaning that it will produce cost savings from the amount of energy reduction. The other two retrofits, while producing greater energy savings, cost more in terms of purchasing, installation and maintenance and cost more in the long run. Furthermore, the global warming potential indicator shows the CO_2 emissions are the lowest for the generic fiberglass because of the decreased requirements from the provincial electricity. Thus, although this retrofit saves the least amount of energy, the energy savings significantly outweighs the emissions and costing required throughout their life cycle. The other two retrofits have indicated that there is a larger trade-off for their energy savings in terms of the considered factors. Accordingly, this developed framework is able to calculate these trade-offs with energy savings whilst also considering key factors that are important for sustainability and functionality.

5.6 Review of Tool and Characteristics

The case study presented in this Chapter was used to demonstrate how to apply BERET. It was important to note that validating this tool was deemed not feasible for this study at this point in time. This would require the monitoring of an actual building in operation throughout the life cycle of its retrofits, and ideally would be compared to an identical building not going through retrofitting. Furthermore, emission levels and energy changes would need to be monitored for an extended period of time. This difficulty in validation has also been expressed in existing research for framework development where case studies are also used to confirm applicability [4-7]. Existing decision-making techniques for building energy retrofitting are also not inclusive of many of the characteristics of BERET, making it challenging to draw conclusions if the results from each tool were to be compared to one another. As a result, the outcomes of the comparison would not indicate the validity of this tool because of the different factors and methods under consideration. Thus, a brief discussion is given in order to summarize the important characteristics that are incorporated into the methodology for the development of BERET that are derived from notable evaluation approaches.

Throughout the development of BERET various important factors were taken into consideration based on what was found to be lacking in the literature and other existing tools or software. As discussed, environmental and economic life cycle assessments were considered in the BEES and ATHENA tools, but they did not consider social and technical factors. It is important to consider a combination of all of the four factors as they are important for the sustainability and functionality of the infrastructure [8]. Furthermore, some existing literature frameworks have considered a combination of the factors but they lack of life cycle thinking, which is a crucial aspect of building a sustainable future [9]. In addition to the inclusion of these aspects, BERET is made to be comprehensive, holistic and easily accessible for asset managers who are not familiar with sustainability requirements to navigate and use for the improvements of their building [10]. Figure 5-7 demonstrates the incorporated characteristics of BERET which have been considered in other discussed notable approaches.

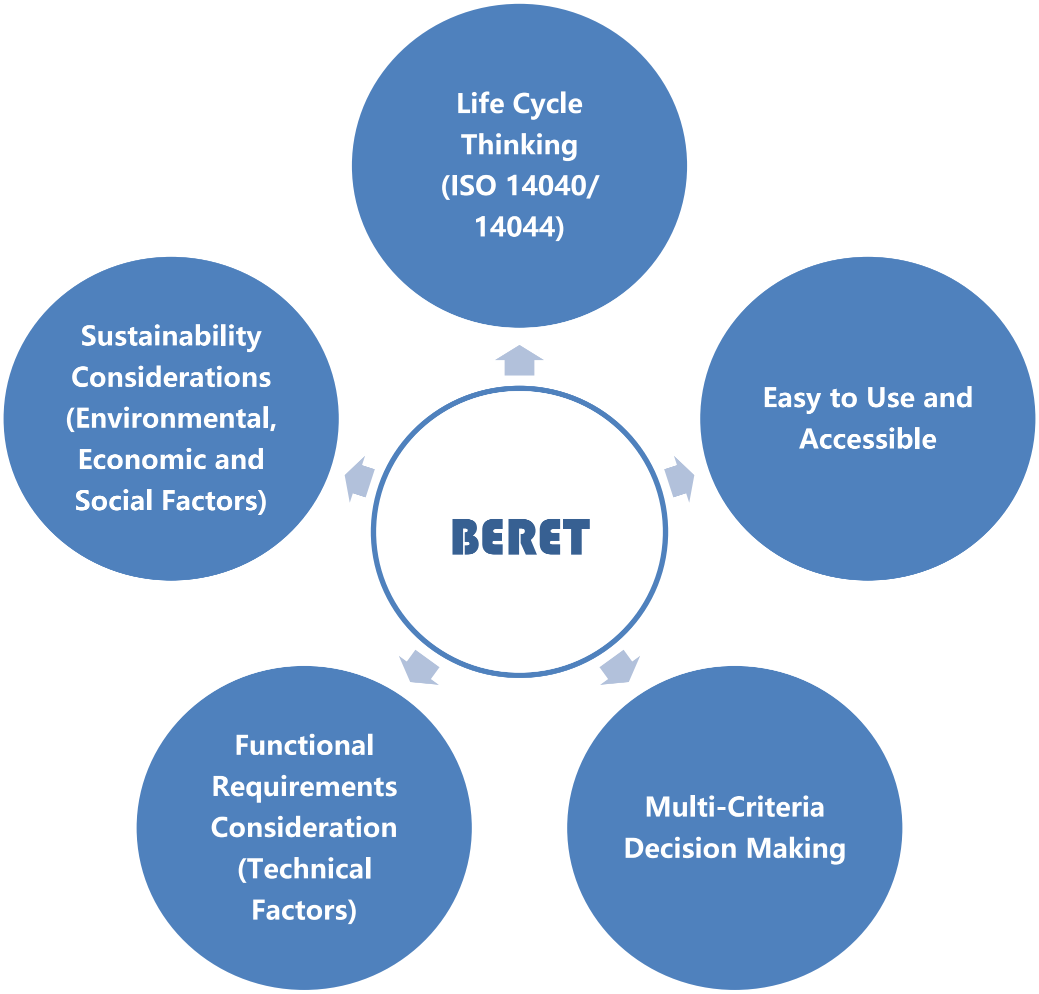


Figure 5-7: BERET Characteristics

5.6.1 Framework Robustness

As discussed, full validation of the BERET system is not possible with current data sets. However, we can demonstrate to a limited degree that the BERET system should be robust as a framework for decision making. Table 5-3 shows four different scenarios with parameter changes for the KERR house analysis. The first scenario shows the results of the original analysis, the second scenario shows the new scores if the three retrofit physical retrofit parameters were increased by approximately 25% while in the third scenario the amounts were decreased by 25%. The fourth scenario shows the change in scores if the category weights were all changed to be equal (25% each).

Table 5-3: BERET Scores for Parameter Changes

Criteria Category	**Original Kerr Building Assessment**			**Size Increase of Approximately 25%**			**Size Decrease of Approximately 25%**			**Changing Category Weights: Equal**		
	R1	**R2**	**R3**	**R1**	**R2**	**R3**	**R1**	**R2**	**R3**	**R1**	**R2**	**R3**
Environmental	27.99	8.34	8.1	27.99	8.34	8.1	26.31	10.58	9.83	23.33	7.09	6.84
Economic	40	0	3.15	40	0	3.15	40	0	5.13	25	0	2.33
Social	0	10	10	0	10	10	0	10	10	0	25	25
Technical	17.15	12.32	14.29	17.15	12.32	14.29	17.15	12.32	14.29	21.44	15.4	17.86
Total	85.14	30.66	35.54	85.14	30.66	35.54	83.46	32.9	39.25	69.77	47.49	48.03

Note:
R1: Insulation - Generic Fiberglass R-13
R2: Window Glazing – Double Glazed Hard Coated Air
R3: Window Glazing – Triple Glazed Hard Coated Argon

The outputted values for all cases show that the preferred alternative is still the fiberglass insulation. For the second scenario the two glazed options show a slight decrease in scores. At this point it is not possible to ascertain if this decrease is within the realm of acceptable statistical variation. However, if the change is real, it may be because that increasing the physical size of the glazing will produce more environmental impacts (ex, emissions from production). The final score for the fiberglass remains unchanged: this suggests that in all subcategories in the BERET framework analysis that fiberglass is still the preferred option and, therefore, when subjected to the MCDM it would still be considered the highest. In the third scenario where the physical parameters were decreased by approximately 25% the glazing retrofit options increased in score slightly. Again, assuming there are no statistical issues, this slight increase in score is reasonable because reduced glazing means reduced physical size and reduced emissions from production, etc. The fiberglass options score has decreased slightly which indicated that in the subcategories of the BERET analysis fiberglass is no longer the top scoring alternative among all categories of assessment. In the fourth option which is the same as the first base scenario but with equal weightings across all four criteria categories of environmental, economic, social and technical, we see the most change in the alternative scores. This again is reasonable because weightings are known to significantly influence the outcome. However, the relative rank of each alternative remains unchanged, fiberglass although it has a lowered score is still the preferred alternative.

The overall conclusion, that can be reached from this limited robustness analysis is that the BERET system does respond appropriately to changes in the input parameters but remains sufficiently robust so that it is not unduly influenced by insignificant changes.

5.7 Best Management Practices

The following best management practices, as shown in Figure 5-8, are recommended for BERET:

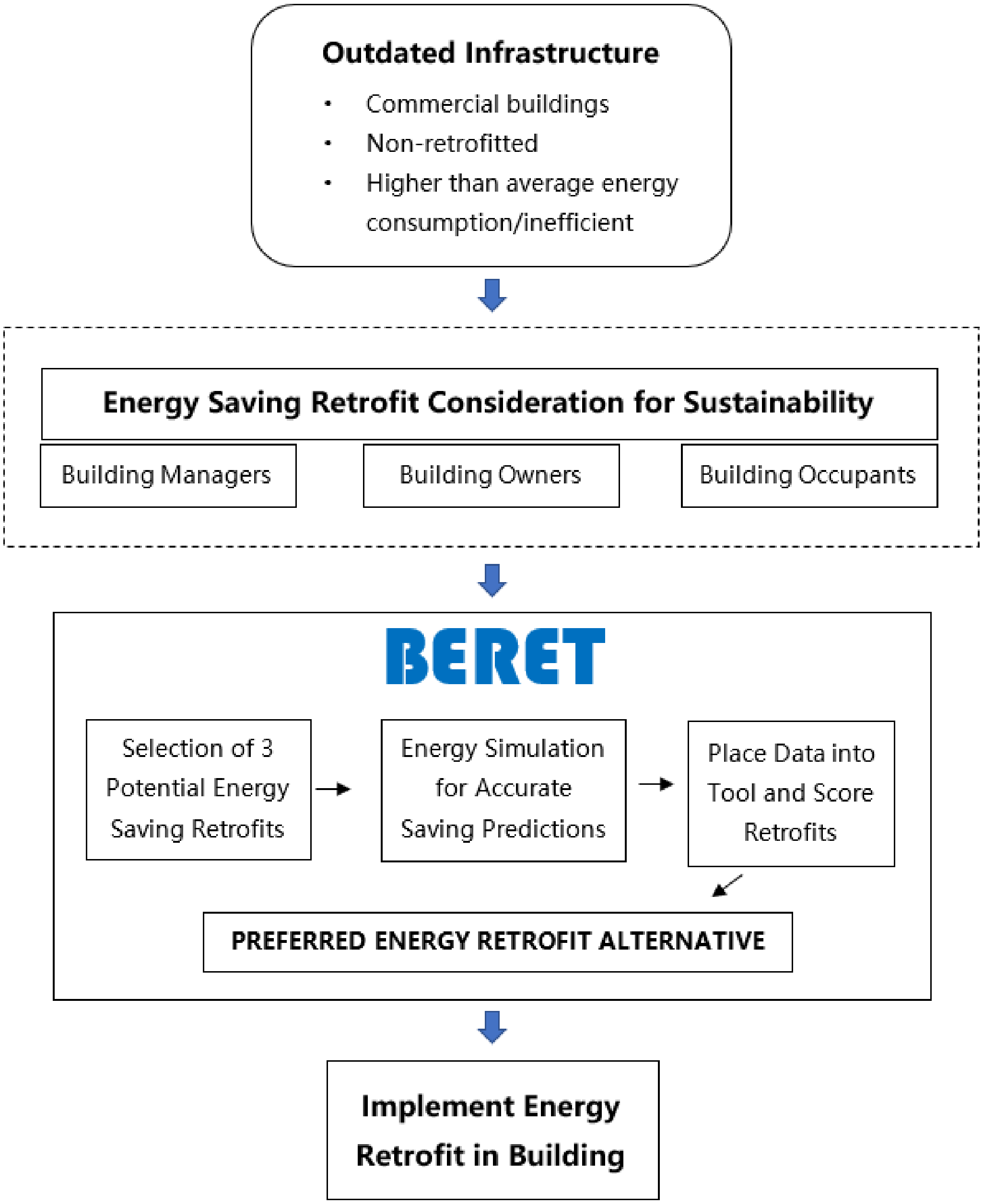


Figure 5-8: Best Management Practices Diagram

BERET is meant to be used for outdated infrastructure, in which no or minimal energy saving retrofits have been implemented and where energy efficiency is low. Higher management will benefit from the use and implementation of the tool in their practices. This includes organizations such as municipalities, commercial office space owners and educational institutions. Given Canada's current role and vision for moving towards a sustainable future, organizations may want to work towards adaptation and action [11]. Furthermore, it is determined that building owners may be motivated to pursue green initiatives in order to "grow tenant demand to lower operating costs associated with electricity, fuel, and water consumption; increase employee productivity; seek more socially conscious investments, and reputation" while building managers may be interested in retrofitting for the replacement of outdated or defective equipment [12]. Many members of an organization will play a role in the retrofitting selection process. These members may have limited sustainability knowledge to make an informed decision of the most appropriate retrofits [5]. However, once building stakeholders such as managers, owners or occupants are looking to update their building in terms of sustainability factors such as costing, technical, environmental or social impacts they can discuss their options and begin the application of BERET.

The tool is meant to compare three retrofits; therefore, the user will need to select three potential energy saving retrofits that will fit into their building. Once the retrofits are selected, an energy simulation or prediction can take place in order to determine the expected energy savings from each retrofit alternative. This will help provide more accurate results from the tool that are more specific to the building under evaluation. Once all of the data is gathered it can be placed into BERET as per the user forms sequence in

Chapter 4. The output will indicate which alternative is most appropriate for the given building through the consideration of the environmental, economic, social and technical impacts. The report within BERET will also indicate the values that were generated for the retrofits in each category to give the user a better understanding of which impacts are highest, and which are lowest. Once the retrofit is selected, owners can implement their selected retrofit into their building

5.8 Summary

The HOT2000 software was useful in determining energy consumption changes for the Kerr Faculty Association House, which provided a more accurate determination of the preferred alternative for a retrofit energy upgrade between three energy retrofit upgrades based on user selected importance of the four criteria categories. If a user would like to be provided with more accurate results, they will need to determine the energy consumption changes through a similar energy simulation software or other resources. BERET is able to generate a report based on the selected values and inputs which will help the user understand which categories each retrofit performed highest in and how the retrofits compare against one another in each category individually.

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CHAPTER 6

DISCUSSION AND CONCLUSION

6.1 Summary and Contributions

Chapter 2 discusses the determination of the key performance indicators that were used for all four categories and how the are determined using existing evaluation tools and literature. Chapter 3 discusses the life cycle assessments that were used in order to incorporate the critical aspect of life cycle thinking into this research. An environmental life cycle assessment, life cycle costing and a social life cycle assessment were all conducted in order to provide data that is used in the comparative evaluation of energy retrofits. Chapter 4 demonstrates the creation of the Building Energy Retrofit Evaluation Tool on Microsoft Excel Visual Basics for Applications (VBA) to be comprehensive and easy for building manager use. It discusses the user interface as well as user forms and data required to conduct the analysis. Chapter 5 provides a case study for the tool in order, demonstrating its ease of use and application as a commercially used office space. The unique contributions of this research are as follows:

Life cycle thinking-based building retrofit evaluation method:

Overall, this research resulted in the creation of an evaluation methodology that is holistic and life cycle based that can be used to help in the decision-making process for energy retrofitting of outdated buildings. This study has addressed the research gap surrounding the life cycle evaluation of sustainable building elements by developing a life cycle impact database to facilitate the process of evaluating the life cycle effects of an energy retrofit.

Building retrofit evaluation tool for building managers:

BERET incorporates the use of life cycle thinking in combination with multi-criteria decision making to assist building managers with the selection of the most appropriate building energy retrofits for their building. A life cycle impact database is embedded into the tool including data for three insulation types and four window upgrades. The four major criteria categories of environmental, economic, social and technical can all be combined to create a scoring tool which utilizes the weighted sum method based on the user requirements for retrofit evaluation

6.2 Limitations of the Study

Limitations of this research are discussed below, with adjustments that were made to mitigate them.

Data collection and availability: This research uses data from a wide variety of sources to help create the life cycle impact database along with additional data for the final evaluation framework. Many environmental, economic, social and technical indicators were found throughout the literature reviews which were selectively chosen to be incorporated in this framework. Some factors may not be considered in the analysis as an extensive and exhaustive list could result in an uncomprehensive and impractical tool. Thus, the key performance indicators included those that are the most prominent factors according the to literature and existing software, as discussed in Chapter 2.

Building energy simulation: In Chapter 5, a case study was completed using an energy simulation through the HOT2000 software for a University of Windsor office building. Energy simulations are highly dependent on the input data, which can be wide ranging and highly variable. Therefore, it was difficult to determine the accuracy of the output data from the building replication.

6.3 Future Research

The extensions that may be made to the scope of this research are discussed below.

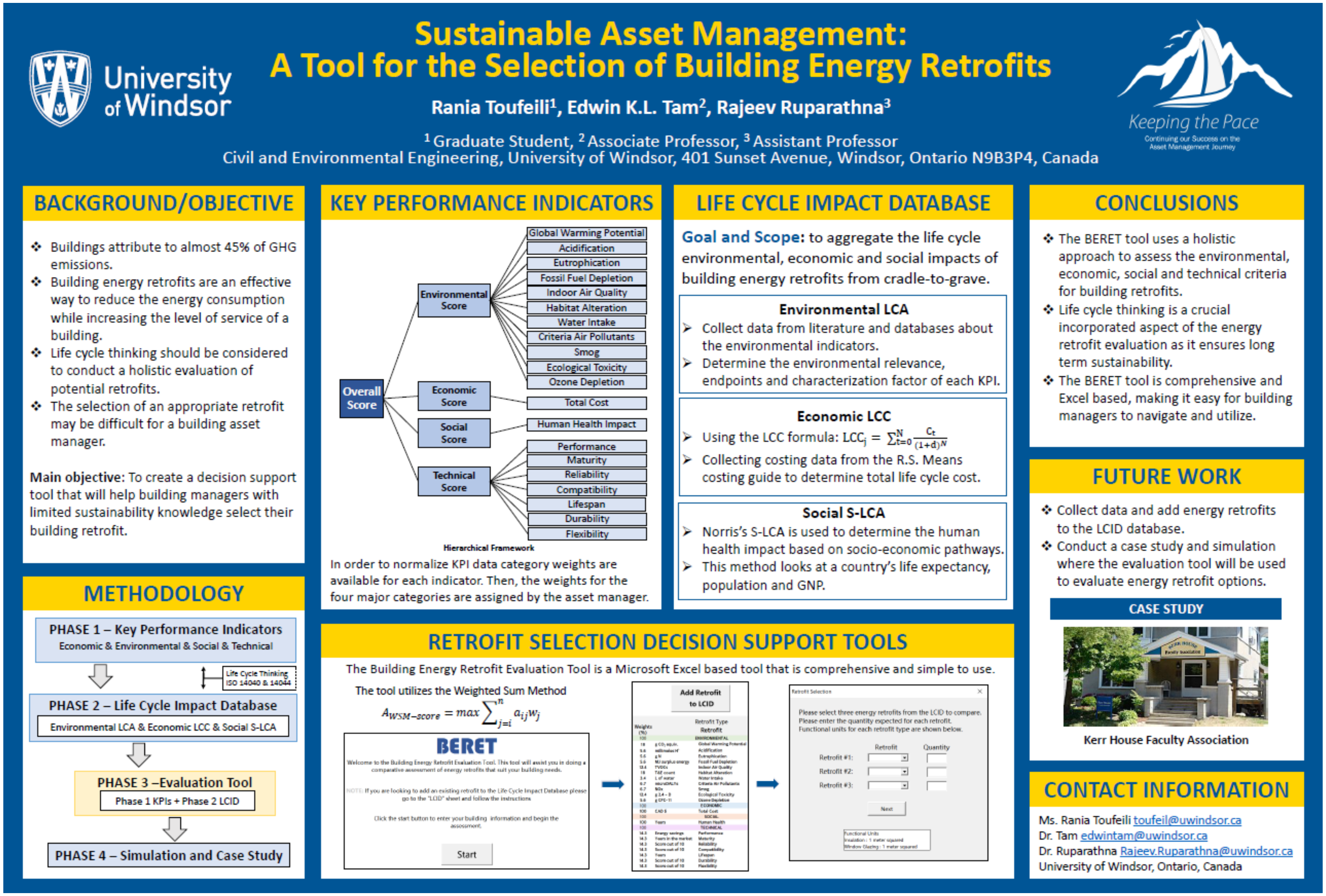
Developing this tool for different types of buildings: this research is applicable to a variety of building types, if electricity is the only energy source used within the building. In the future, research data may be collected so that new parameters can be added to include buildings which use a combination of natural gas and electricity. Modifications can also be made to the VBA software for this.

Integrating a method to estimate the energy savings: Each building is unique to the amount of energy savings that will be made from a retrofit. Thus, the energy savings percentage that is currently placed with the LCID (technical performance KPI) is not precisely applicable to every building since it is gathered from the limited available literature as a general value. Data will be required to effectively compare the changes in building materials. This data can be gathered through energy simulations and other types of studies. Future research could be done to integrate predicted energy savings of a specific building into the tool.

Extended Life Cycle Assessments and Adding Retrofits: As discussed, the tool is designed for the analysis of the implementation of a new retrofit into a building without considering the implications of removing the previous materials for an existing building. This research focuses only on the implementation of new retrofits and does not focus on the end of life management of the removed building materials. Additional studies are required to determine how the life cycle of the previous replaced components is impacting the installation of the new energy saving retrofit. Furthermore, the existing database can be extended to include the life cycle impacts of other popular retrofits.

Further Development of Framework Robustness: To further enhance the applicability of this framework across multiple scenarios and its output confidence, a sensitivity analysis beyond what was presented in this thesis about robustness should be undertaken. In addition, the framework can be further internally modified to account for combinations of retrofits if so desired by a building manager.

APPENDIX A: CNAM CONFERENCE RESEARCH POSTER BOARD



Sustainable Asset Management: A Tool for the Selection of Building Energy Retrofits

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BACKGROUND/OBJECTIVE

- Buildings attribute to almost 45% of GHG emissions.
- Building energy retrofits are an effective way to reduce the energy consumption while increasing the level of service of a building.
- Life cycle thinking should be considered to conduct a holistic evaluation of potential retrofits.
- The selection of an appropriate retrofit may be difficult for a building asset manager.

Main objective: To create a decision support tool that will help building managers with limited sustainability knowledge select their building retrofit.

METHODOLOGY

PHASE 1 – Key Performance Indicators
Economic & Environmental & Social & Technical

Life Cycle Thinking ISO 14040 & 14044

PHASE 2 – Life Cycle Impact Database
Environmental LCA & Economic LCC & Social S-LCA

PHASE 3 –Evaluation Tool
Phase 1 KPIs + Phase 2 LCID

PHASE 4 – Simulation and Case Study

KEY PERFORMANCE INDICATORS

Overall Score

Environmental Score: Global Warming Potential; Acidification; Eutrophication; Fossil Fuel Depletion; Indoor Air Quality; Habitat Alteration; Water Intake; Criteria Air Pollutants; Smog; Ecological Toxicity; Ozone Depletion

Economic Score: Total Cost

Social Score: Human Health Impact

Technical Score: Performance; Maturity; Reliability; Compatibility; Lifespan; Durability; Flexibility

Hierarchical Framework

In order to normalize KPI data category weights are available for each indicator. Then, the weights for the four major categories are assigned by the asset manager.

LIFE CYCLE IMPACT DATABASE

Goal and Scope: to aggregate the life cycle environmental, economic and social impacts of building energy retrofits from cradle-to-grave.

Environmental LCA

- Collect data from literature and databases about the environmental indicators.
- Determine the environmental relevance, endpoints and characterization factor of each KPI.

Economic LCC

- Using the LCC formula: $LCC_j = \sum_{t=0}^{N} \frac{C_t}{(1+d)^N}$
- Collecting costing data from the R.S. Means costing guide to determine total life cycle cost.

Social S-LCA

- Norris's S-LCA is used to determine the human health impact based on socio-economic pathways.
- This method looks at a country's life expectancy, population and GNP.

RETROFIT SELECTION DECISION SUPPORT TOOLS

The Building Energy Retrofit Evaluation Tool is a Microsoft Excel based tool that is comprehensive and simple to use.

The tool utilizes the Weighted Sum Method

$$A_{WSM-score} = max \sum_{j=i}^{n} a_{ij} w_j$$

BERET

Welcome to the Building Energy Retrofit Evaluation Tool. This tool will assist you in doing a comparative assessment of energy retrofits that suit your building needs.

NOTE: If you are looking to add an existing retrofit to the Life Cycle Impact Database please go to the "LCID" sheet and follow the instructions

Click the start button to enter your building information and begin the assessment.

Please select three energy retrofits from the LCID to compare.
Please enter the quantity expected for each retrofit.
Functional units for each retrofit type are shown below.

Retrofit #1:
Retrofit #2:
Retrofit #3:

Functional Units
Insulation : 1 meter squared
Window Glazing : 1 meter squared

CONCLUSIONS

- The BERET tool uses a holistic approach to assess the environmental, economic, social and technical criteria for building retrofits.
- Life cycle thinking is a crucial incorporated aspect of the energy retrofit evaluation as it ensures long term sustainability.
- The BERET tool is comprehensive and Excel based, making it easy for building managers to navigate and utilize.

FUTURE WORK

- Collect data and add energy retrofits to the LCID database.
- Conduct a case study and simulation where the evaluation tool will be used to evaluate energy retrofit options.

CASE STUDY

Kerr House Faculty Association

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APPENDIX B: LIFE CYCLE IMPACT DATABASE DATA

Insulation Data for LCID

Retrofit Name		Generic Cellulose R-13	Generic Fiberglass R-13	Generic Mineral Wool R-13
		ENVIRONMENTAL [1]		
g CO_2 equiv.	Global Warming Potential	2480	2640	3920
g SO_2 equiv.	Acidification	34.6	33.9	45.7
g N	Eutrophication	2.13	2.27	2.53
MJ surplus energy	Fossil Fuel Depletion	36.6	40.2	56.4
TVOCs	Indoor Air Quality	1.17	1.39	2.55
T&E count	Habitat Alteration	0	0	0
L of water	Water Intake	1.78	5	7.04
microDALYs	Criteria Air Pollutants	0.15	0.59	0.59
g O_3 equiv.	Smog	1130	1160	1230
g 2,4 – D	Ecological Toxicity	7.03 x 10-4	9.26	11.36
g CFC-11	Ozone Depletion	1.46 x 10-6	2.36 x 10-5	3.0 x 10-5
		ECONOMIC [2]		
CAD $	Total Cost	8.95	19.04	13.61
		SOCIAL		
Years	Human Health	701.36 [3]	20364.92 [4]	20083.46 [5]
		TECHNICAL		
Energy savings (%)	Performance	27 [6]	27 [6]	27 [6]
Score out of 3	Maturity	3 [7]	3 [8]	3 [9]
Score out of 3	Reliability	4 [10]	4 [10]	4 [10]
Score out of 3	Compatibility	4 [11]	3 [11]	3 [12]
Years	Lifespan	30 [13]	50 [13]	60 [13]
Score out of 3	Durability	5 [13]	5 [13]	5 [13]
Score out of 3	Flexibility	1 [13]	1 [13]	1 [13]

*Note: Citations are available in the superscript next to the data points. Reference list is available at the end of this appendix.

Window Glazing Data for LCID

Retrofit Name		Double Glazed Hard Coated Air	Double Glazed Hard Coated Argon	Triple Glazed Hard Coated Air	Triple Glazed Hard Coated Argon
		ENVIRONMENTAL [1]			
g CO2 equiv.	Global Warming Potential	132000	133000	134000	134000
g SO2 equiv.	Acidification	1160	1160	1180	1180
g N	Eutrophication	33.1	33.7	33.5	34
MJ surplus energy	Fossil Fuel Depletion	1490	1490	1510	1510
TVOCs	Indoor Air Quality	25.8	25.8	26.6	26.6
T&E count	Habitat Alteration	0	0	0	0
L of water	Water Intake	380	383	379	384
microDALYs	Criteria Air Pollutants	14.45	14.49	14.75	14.81
g O3 equiv.	Smog	10500	10600	10600	10600
g 2,4 – D	Ecological Toxicity	236	236	240	241
g CFC-11	Ozone Depletion	0.00486	0.00488	0.00485	0.00488
		ECONOMIC [2]			
CAD $	Total Cost	888.44	932.93	1184.11	1243.81
		SOCIAL [14]			
Years	Human Health	107063.45	107063.4	107063.35	107063.33
		TECHNICAL			
Energy savings (%)	Performance	27 [6]	27 [6]	27 [6]	27 [6]
Score out of 3	Maturity	3 [15]	3 [15]	3 [15]	3 [15]
Score out of 3	Reliability	3 [16]	2 [16]	4 [16]	3 [16]
Score out of 3	Compatibility	3 [16]	3 [16]	3 [16]	3 [16]
Years	Lifespan	20 [16]	20 [16]	20 [16]	20 [16]
Score out of 3	Durability	5 [17]	5 [17]	5 [17]	5 [17]
Score out of 3	Flexibility	1 [15]	1 [15]	1 [15]	1 [15]

*Note: Citations are available in the superscript next to the data points. Reference list is available at the end of this appendix.

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