CSCE Annual Conference
Growing with youth – Croître avec les jeunes

Laval (Greater Montreal)
June 12 - 15, 2019

RETHINKING ENERGY RETROFIT EVALUATION: A LIFE CYCLE THINKING BASED APPROACH

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Abstract: Climate change poses a serious global threat, with existing outdated infrastructure as a major contributor. Today, 45% of Canada's greenhouse gas emissions can be attributed to producing heat and electricity for buildings. Green building energy retrofits can help decrease the energy consumption and resulting emissions from a building. Green retrofitting also presents many environmental, social and economic benefits (sustainability) when compared against replacing an existing building with a new one. However, before applying energy retrofits, their potential benefits to sustainability must be evaluated. Much of the previous research focuses on economic or environmental criterion for retrofit evaluation and do not consider all three pillars of sustainability. Moreover, the published literature has overlooked life cycle environmental, economic and social analysis for building retrofits. This paper aims to develop a methodological framework for evaluating energy retrofits to address these literature gaps. The proposed framework incorporates both multi criteria decision making (MCDM) and life cycle thinking to develop a novel retrofit evaluation method. A total of 20 key performance indicators (KPI) for retrofit evaluation are identified through content analysis. These determined KPIs are normalized and aggregated using the weighted sum method (WSM) to create a more complete set of evaluation criteria with respect to environmental, economic, social and technical aspects of building energy retrofits. An illustrative case study is done to demonstrate the use of the framework. This developed methodology is comprehensive, simulation-based and adaptable to a variety of different retrofits and building types.

1 INTRODUCTION

Much of today's existing occupied infrastructure is outdated and inefficient with regards to energy consumption. Buildings in particular account for 45% of global GHG emissions, by providing important necessities such as lighting, heating and electricity to occupants (Jagarajan et al. 2017). Even though it is unrealistic to replace all outdated buildings, accepting the status quo and their current conditions negatively impacts the environment, economy and society. Thus, the greatest potential to reduce the environmental impact of energy consumption over the next several decades lies within the building stock (Ding 2013). Dong, Kennedy, and Pressnail (2005) highlighted the importance of "building maintenance, repair, renewal, retrofit, adaptive re-use and recycling" as a key driver for sustainable development in the construction sector. Sustainable building solutions has been a popular research stream, with building energy retrofits as a key contributor to the development of more energy efficient buildings.

Energy retrofitting is an effective strategy which helps to reduce the energy consumption which in turn reduces GHG emission and operational cost. Energy 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” (Latham 2000). These retrofitting technologies contribute to a critical global movement towards a more sustainable future by presenting many environmental, economic and social benefits when compared against deconstruction and replacing an existing building (Jagarajan et al. 2017). Although energy retrofits are beneficial, it may not be feasible to fully retrofit a building because of the cost. Thus, a thorough analysis is needed when selecting the appropriate retrofit for a building because this selection will be challenging without the proper resources.

Building retrofits have a complex relationship with their environment and many factors should be taken into account, including the economical, technical, social and ecological aspects (Asadi et al. 2012). 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) (Si et al. 2016). Further, 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 (Lippiatt 2007). A comprehensive literature review highlighted two key knowledge gaps on energy retrofit evaluation. First, the existing decision aid tools available are not complete and comprehensive as they do not consider all sustainability criteria. Despite the amount of research to date on retrofit selection tools, there is a lack of established benchmarks and criteria for environmental significance. The technical, economic and environmental implications of green retrofitting has not been studied enough (Jagarajan et al. 2017). A significant amount of the research in the field focusses only on the evaluation of a single economic criteria (Si et al. 2016). Second, life cycle impacts related to sustainability criteria have not always been considered. Life cycle thinking is essential to develop superior and sustainable buildings, with life cycle assessments as valid tools to incorporate life cycle thinking (Ingrao et al. 2018).

In order to address the knowledge gaps discussed, this research paper’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. The resulting framework can be employed by building managers in their energy retrofit selection and decision making.

2 METHODOLOGY

The methodology for this framework is conducted in two parts. The first part deals with determining a set of KPIs for the categories of environmental, economic, social and technical. 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 are reviewed and discussed. 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 is established and normalized. Finally, a set of equations is developed to apply the framework.

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. Many studies suggest that these four criteria should be considered when selecting green technologies, such as in energy retrofits (Si et al. 2016; Kumar et al. 2017; Akadiri and Olomolaiye 2012). Sustainability criteria (environmental, economic and social) are essential in "green technology" decision making (Si et al. 2016). Furthermore, technical criteria are important in building material selection decision making as many studies focus heavily on them to meet functional requirements (Akadiri and Olomolaiye 2012). A hierarchical framework (Figure 1) outlines the KPIs chosen for each criterion and their formula notations. There are 20 KPIs in total; eleven in environmental, one in economic, one in social and seven in technical. The selection of these varying criteria is detailed in the respective sections below.

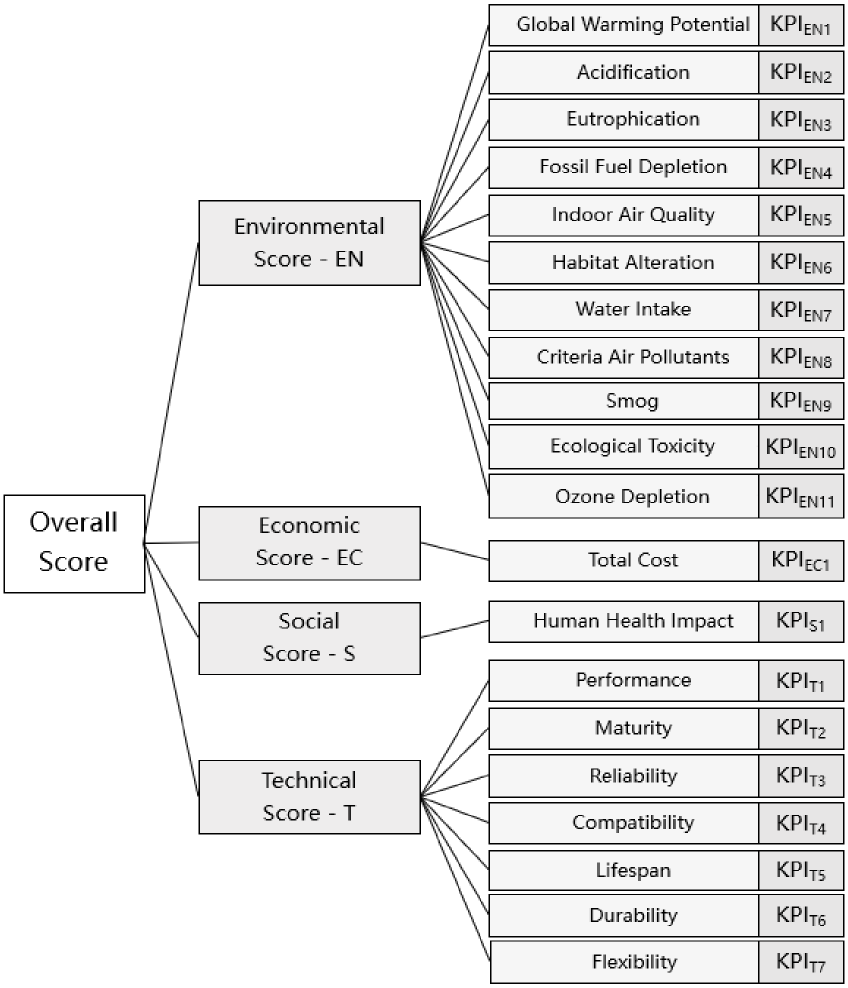

Figure 1: Hierarchical Framework

3.1 Environmental

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 research 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 (Athena Sustainable Materials Institute 2014; Lippiatt 2007). 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 pollutant and ecological toxicity. Athena explains that water use and habitat alteration are highly site specific and therefore is 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.

3.2 Economic

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 (Lippiatt 2007). These can be combined into one KPI of total cost, which can be determined using the LCC approach.

3.3 Social

There are various social life cycle assessment methodologies available such as the most popular methods by Dreyer, Norris, Hunkeler and Weidema. Human well-being is found to be the basis for all social life cycle assessments (SLCAs). SLCA is more complex than environmental LCAs or LCC as it is “based on the way business affects human well-being” (Subramanian 2015). 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 (Subramanian 2015). Of all these popular SLCA methods that were reviewed Norris’s SLCA is 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 (Subramanian 2015).

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 (Norris 2006). Thus, the KPI for the social category becomes human health impact which is determined through socio-economic pathways.

3.4 Technical

The technical KPIs for this framework are determined through the review of journal publications and content analysis using Engineering Index (Compendex) and focusing on resources related to the terms “green building” and “technical criteria”, in order to find technical criteria which considered product selection and sustainability. 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 (Si et al. 2016). 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 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 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. 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. 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. The five most commonly mentioned indicators mentioned in these articles (in over 15% of them) includes performance/efficiency, maturity, reliability, compatibility and lifespan, which present some overlap with the indicators presented by Si et al. (2016).

These additional indicators (maturity and lifespan) are 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.

4 FRAMEWORK

In order to apply the 20 KPIs determined and discussed above a multi criteria decision making method is chosen to structure the framework. The weighted sum method is chosen and discussed in detail in the following section along with an illustrative case study to demonstrate the use of the framework.

4.1 Multi Criteria Decision Making

There is substantial research to date on methods relating to retrofit selection of existing buildings (Jagarajan et al. 2017). Gore, Murray, and Richardson (1992) have described a general procedure for decision making with the following steps: setting objectives; defining the problem; searching for alternatives; evaluating the alternatives; making a choice; and implementing. This general method appears to be the basis for the various decision-making techniques available for the evaluation of building retrofits and is applicable to the framework in this research. Thus, MCDM methods have been successfully implemented in research for green technology selection (Si and Marjanovic-Halburd 2018). Jafari and Valentin (2017) created an “optimization framework for building energy retrofits” focusing primarily on optimization of cost savings. Ma et al. (2012) provided “a systematic approach” to cost-effective retrofit selection. Furthermore, Si et al. 2016) 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. In addition, Menassa (2011) presents a “quantitative approach to determining the value of investment in sustainable buildings” focusing on life cycle costs and perceived benefits of investment. Collier et al. (2013) utilized the Multi-Attribute Value

Theory for roofing retrofit selection and the development of more comprehensive criteria. There are also other researchers which have developed methods or tools to aid in retrofit selection methods.

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) (Si et al. 2016). 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 (Chen, Hwang, and Hwang 1991).

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 (Tscheikner-Gratl et al. 2017). 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 (Kabir, Sadiq, and Tesfamariam 2014). To apply the WSM, a normalization scheme must be applied for the variables in the matrix. 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 (International Standards Organization 2006). Steps and formulas for this application are detailed in section 4.2.

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 their 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 (Ibáñez-Forés, Bovea, and Pérez-Belis 2014). 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 KPIs 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 (Lippiatt 2007). 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%. Not many weighting schemes are found through 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 optimal weighting methods (Wang et al. 2009). All KPI category weights for along with the KPI units can be seen in Table 1 below.

Table 1: 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	millimoles H^+	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	NOx	6.7
	KPI_{EN10}	Ecological Toxicity	g 2,4 – D	12.4
	KPI_{EN11}	Ozone Depletion	g CFC-11	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	Years in the market	14.3
	KPI_{T3}	Reliability	Score out of 10	14.3
	KPI_{T4}	Compatibility	Score out of 10	14.3
	KPI_{T5}	Lifespan	Years	14.3
	KPI_{T6}	Durability	Score out of 10	14.3
	KPI_{T7}	Flexibility	Score out of 10	14.3

The formulas for normalizing the KPI values are shown in equations [1] and [2] (Jahan and Edwards 2015). If a high value of KPI is desired, each alternative KPI unit value $r_{alt,i}$ will be normalized by dividing it by the highest alternative unit value r_{alt}^{max} to calculate the normalized value $KPI_{alt,i}$. If a low value of KPI is desired, the smallest unit value amongst all alternatives r_{alt}^{min} will be divided by the unit values for each of the alternatives $r_{alt,i}$ to calculate the normalized value $KPI_{alt,i}$. Equation [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 w_i is the weight if the importance of the i-th KPI. Equation [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 retrofit with the largest overall score will determine which alternative is best. An illustrative case study is shown in section 4.3 to demonstrate the normalization process and use of the framework.

[1] $KPI_{alt,i} = \frac{r_{alt,i}}{r_{alt}^{max}}$

[2] $KPI_{alt,i} = \frac{r_{alt}^{min}}{r_{alt,i}}$

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

[4] $\text{Retrofit Score} = Score_{EN} * W_{EN} + Score_{EC} * W_{Ec} + Score_{S} * W_{s} + Score_{T} * W_{T}$

4.3 Illustrative Example

The following illustrative example is used in order to demonstrate how the framework can be applied. Table 2 demonstrates collected values for each of the KPIs for two types of insulations: expanded polystyrene (EPS) and extruded polystyrene (XPS) with environmental data collected from Independently Certified Product Declarations (EPS Industry Alliance 2017; Owens Corning 2013) .Values for the economic costs were estimated using RS Means Green Building Costs 2019 (Gordian 2019). Other information regarding technical data was determined from an article by Bozsaky (2011) concerning the history of insulation. No data was available for the Human Health costs. Data that was not available is assigned a value of NA. A weight was also selected and assigned to each major category, totalling to 100%.

Table 2: Case Study Values

Category and Overall Weight (%)	KPI	Category Weight (%)	Units	EPS	XPS
EN = 30	KPI_{EN1}	18	g CO_2 equiv.	2790	60800
	KPI_{EN2}	5.6	millimoles H^+	460	1780
	KPI_{EN3}	5.6	g N	0.36	0.985
	KPI_{EN4}	5.6	MJ surplus energy	71.4	80.7
	KPI_{EN5}	12.4	TVOCs	NA	NA
	KPI_{EN6}	18	T&E count	NA	NA
	KPI_{EN7}	3.4	L of water	9.94	37.9
	KPI_{EN8}	6.7	microDALYs	NA	NA
	KPI_{EN9}	6.7	NOx	200	208
	KPI_{EN10}	12.4	g 2,4 – D	NA	NA
	KPI_{EN11}	5.6	g CFC-11	1.6×10^{-5}	0.363
EC = 35	KPI_{EC1}	100	CAD $	60.4	78.3
S = 10	KPI_{S1}	100	Years	NA	NA
T = 25	KPI_{T1}	14.3	Energy savings	NA	NA
	KPI_{T2}	14.3	Years in the market	69	78
	KPI_{T3}	14.3	Score out of 10	NA	NA
	KPI_{T4}	14.3	Score out of 10	NA	NA
	KPI_{T5}	14.3	Years	60	60
	KPI_{T6}	14.3	Score out of 10	NA	NA
	KPI_{T7}	14.3	Score out of 10	NA	NA

* All values are determined for 1m^2 of material wit a thickness providing an average thermal resistance of $R_{SI} = 1\ m^2 \cdot K/W$ [R-Value of 5.678 hr·ft^2·°F/BTU] and with a building service life of 60 years.

By following the calculation method in section 4.1. The overall score for EPS is 0.568 while the overall score for XPS will be 0.39, making the EPS more favorable in terms of the chosen category weights. Thus, the best energy retrofit alternative would be to implement the EPS insulation instead of the XPS insulation.

5 DISCUSSION AND CONCLUSIONS

Buildings, one of the largest contributors of green house 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 by the decision maker to suit their needs. Furthermore, values for the KPIs are normalized in order to apply the framework. This research presents limitations with respect to the data collection and uncertainties. There are a wide variety of indicators available in literature and tools for the categories that a building manager may want to include but may not be considered for the purposes of this decision aid framework. Furthermore, the framework may generate different results depending on the sources for which the values for the KPIs are collected. The illustrative example in this research did not include all the values for the varying criterion due to limited available data. Thus, further resources such as databases and literature are needed to source KPI values. This can help conduct a more complete analysis that is more representative of the frameworks' output.

In order to address some of these drawbacks and for future work, a life cycle impact database is underway to generate the values for the KPIs belonging to the environmental, economic and social categories. This life cycle impact database will generate values for the varying KPIs through an environmental LCA, economic LCC and social SLCA. An excel based retrofit selection tool is also underway which will combine a life cycle impact database with the framework to aid with decision making.

References

Akadiri, Peter O., and Paul O. Olomolaiye. 2012. "Development of Sustainable Assessment Criteria for Building Materials Selection." *Engineering, Construction and Architectural Management* 19 (6): 666–87. https://doi.org/10.1108/09699981211277568.

Asadi, Ehsan, Manuel Gameiro Da Silva, Carlos Henggeler Antunes, and Luís Dias. 2012. "Multi-Objective Optimization for Building Retrofit Strategies: A Model and an Application." *Energy and Buildings* 44 (1): 81–87. https://doi.org/10.1016/j.enbuild.2011.10.016.

Athena Sustainable Materials Institute. 2014. "User Manual and Transparency Document," no. September. www.athenasmi.org.

Bozsaky, Dávid. 2011. "The Historical Development of Thermal Insulation Materials" 2 (2010): 49–56.

Chen, S. J, C. L Hwang, and F. P Hwang. 1991. "Fuzzy Multiple Attribute Decision Making: Methods and Applications."

Collier, Z. A., D. Wang, J. T. Vogel, E. K. Tatham, and I. Linkov. 2013. "Sustainable Roofing Technology under Multiple Constraints: A Decision-Analytical Approach." *Environment Systems and Decisions* 33 (2): 261–71. https://doi.org/10.1007/s10669-013-9446-5.

Ding, Grace. 2013. "Demolish or Refurbish - Environmental Benefits of Housing Conservation." *Australasian Journal of Construction Economics and Building* 13 (2): 18–34. https://doi.org/10.5130/ajceb.v13i2.3322.

Dong, Bonnie, Christopher Kennedy, and Kim Pressnail. 2005. "Comparing Life Cycle Implications of Building Retrofit and Replacement Options" 1063: 1051–63. https://doi.org/10.1139/L05-061.

EPS Industry Alliance. 2017. "Enviromental Product Declaration : EPS."

Gordian. 2019. *Green Building Costs with RS Means*. 9th ed.

Gore, C, K Murray, and B Richardson. 1992. *Strategic Decision-Making*. USA: Cassell Press.

Ibáñez-Forés, V., M. D. Bovea, and V. Pérez-Belis. 2014. "A Holistic Review of Applied Methodologies for Assessing and Selecting the Optimal Technological Alternative from a Sustainability Perspective." *Journal of Cleaner Production* 70: 259–81. https://doi.org/10.1016/j.jclepro.2014.01.082.

Ingrao, Carlo, Antonio Messineo, Riccardo Beltramo, Tan Yigitcanlar, and Giuseppe Ioppolo. 2018. "How Can Life Cycle Thinking Support Sustainability of Buildings? Investigating Life Cycle Assessment Applications for Energy Efficiency and Environmental Performance." *Journal of Cleaner Production* 201: 556–69. https://doi.org/10.1016/j.jclepro.2018.08.080.

International Standards Organization. 2006. "ISO 14044." *Environmental Management - Life Cycle Assessment - Requirements and Guilelines* 2006 (7): 652–68. https://doi.org/10.1007/s11367-011-0297-3.

Jafari, Amirhosein, and Vanessa Valentin. 2017. "An Optimization Framework for Building Energy

Retrofits Decision-Making.” *Building and Environment* 115: 118–29. https://doi.org/10.1016/j.buildenv.2017.01.020.

Jagarajan, Rehmaashini, Mat Naim Abdullah Mohd Asmoni, Abdul Hakim Mohammed, Mohd Nadzri Jaafar, Janice Lee Yim Mei, and Maizan Baba. 2017. “Green Retrofitting – A Review of Current Status, Implementations and Challenges.” *Renewable and Sustainable Energy Reviews* 67 (September 2016): 1360–68. https://doi.org/10.1016/j.rser.2016.09.091.

Jahan, Ali, and Kevin L Edwards. 2015. “A State-of-the-Art Survey on the Influence of Normalization Techniques in Ranking : Improving the Materials Selection Process in Engineering Design,” no. May 2016. https://doi.org/10.1016/j.matdes.2014.09.022.

Kabir, Golam, Rehan Sadiq, and Solomon Tesfamariam. 2014. “A Review of Multi-Criteria Decision-Making Methods for Infrastructure Management.” *Structure and Infrastructure Engineering*. Taylor & Francis. https://doi.org/10.1080/15732479.2013.795978.

Karunathilake, Hirushie, Kasun Hewage, Walter Mérida, and Rehan Sadiq. 2019. “Renewable Energy Selection for Net-Zero Energy Communities: Life Cycle Based Decision Making under Uncertainty.” *Renewable Energy* 130: 558–73. https://doi.org/10.1016/j.renene.2018.06.086.

Kumar, Abhishek, Bikash Sah, Arvind R. Singh, Yan Deng, Xiangning He, Praveen Kumar, and R. C. Bansal. 2017. “A Review of Multi Criteria Decision Making (MCDM) towards Sustainable Renewable Energy Development.” *Renewable and Sustainable Energy Reviews* 69 (March): 596–609. https://doi.org/10.1016/j.rser.2016.11.191.

Latham, Derek. 2000. *Creative Re-Use of Buildings*. Dorset: Donhead Publishing. http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?db=pubmed&cmd=Retrieve&dopt=AbstractPlus&list_uids=3fyPAQAACAAJ%5Cnpapers://4288930b-a4ef-455e-b9f1-a5519c267225/Paper/p1176.

Lippiatt, Barbara C. 2007. “NISTIR 7423 B Uilding for E Nvironmental and E Conomic S Ustainability Technical Manual and User Guide ®.” *National Institute of Standards and Technology*. http://fire.nist.gov/bfrlpubs/build07/PDF/b07018.pdf.

Ma, Zhenjun, Paul Cooper, Daniel Daly, and Laia Ledo. 2012. “Existing Building Retrofits: Methodology and State-of-the-Art.” *Energy and Buildings* 55: 889–902. https://doi.org/10.1016/j.enbuild.2012.08.018.

Menassa, Carol C. 2011. “Evaluating Sustainable Retrofits in Existing Buildings under Uncertainty.” *Energy and Buildings* 43 (12): 3576–83. https://doi.org/10.1016/j.enbuild.2011.09.030.

Norris, Gregory A. 2006. “Social Impacts in Product Life Cycles.” *International Journal of Life Cycle Assessment*, 96–103. https://doi.org/10.1016/0011-3840(91)90022-H.

Owens Corning. 2013. “FOAMULAR ® Extruded Polystyrene (XPS) Insulation.”

Si, Jin, and Ljiljana Marjanovic-Halburd. 2018. “Criteria Weighting for Green Technology Selection as Part of Retrofit Decision Making Process for Existing Non-Domestic Buildings.” *Sustainable Cities and Society* 41 (July 2017): 625–38. https://doi.org/10.1016/j.scs.2018.05.051.

Si, Jin, Ljiljana Marjanovic-Halburd, Fuzhan Nasiri, and Sarah Bell. 2016. “Assessment of Building-Integrated Green Technologies: A Review and Case Study on Applications of Multi-Criteria Decision Making (MCDM) Method.” *Sustainable Cities and Society* 27: 106–15. https://doi.org/10.1016/j.scs.2016.06.013.

Subramanian, Muthu Senthilkannan. 2015. *A Review of Social Life Cycle Assessment Methodologies*. *Springer*. Vol. 6. https://doi.org/10.3390/su6074200.

Tscheikner-Gratl, Franz, Patrick Egger, Wolfgang Rauch, and Manfred Kleidorfer. 2017. “Comparison of Multi-Criteria Decision Support Methods for Integrated Rehabilitation Prioritization.” *Water (Switzerland)* 9 (2). https://doi.org/10.3390/w9020068.

Wang, Jiang Jiang, You Yin Jing, Chun Fa Zhang, and Jun Hong Zhao. 2009. “Review on Multi-Criteria Decision Analysis Aid in Sustainable Energy Decision-Making.” *Renewable and Sustainable Energy Reviews* 13 (9): 2263–78. https://doi.org/10.1016/j.rser.2009.06.021.

Wimmler, C., G. Hejazi, E. de Oliveira Fernandes, C. Moreira, and S. Connors. 2015. “Multi-Criteria Decision Support Methods for Renewable Energy Systems on Islands.” *Journal of Clean Energy Technologies* 3 (3): 185–95. https://doi.org/10.7763/JOCET.2015.V3.193.